The ALFA Detector and Physics Program

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Abstract
The ALFA detector is dedicated to obtaining a precise absolute calibration for luminosity measurements at the ATLAS experiment. Fiber trackers are installed in Roman Pots at a distance of 240m from the interaction point on both sides of the detector. In special runs with high β^* optics the pots approach the beam to distances of order a millimeter, allowing elastically scattered protons to be detected at extremely small angles. Extracting the differential cross section in the corresponding Coulomb-Nuclear interference kinematic region as a function of the squared four-momentum transfer t leads to luminosity measurements with a precision of 3%.

1 Introduction

The luminosity relates event rates to cross sections - the main observable quantity of all accelerator-based experiments. Its value is defined by the machine parameters: beam currents, transverse beam widths and revolution frequency. A good measurement of the luminosity is required to ensure precise cross section measurements and to give fast feedback for beam tuning and monitoring for optimal operation of the LHC.

ATLAS follows a number of different approaches to measure the luminosity [1]. The first method is based on direct calculation based on the knowledge of LHC machine parameters. A precision of around 20% - 30% is envisaged at the LHC startup. After some years of dedicated machine studies, 5% accuracy seems to be the end point of this method. The second type of luminosity measurement involves counting the rate of a process with a well-known cross-section. For example, the production of lepton pairs via the QED two-photon process can be precisely calculated and used as in luminosity measurements. However the QED cross sections are small and resulting event rates are at the statistical limit, especially in the low luminosity phase. The QCD production of W and Z bosons is a more promising process with a large cross section and a clean signature. It is one of the best known QCD cross sections and the main uncertainty comes from the PDFs. Including the experimental uncertainties a total luminosity error of 10% seems feasible. The PDFs may become more contrained when LHC data are available and the luminosity error from this method might reach 5% after some years of LHC running.

The third method is related to the elastic proton scattering process. This rate is linked to the total interaction rate through the optical theorem and will provide several additional options to determine the luminosity. The standard approach combines the total interaction rate R_{tot} and the forward elastic rate $R_{el}(t=0)$ via the optical theorem and determines the luminosity as

$$L = \frac{1}{16\pi} \frac{R_{tot}^2 (1+\rho^2)}{dR_{el}/dt(t=0)} \ .$$

Here ρ is the ratio of the real to the imaginary part of the elastic forward scattering amplitude, which lies in the range 0.13-0.14 at LHC energies [2]. Small-angle elastic scattering has traditionally been used to get a handle on the luminosity calibration at hadron colliders via equation 1. This generally requires a precise knowledge of the inelastic rate over the full rapidity range, in contrast to the limited rapidity coverage of real detectors such as ATLAS. However, if very small scattering angles, corresponding to very small momentum transfers t, can be covered, the cross section becomes sensitive to the electromagnetic scattering. Via the precisely known Coulomb interaction, a calibration can then be performed without measurement of the inelastic rate. This option is pursued by the ATLAS collaboration, for which the ALFA detector [3] is currently under construction. In order to reach the Coulomb-Nuclear interference region where the electromagnetic and strong interaction amplitudes are of similar size, scattering angles of about 3.5 μrad must be covered, corresponding to $|t| = 0.00065$ GeV^2. To reach the Coulomb region is a very challenging task, since the tracking detectors have to be moved to a very close distance of about 1.5 mm from the circulating beams. If this can be managed, a luminosity error of 3% seems to be feasible.

Some details of tracking detectors in the Roman Pots, the Monte Carlo estimates for the luminosity determination and the present status of the main ALFA components are described in the next chapters. This can only be achieved with special beam optics with a very high β^*=2625m yielding a parallel-to-point focusing and a low normalised emittance $\epsilon_N = 1\mu$rad m. In addition, the detector has to be operated very close to the beam at a distance of about 1.5 mm, corresponding to 12 σ of the beam width. Dedicated runs are foreseen at low luminosity with these special beam conditions for measurement with ALFA, which can accumulate in 100 hours of beam time sufficient statistics to achieve a luminosity calibration with an accuracy of 3%, including systematic uncertainties [6].

