Proton Timing for ATLAS Forward Physics with Diamond Detectors.

G. Chiodini[1] ,A. Corvaglia [1] ,P. Fiore [1] ,F. Oliva ,N. Orlando [1,2] ,C. Pinto [1,2] and S. Spagnolo [1,2].

[1]Istituto Nazionale di Fisica Nucleare, Sezione di Lecce, Italy.

[2]Dipartimento di Fisica, Università del Salento, Italy.

The Lecce group in August 2012 proposed to the ATLAS Forward Physics (AFP) collaboration to replace the QUARTIC timing detector with Diamond detectors to solve two main limitations: photodetector radiation damage and large detector size. In fact, between the most interesting features of this material there are the very high tolerance to big radiation doses and the intrinsic speed of the collected signal (related to the high mobility of the charge carriers).

The AFP collaboration wrote a proposal [1] to extend the ATLAS physics program by selecting p-p collisions at LHC where the protons remains intact (forward protons) and a central system X is produced. These processes proceed mainly by the Feynman diagrams of Figure 1, which turn LHC in a gluon-gluon collider and a photon-photon collider.

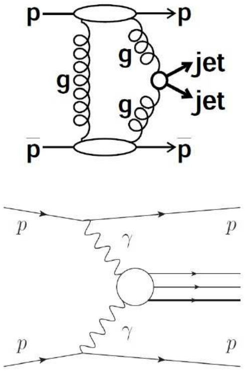

Figure 1. Central Exclusive Production via the exchange of di-gluon system (top) and EW production of a central system X by two photons exchange (bottom).

The Central Exclusive Production (CEP) pp $\rightarrow$ pϕp is very attractive for resonances and new particles studies because the di-gluon system obeys a J$_z$=0, C-even, P-even, selection rule. In addition, production of W or Z pair, via photon-photon collisions pp $\rightarrow$ p$\gamma\gamma$p$\rightarrow$ pW(Z)W(Z)p with both protons tagged, allows the probing of EW anomalous coupling with unprecedented precision at LHC. Finally, measuring the invariant mass of the two tagged protons is possible to trigger on the production of new invisible particles, such as monopoles pp $\rightarrow$ p$\gamma\gamma$p$\rightarrow$ pMMp, and measure their mass with the missing mass technique.

The AFP apparatus consists of high precision tracking and timing detector at about 220 m upstream and downstream of the ATLAS interaction point to detect protons scattered at small angles and with small momentum losses. The tracking detector must be capable to measure the proton fractional momentum losses in the range 0.02< η <0.2 (corresponding to central mass from few hundreds GeV to few TeV) with a precision of about 4-5 GeV in the invariant mass. The timing detector must be capable to tag protons with 10 ps time precisions, in such a way to correctly associate protons coming from the same primary vertex and detected in the opposite AFP arms from combinatorial background. The baseline technologies for AFP detector are 50x250 μm^2 Hybrid Silicon Pixel detector with edge-less 3D pixel silicon sensors for the tracking and solid state Cherenkov radiator readout by micro-channel plate photomultiplier tube (MCP-PMT), named QUARTIC, for the timing.

The timing detector is crucial to integrate high total luminosity and studies process with cross-section of the level of few fb, such as EW anomalous coupling and possible BSM Heavy Objects. This is possible only collecting data in normal LHC physics runs, where the high pile-up conditions make primary vertex separation necessary. The MCP-PMT photodetector used by the QUARTIC is subject to radiation damage and likely must be replace every few years of running. Moreover, the QUARTIC radiator is quite large in size and difficult to fit in a traditional Roman Pot mechanical insertions and a more sophisticated solution is likely necessary, such as a moveable Hamburg Beam-pipe.

The Lecce group in August 2012 proposed to the AFP collaboration to replace the QUARTIC timing detector with Diamond detectors. The envisaged advantages of using diamond detectors are:

- Radiation resistance above 10^{16} 1 MeV n. eq./cm^2.

