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FAST TIMING DETECTORS FOR LEADING PROTONS AT THE LHC: QUARTIC*

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The study of exclusive reactions $p+p\to p+X+p$ at the LHC at high luminosity requires a high precision measurement of the time difference Δt between the protons to reduce pile-up background. With $\sigma(t)=15$ ps the z-position of the interaction, *if and only if they came from the same collision*, is determined to $\sigma(z)=3$ mm. I discuss the development of quartz or sapphire Cherenkov counters with this goal.

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Central exclusive reactions at the LHC, defined as $p+p\to p+X+p$ with both protons detected, is especially interesting in the high mass and electroweak sectors with, *e.g.*, $X=W^+W^-$, $H(125)$, and jets. A proposal to study this physics has now been endorsed by CMS and TOTEM as a joint project: CT-PPS for CMS-TOTEM-Precision Proton Spectrometers. But these cross section are low, $\sim$ fb–pb, and require data at high luminosity with pile-up, $\mu\sim 30$–40 events per bunch crossing. Most events with two protons are pile-up background, with $(p+X)$ and $(Y+p)$ diffractive events in the same bunch crossing. Kinematic constraints cannot reduce this background enough, but measuring the time difference Δt between the protons, which gives $z(interaction)$ *if* they came from the same collision, can give a large (~ 20–$30\times$) reduction factor[1]. If the time resolution of one detector is $\sigma_{\rm t}$, the resolution on the time difference is $\sigma(\Delta t)=\sqrt{2}\,\sigma_{\rm t}$. As the z measurement from the proton timing is $z_{pp}=\frac{1}{2}c\,\Delta t$, we have $\sigma(z_{pp})=\frac{1}{2}c\,\sqrt{2}\,\sigma_{\rm t}=c\,\frac{\sigma_{\rm t}}{\sqrt{2}}=3.18$ mm for $\sigma_{\rm t}=15$ ps. We have demonstrated

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[1] This was first proposed for an exclusive Higgs search at the Tevatron [1], a Letter of Intent which did not become a proposal.

such a resolution if one uses four QUARTIC detectors in series, each having $\sigma_{\rm t} = 30$ ps. But several improvements are "on paper", and we are far from any intrinsic limit; one could hope for $\sigma_{\rm t}$ of a few ps in the future, and the background would be reduced proportionately. The spread in path lengths of a proton is insignificant, contributing $\lesssim 1$ ps. Proton times are measured with respect to a reference clock signal, *e.g.* an RF signal stabilized with a phase-locked loop at the picosecond level. Real $p + X + p$ events can check the calibration of Δt at least hourly if necessary. Measuring the absolute times of the protons is only useful at the ~ 0.5 ns level to reject out-of-time background, but cannot reduce pile-up without knowing the absolute time of the collision from the central detector with resolution $\lesssim 50$ ps or so (the events are spread in time by $\sigma(\text{spread}) \sim 150$ ps). Adding precision timing to the central calorimetry may happen eventually, and would provide additional pile-up background reduction.

The requirements for timing detectors for CT-PPS are: (a) time resolution $\sigma_{\rm t} \sim 10$ ps, (b) edgeless on the beam side, $\Delta x \lesssim 200$ μm, (c) radiation hard close to the beam, $\sim 10^{15}$ p/cm^2, (d) fast readout to record every bunch crossing with 25 ns spacing, (e) segmentation for multi-hit capability, especially close to the beam. The present baseline for the project has quartz bars as Cherenkov radiators, read out with SiPMs. We tested two bar geometries, the "angled-bar" and "L-bar" configurations [2]. The former has several bars inclined at the Cherenkov angle of 48° onto a photodetector, in that case a MicroChannel Plate PMT (MCP-PMT) perpendicular to the bars. This is an isochronous design, in which the fastest light from each bar arrives simultaneously (as a wavefront) at the photodetector. The angled-bar QUARTIC is the baseline for the ATLAS AFP project. The other geometry has bars in the form of an L, with one leg, the radiator bar, parallel to the proton path and the other a light-guide bar at 90°. If the protons are really parallel to the radiator bar, and as long at the refractive index satisfies $n > \sqrt{2}$ (quartz has $n \sim 1.48$) most of the radiated Cherenkov photons reach the photodetector by total internal reflection (assuming perfect, clean surfaces). No mirrors! We made and tested a module with 3×3 mm^2 bars onto MPPC's of the same dimensions in a plane array. This is not an isochronous design, so a single-channel MCP-PMT cannot be used, but a multi-anode (with 3×3 mm^2 pads) MCP-PMT is an option if cross-talk between the channels is small. MCP-PMTs are faster than SiPMs and have better quantum efficiency, but photocathode damage by positive ion feedback from the MCP has been an issue. This is on the way to being solved [3]. SiPMs are relatively cheap, available in sizes from 1×1 mm^2 to 3×3 mm^2, but have a worse SPTR (Single Photon Time Resolution) than MCP-PMTs and are not nearly as radiation-hard. In the L-bar design the light-guide length keeps the SiPMs away from the beams, and they can be in a shielded enclosure to minimize radiation damage. In our design the SiPMs are held by pressure between the quartz bar and the readout board, so they can easily be replaced in a short access if needed, but hopefully this is not necessary more than twice a year (about 50 fb^{-1}).

