"Particle Detectors: Operating Principles and Calibration Issues"

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Abstract

Technological advances in particle detection instrumentation is one of two factors underlying the considerable progress in nuclear and hadronic physics of the last 50 years; the other being the development and extension of theoretical techniques. Fifty years ago, particles were detected in small table-top size devices at rates of a few per second. Today, detectors the size of auditoriums are filled with instruments generating hundreds of thousands of signal channels with overall event rates in the tens of thousands. It can seem overwhelmingly to a new student, but I hope to cut through the complexity by elucidating the underlying principles of operation of most of the common particle detection instruments.

Particle Interactions with Matter

For a variety of detection techniques I will start by explaining the primary interaction of the particles to be detected with matter, for example: ionization and production of light through the Cerenkov, transition radiation and synchrotron radiation processes. These interactions form the first step toward the goal of measuring the time, spatial trajectory and energy deposition of the charged and neutral particles emanating from the beam-target region in order to reconstruct the full 4-momentum structure of one event.

Signal Generation in Particular Instruments

In this section, I will describe the signal generation process for several detectors; for example, how the primary ionization trail left by a charged particle in a wire chamber is converted by a high-gain "avalanche process" into an electric current large enough to be amplified and digitized by subsequent electronic modules.

I will outline this signal generation process for the common detector types, showing how the original response (ionization or light) is amplified, digitized and recorded by the subsequent amplification and discrimination devices in order to measure the time, energy and spatial location of the particle traversing the detector.

Various Detector Operating Parameters and Performance Specifications

In this part of the lecture, I will describe the performance specifications (efficiency, background rejection, accuracy) of various types of detectors. In particular, I will talk about actual implementations in current and previous detector set-ups of charged-particle tracking detectors. I will cover wire chambers, for example, drift chambers and straw-tube chambers, micro-pattern gas detectors such as gas electron multipliers, (GEM's), and micro-mesh gas detectors (Micromegas), and tracking devices formed from Silicon, patterned with either strip or pixel readout.

I will summarize the typical size, granularity, efficiency, spatial resolution and rate-tolerance of these various tracking devices, as well as give a feeling for price and maintenance issues involved. I will give a briefer overview of similar specifications for Cerenkov and calorimetric detectors. I will conclude by showing how one might develop an entire detector by assembling the various sub-detectors into one overall plan.

Calibration Methods

Concentrating on one particular type of detector, drift chambers, I will walk the audience through the various steps involved in calibrating such devices.

The primary purpose of a drift chamber is to provide a sharply-defined spatial location through which the track must have passed, as input to track reconstruction software which can determine a best fit to the position, momentum and trajectory of a charged particle. However, the spatial location is not directly measured. Instead, the amplified and discriminated "avalanche" current is input to a time to digital converter (TDC) which produces a time signal. After correcting for a variety of factors, such as cable delays, particle flight-time, and signal "time-walk", the corrected time is converted into a distance of closest approach (DOCA) from the wire. I will talk about various common features to the distance to time function which follow directly from understanding the electric field surrounding the wire and the physical process by which an ion "drifts" through a gas while being pulled by the electric field and having its local trajectory curved by the magnetic field. I will conclude this section with a brief demonstration of a modern "GUI-driven" calibration program which allows the calibrator to intuitively understand and correct for all of these effects.

No discussion of calibration is complete without a specification for the data-base which stores and orders the many thousand items of data generated in the calibration procedure. I will present a particular data-table design as well as an indexing scheme which clearly distinguishes between trial and final calibrations.

Reconstruction Software

I will elucidate "off-line" event reconstruction with one example: finding and fitting charged-particle tracks with the goal of determining the charged particle's momentum, angle and trajectory through the detector. I will discuss the information flow leading from signal to time hit to spatial hit to final trajectory by presenting a schematic of an object model. The goal of such a design is to understand which methods are required at each stage of information refinement, and how to associate these methods with quasi-independent objects which must communicate and cooperate with other such operators. I will ground this abstract discussion in concrete reality by showing one example being written for a new large-acceptance device being built at Jefferson Lab in Newport News, the "CLAS12" detector.

What Can Go Wrong

I will end the lecture with a series of anecdotes of real historical problems that have happened with detectors. Though not a substitute for making your own mistakes, I present these in a light-hearted attempt to convince you to plan for the best and prepare for the worst. In the words of the 5-year-old son of a colleague who was doing his first experiment: when she asked him what he had learned he quickly responded, "never make the wrong mistake".

Bibliography

For an excellent overview, read the article **"Particle Detectors"**, by K. Kleinknecht, published in Physics Reports 84 (1982) pg.85.

For the classic paper on wire chamber operation, see the article **"Principles of Operation of Multiwire Proportional and Drift Chambers"**, by F. Sauli, published as CERN report: CERN-77-09.