Figure 2. Proposed diamond detectors geometrical layout to tag forward proton at LHC with 10 ps time resolutions .

- No cooling required.
- Robust.
- Possible to trigger on high missing mass.

Anyway, there are critical points about the diamond detector solutions that must be addressed. These are:

- Small signal/noise ratio for minimum ionizing particles
- Final sensor costs.
- Procurement of diamond detector-grade sensors of large size and in large quantities.

To address the last two points we are in contact with two highly qualified vendors: Element 6 (Bristol) and Element II-VI (USA). Both vendors are capable to deliver large size detector-grade poly-crystal diamond sensors making the procurement of the material of reduced risk and likely less expensive than expected few year ago. The first point instead is more technical and requires an extensive R&D program to prove that a diamond detector can meet such a good time resolution.

Time resolution is determined by strongly inter-related and conflicting requirements such as: signal rise-time, noise, and power consumption. In fact, time resolution σ_T is approximately given by the following formula: $\sigma_T = \frac{T_{rt}}{S/N}$, where T_{rt} is the signal rise-time and S/N the signal-to-noise-ratio. CVD diamond-sensor detectors are already successfully used in nuclear physics for time-of-flight measurements of relativistic ions (atomic number Z>1), in which the signal intensity is high, reaching time resolutions of the order of tens of ps. This result suggests the possibility of using diamond detectors for time-of-flight applications also for minimum-ionizing particles for which presently, due to the small amplitude of the diamond signal or, better, to the signal-to-noise ratio (S/N) of the available front-end electronics, the time resolution is limited only to a few hundred ps [2].

We are investigating the possibility tag the 7.5 TeV protons at LHC with a a time resolution comparable to the one obtained with relativistic ions using high-quality polycrystalline diamond.

Figure 3. Diamond detectors connected to Front-end electronics in experimental area during the October 2012 testbeam at T4-H6 North Area CERN with 120 GeV pion beam.

The proposed detector layout for each AFP arms is sketched in Figure 2 and it is made of 8 layers of diamond detectors inclined by about 65^0 with respect to the incoming protons. The use of eight layer is dictated by the aimed final time resolution of 10 ps that can be reached making a weighted average between eight independent time measurements of about 30 ps resolutions. This requires to improve the actual time performance of diamond detector with MIP particles a factor of about an order of magnitude. Placing the diamond sensor with a large angle with respect to the coming protons and relying on the relativistic rise of the proton energy lost at 7.5 TeV with should get a significant increase in the signal-to-noise ratio. Finally, we want to employ a low-noise, low-capacitance, high-speed and high “beta’, Si-Ge hetero-junction transistor as first amplifier stage integrated on the diamond sensors in order to reduce the stray capacitance and consequently the equivalent input noise. The proposed front-end will allow an increase of the signal-to-noise ratio and an optimization of the signal shaping time, thus maximizing the time resolution.

We wanted to verify experimentally that the signal collected by a poly-crystal diamond increase with the track angle inclination and the time resolution improve accordingly to the expectations. In fact, the poly-crystal nature of the sensor could create dynamic trapping phenomena and deteriorate the time resolution. In October 2012, we placed two diamond strips detector at different angle with respect to a 120 GeV pion beam at CERN and recorded the signal waveforms from the two central strips with a 200 ps sampling time using a LECROY oscilloscope (see

Figure 3). Analyzing off-line the time-of-flight between the two detectors we could extract a time resolution of about 260 ps at 25^0 track inclination. In order to increase the statistics at different angles and perform more sophisticated off-line analysis (see [3]) we used the WAVECATHER26 DAQ of the Saclay group based on the dedicated ADC sampling chip SAMPIC. The table below reports the results obtained by an on-line analysis made by the Saclay group.

Angle[^{0}]	Mean[V]	$\sigma_T[ps]$
90	0.130	523
65	0.127	543
45	0.180	431
25	0.195	302

Table 1
Measured average pulse height and time resolution with poly-crystal diamond detector for different track angle inclinations.

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