2 The ALFA detector

Roman Pot stations equipped with two vertically movable Roman Pots housing the detectors will be installed in the LHC on both sides of the interaction point at a distance of 240 m. There will be two stations separated by 4 m on each side, thus in total 8 pots will be instrumented with ALFA detectors. Figure 1 shows an ALFA Roman Pot station in relation to the beampipe. Each unit consists of the Pots housing the detectors and the support and moving mechanics such as bellows, roller screws, motor drives, positioning sensors etc. To minimize the amount of material in front of the detectors the pots have thin 80μm windows. The interior of the Pot will be in a secondary vacuum of about 1 mbar to avoid deformations induced by the LHC primary vacuum. The 4m separation of the pairs of pots on either side of the interaction point ensures precise tracking. The positioning precision due to the Pot moving system is expected to be 10μm. The position of the Pot in respect to the circulating beam will be determined by LVDTs with a precision of $\pm$ 20μm. The Roman Pots are considered as machine elements and their movement is included in the LHC collimator control system.

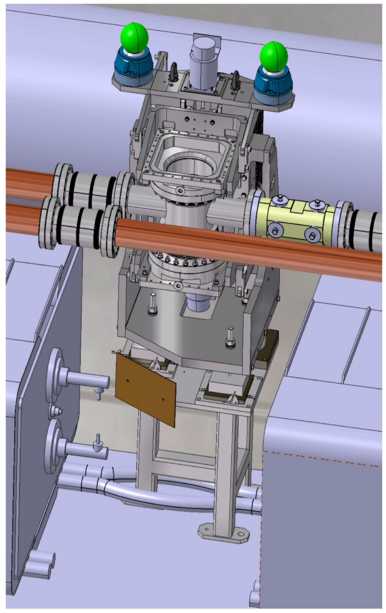

Fig. 1: Schematic drawing of the ALFA Roman Pot station.

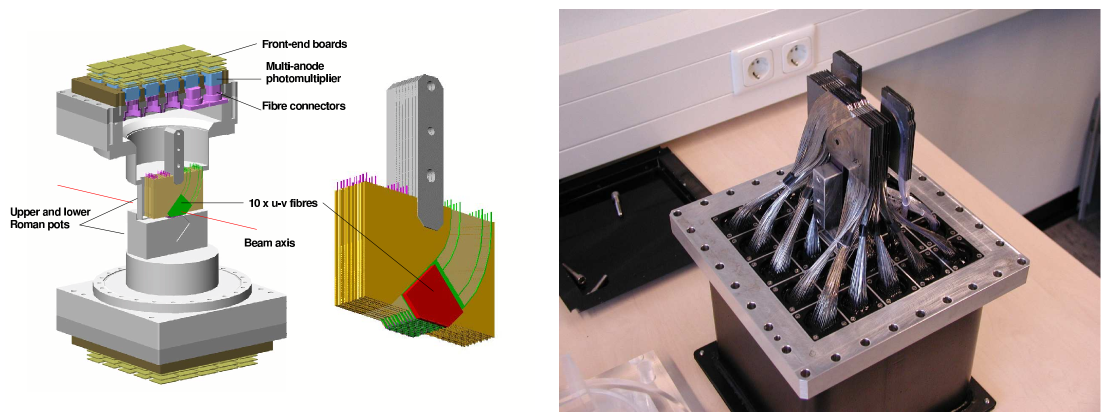

Fig. 2: Conceptual design of the ALFA tracker with multi-layer fiber detectors inserted and a photograph of a full-size prototype.

The design of the ALFA tracker is shown in Fig. 2. The tracking detectors are multi-layer scintillating fiber structures as illustrated in fig. 2. Layers of two times 64 KURARAY SCSF-78 single cladding fibers of square 0.5×0.5 mm^2 cross section are glued in stereo geometry on a Titanium substrate. Ten of such substrates, staggered by 71μm, are precisely assembled on a support structure. The ultimate resolution of such a detector arrangement is 14μm and in previous test beam measurements values of 25μm have been achieved [4, 5]. The spacing of the planes in beam direction is 2.5mm results in an inclination of the staggered fibers by 28mrad relative to the beam axis. Hence not to benefit from the staggering the detector axis should be aligned with the beam axis with an precision around 3mrad.