A novel quartz bar geometry was presented at this workshop by Brandt [3], the LQ-bar. It combines the 48° angled bar and the L-bar, but recovers light emitted at the opposite azimuth ϕ, pointing away from the photodetector, with a cut-off bar end which is mirrored. This is promising, and can also adapt the QUARTIC to fit in Roman pots (RP). The L-bar design we made and tested at Fermilab is for a moving beam pipe (MBP), but can be modified to fit in a Roman pot, as that will be the vacuum mechanics for 2015–2016.

Figure 1 shows the 20-channel L-bar QUARTIC module (MBP design) made for Fermilab tests. The area covered is a 5×4 array of quartz bars, each 3×3 mm^2, so the active width is 15 mm (x, hor.) $\times$ 12 mm (y, vert.). With this design increasing the x-coverage is simple, but any increase in the y-coverage results in a longer (in z) detector (the L-bend converts y to z). In principle, the spatial granularity can be increased close to the beam, with 2×2 mm^2 or even finer bars. However, apart from the longer z-space needed there are correspondingly more internal reflections along the bars (which should not matter if the surfaces are perfect; this would need testing) and very fine bars would be fragile. Other options would be rectangular bars, which could allow (*e.g.*) $\Delta x = 1$ mm close to the beams, with less

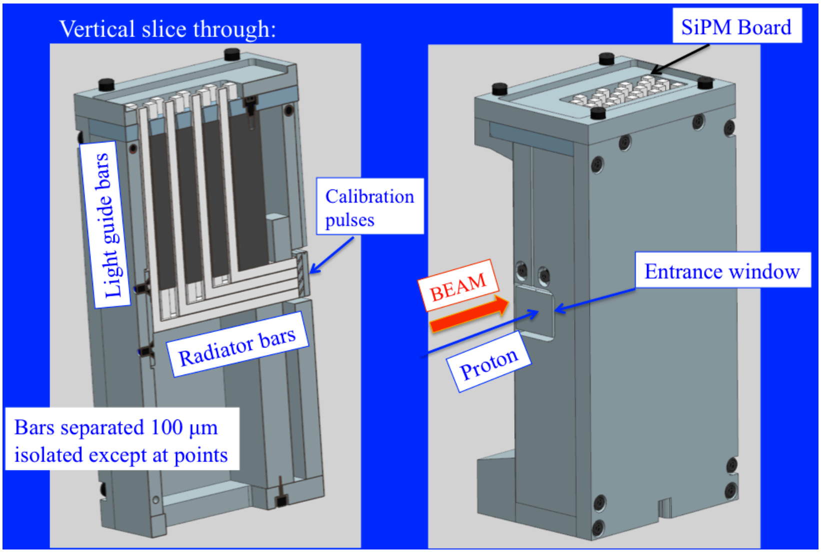

Fig. 1. Design of the L-Bar QUARTIC (MBP version) with 20 SiPM channels.

granularity in y. However, in the RP version adding x-channels increases the length as well as the variation in radiator bar lengths (not identical in this design). A feature of the L-bar design is that protons through some bars also traverse the light-guides of other bars. Those (smaller) signals worsen the granularity, although when one has a single proton through the array the extra signals *may* be included in the time measurement.