As visible in fig. 2 the most fiber ends are cut at the lower edge under 45°. Apart from these cuts the fibers are aluminized to increase the light yield. For fibers with 90° ends the gain is about 75%, while for 45° ends about 50% of the light undergoes a reflection at the uncoated edge. The fibers are routed over 25cm distance to a connector flange. All 64 fibers of a plane are grouped into a 8×8 matrix to be coupled to the photo-cathode of the Multi Anode Photo-Multiplier Tube (MAPMT) Hamamatsu H7546B. This device has a gain around 10^6 at the maximum voltage of 1000V. The cross talk between adjacent channels is at the level of 2-3 %.

To ensure an exact positioning of the fiber detectors in respect to the LHC beam, which can vary from fill to fill, each Roman Pot is equipped with a pair of overlap detectors. These detectors move with the Pots and measure the relative vertical positions of the upper and lower tracking detectors. The measurement principle is the common tracking of halo particles in both overlap detectors. These detectors consist of 3 planes of 30 horizontally arranged fibers staggered by 166μm to each other. The achievable precision depends mainly on the statistics of accumulated halo tracks. A positioning precision of 10μm of the upper and lower detectors are needed to keep the contribution to the luminosity error below 2%. All 180 fibers of the overlap detectors in a Pot are read out by 3 MAPMTs H7546B.

Both main and overlap detectors are equipped with corresponding trigger counters which cover the active area. For the main detectors two trigger tiles of fast plastic scintillator BICRON BC-408 are used in coincidence. The overlap detectors are covered by a single trigger tile. The light signals from the scintillators are guided by bundles of clear 0.5mm round double cladding KURARAY fibers to the photo-multipliers. To amplify the trigger signals 4 single channels photo-multipliers R7401P with Bialkali photo-cathode or the new type R9880U with Super-Bialkali photo-cathode and enhanced quantum efficiency around 35% are foreseen.

A proton traversing a 0.5 mm scintillating fiber gives on average a light signal of 4 photo-electrons. The MAPMT H7546B with a typical gain of 0.5 - 1.0×10^6 leading therefore to signals charge of 0.3-0.6 pC at the amplifier input. The readout electronics is a stack of printed circuit boards, named PMF, located on top of each MAPMT. The MAPMT signals are fed into the MAROC2 readout chip, which performs amplification and shaping. The signals are compared to a threshold and the resulting digital data serially transmitted to the motherboard. The motherboard serialize the data from 23 PMF units and send them via an optical link to the central ATLAS data acquisition system.

3 The Measurement Principle

The detectors have to approach the circulating beams between 1 and 2mm distance, which requires well collimated beams under special optics. This optics at high β^* = 2625m and 90° phase advance yields a parallel-to-point focusing i.e. a linear relation between the track position in the fiber detectors and the scattering angle at the IP.

The expected detector performance was estimated by Monte Carlo simulation of elastic pp-scattering [6]. A modified version of PHYTIA6.4, to include the Coulomb-term and the real part of the nuclear elastic scattering amplitude, plus the beam transport program MADX were used for this purpose [7,8]. Accepted events are requested to fulfill the left-right trigger condition and have a space point reconstructed in 4 fiber detectors. The resulting hit pattern in the ALFA fiber detectors is shown in fig. 3.

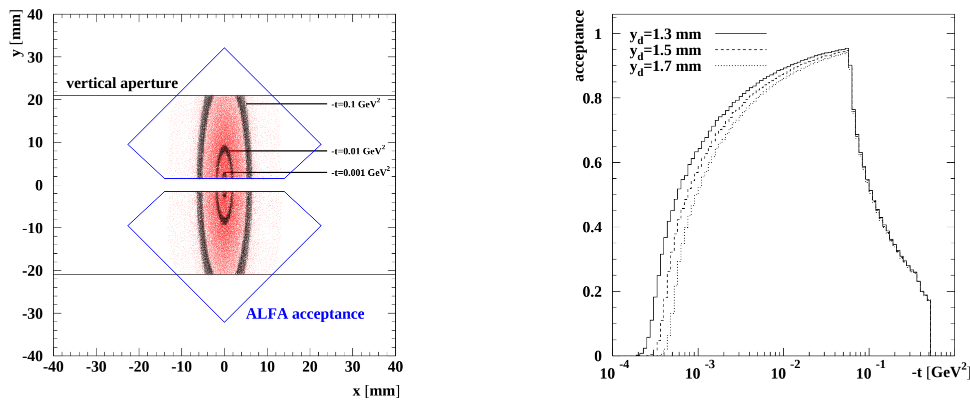

Fig. 3: Hit pattern of protons and acceptance in dependence on t.

Also shown in fig. 3 is the geometrical acceptance in dependence on t. The distance of closest approach to the beam centers is assumed between 10 and 20 σ_{beam}, depending on the halo conditions. For a distance of 1.5 mm about 67$\%$ of all events in the t-range 0.5 10^{-5} to 0.5 GeV^2 are accepted.

The absolute luminosity is obtained from a fit of the elastic scattering cross section formula to the reconstructed and corrected t-spectrum. Apart from the luminosity L, the nuclear slope b, the ratio of real and imaginary scattering amplitude ρ and the total cross section σ_{tot} are determined.

$$\frac{dN}{dt} = \pi L \left| -\frac{2\alpha}{|t|} + \frac{\sigma_{tot}}{4\pi}(i+\rho)e^{-b|t|/2} \right|^2$$

Out of 10 million generated elastic events 6.6 million with an acceptance above 50$\%$ are used for the luminosity fit. The simulated and reconstructed t-spectrum with a linear scale for the rate is shown in fig. 4. The large total cross section ensures the collection of enough events to keep the statistical error small. For 6.6 million events the statistical errors of the luminosity and the total cross section are 1.8$\%$ and 0.9$\%$, respectively. Some systematic uncertainties which are not taken into account in the fit procedure are: the beam divergence and crossing angle at the IP $(0.3\%, 0.2\%)$, the uncertainties in the knowledge of the optical functions and phase advance to convert the hit points into a scattering angle at the IP $(0.6\%, 1.0\%)$, detector resolution and alignment $(0.3\%, 1.3\%)$, and finally statistical fluctuations in the background subtraction (1.2%). These values combined with the statistical error result in a total error of 3$\%$ [6].

Based on this Monte Carlo study about 100 hours running at a low luminosity of $1.0\times 10^{27} cm^{-2}s^{-1}$ are necessary to collect the used data sample [3].

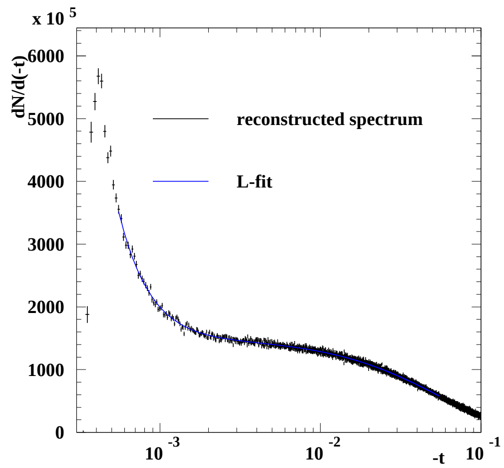

Fig. 4: Reconstructed t-spectrum for detectors placed at 1.5 mm distance.

4 The Status of ALFA Components

This chapter gives a brief review about the production status of the main components in summer 2008: the fiber detectors, the electronics, and the mechanics.