We did beam tests at Fermilab (with 120 GeV protons) with four L-bars in-line, with both 30 mm and 40 mm radiator bars, and Hamamatsu S-10362-330050C SiPMs. After pre-amplifiers and clipping, the signals were about 80 mV with an 800 ps risetime (measured on a DRS4 'scope). The reference time was provided by a Photek PMT240 in the beam; Cherenkov light in the 8 mm quartz window gives a $\sigma_{\mathrm{t}} = 8$ ps detector. The measured single-bar resolution was $\sigma_{\mathrm{t}} \sim 30$ ps for both 30 mm and 40 mm bars. Simulations (GEANT) predict that the resolution improves with bar length up to about 40 mm, even though the light generated at the front of the radiator arrives late. This is probably not true with a faster photodetector (*e.g.* MCP-PMT); we plan to measure this in our next beam tests. This resolution does not yet meet our goals. In the L-bar + SiPM design at least two potential improvements are: (a) Using sapphire bars instead of quartz; the refractive index is higher ($n = 1.70$ *cf.* 1.48) giving more light per cm, but there is higher dispersion. Simulations predict an improvement by 20–30%. (b) Using faster SiPMs, such as the S12652-050C. To reach 10–15 ps will require 3–4 QUARTICS in-line, which has the advantages of multiple measurements ("time-track") for redundancy and to monitor resolution and efficiency, as well as being less demanding on the electronics. However, the increased material causes interactions (the nuclear interaction length of quartz is $\lambda_{\mathrm{int}} = 44.5$ cm). The detector will be after the tracking, but the time measurement will be worse for some events.

The 20-channel prototype, Fig. 1, was made to solve the "mechanical" issues of having a close-packed array, with 100 μm gaps between bars to maintain total internal reflection, edgelessness (< 200 μm) on the beam side, with an appropriate SiPM array. We planned on testing both quartz bars (made in the L-form) and sapphire bars, but the latter were provided as straight bars and we glued them at 90°. This turned out to be not robust, and we plan to use no glue in the next version. The main housing was machined (by electro-erosion) from a block of aluminum, but could be 3D-printed, and we did use 3D-printing for a light-guide bar spacer plate. Once a module is designed, this can be precise, robust and it is relatively cheap to make additional copies. The design has a built-in LED flasher to monitor all channels when there is no beam. One could use a PiLas laser to monitor also the time resolutions. The SiPMs are simply placed in rectangular holes, connected to the readout board through a transverse-

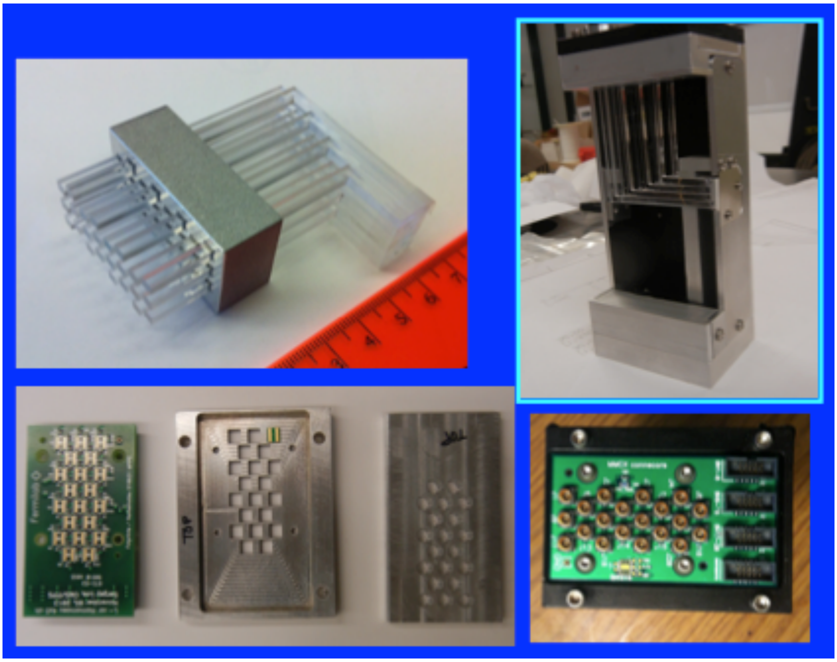

Fig. 2. Parts of 20-channel QUARTIC module. Top left: Quartz bars in mounting jig (removed during assembly). Bottom left: Readout board showing connectors to SiPMs, SiPM-holder plate, light-guide holding plate. Bottom right: Connectors for signals, LV and monitoring. Top right: Assembled module with (100 μm) sideplate removed.

conducting film, and can be easily replaced. Radiation damage to SiPMs is an issue, but by having them a suitable distance above the LHC beams there is space for shielding; even the light guides can come through a lithiated polyethylene (or similar) block. This needs more study.

Replacing the SiPMs with a MCP-PMT, with an anode-pad pattern matching the bars, is an attractive possibility, as the lifetime issues are now (hopefully) being solved [3]. Unlike the large central detectors in LHC experiments, the CT-PPS and AFP detectors are few and small and can be replaced by improved versions on a yearly time scale, or more often. In the moving beam pipe design there can be longitudinal space for more than one detector type; the Roman pots have less longitudinal space. Having at least one QUARTIC in each arm in 2015 will enable *in situ* tests with real $p + X + p$ events.

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