To enlarge the light yield and to reduce the optical cross talk all fibers are coated by a thin Aluminum layer. The gain is about 75% for fibers cutted by 90° and 50% for the 45° fibers. The far end of the fibers are coated by sputtering technology in LIP Lisbon, followed by the side coating via vacuum evaporation at CERN. All fibers for detector production can be ready at the end of 2008. The fibers are glued on precise Titanium substrates which were produced by electro-erosion in HU Berlin. These substrates have precision holes and edges to ensure the staggering of the fiber layers. This production step is finished and the 3D measurements confirmed an accuracy below 10μm. In the next step the fiber detectors are produced by capillary gluing at JLU Giessen. After that the assembling of the complete detector insert is performed, the routing of all fibers to the MAPMT connectors, the gluing and milling of the connectors. A prototype-1 detector has been produced for installation issues in the tight environment of the Roman pot. Another prototype-2 detector is ready for use in a test beam measurement in summer 2008. To benefit from the staggering all fiber positions are measured by microscope at DESY Hamburg. The fiber positions are described by straight lines, which are stored in a data base and used for the track reconstruction. The precise positioning is limited due to some inherent conditions: the RMS of the fiber diameter, defects from the Aluminum coating, the precision of approaching the edges due to dust particles and the bending force on the fibers, and more. In some substrates of the prototype-2 deviations of about 100μm from the nominal staggering have been observed. This results in a reduced resolution of 40μm, while 25μm has been measured in the 2006 test beam campaign for a detector with 16 fibers per layer [4, 5]. Presently we investigate possible reasons for the staggering deviations to ensure that all detectors have similar quality close to the demands of the design. The detector insert is completed by corresponding trigger substrates. The essential demand for these substrates is a good light yield to guarantee 100% trigger efficiency. The test beam campaign 2007 in a DESY 6 GeV electron beam has shown a sufficient light yield between 30 and 40 photo-electrons using clear fiber bundles as flexible light guides. The fibres are coupled by optical connectors through the vacuum flange to multi-anode PMTs (MAPMT) with 64 pixels. The MAPMTs are connected through a stack of PCBs to the MAROC read-out chip, which performs amplification, shaping, gain equalisation and discrimination of the signals. Signals from MAROC are further processed by a FPGA which samples the signals at 40 MHz, stores the data for the L1 latency and transmits the buffer serially to the motherboard in case of a positive trigger signal. All signals of a single ALFA detector with 23 MAPMTs are collected by the motherboard which transmits the signals via optical link to the ATLAS DAQ. The connection to the central ATLAS trigger processor is also done via optical link, while the control of the motherboard and connected components is achieved by an ELMB module. The scintillation signals from the individual fibers are amplified in the 64 channel MAPMTs H7546B. The gain and uniformity measurements to correct differences in the subsequent front-end electronics are performed for each device at DESY Hamburg. The front-end electronics consists of a so-called PMFs which are 3-layer-stacks of PCBs close to the MAPMTs. Each PMF contains a MAROC2 read-out chip, which performs amplification, shaping, gain equalisation and discrimination of the signals. Signals from MAROC2 are further processed by a FPGA which samples the signals at 40 MHz, stores the data for the L1 latency and transmits the buffer serially to the motherboard. For the test beam campaign with prototype-2 32 PMFs were produced in LAL Orsay. The S-curve measurements have shown are very good quality in terms of homogeneity, linearity and sensitivity to expected fiber light signal of 4 to 5 photo-electrons.

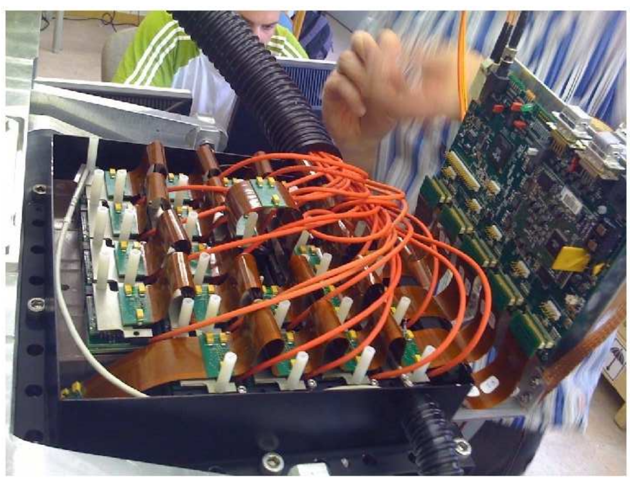

Fig. 5: Front-end electronics: Kapton cables each connected to 5 PMFs sitting on top of the MAPMTs.

The Roman Pot mechanics has to fulfill high demands on precision and positioning reproducibility. Mechanical and optical position measurements have been performed with a preprototype. Some front-back and left-right distortions up to 200μm have been observed in extreme positions. However their contribution to the total luminosity error is uncritical below 0.2%. In addition the stiffness of the slides keeping the pots have been improved replacing the Aluminum by Steel slides. The mechanical components for all stations received from Prague and are now assembled at CERN.

In summer 2008 a full Roman Pot was tested in the CERN test beam H8. A telescope of silicon strip detectors has been used for tracking. The data analysis is underway and will be published as internal ATLAS note. The schedule of the ALFA installation depends on the LHC machine status. A possible scenario is the installation of the mechanics in spring 2009. The pots itself are machined at CERN and should be installed together with the station mechanics to avoid another break of the LHC vacuum. The production of fiber detectors could be finished 2009 and their installation completed in the shut down 2009/2010.

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