The CT-PPS project: detector hardware and operational experience

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Physics motivations

Central Exclusive Production

\[ pp \rightarrow p \oplus X \oplus p \]

photons or gluon exchanges
\[ \oplus \] rapidity gap

\( X = \text{high-}E_T \text{ jets, WW, ZZ, } \gamma\gamma, \ldots \) measured in the central detector

Measurement of two scattered protons fully determines the kinematics of the central system \( X \):

- \( \xi \) : fractional momentum lost by the proton
- \( t \) : 4-momentum transfer squared

![Gluon-gluon interaction. Additional gluon(s) exchange needed to conserve the colour](image1.png)

![Photon-photon interaction.](image2.png)
The CMS-TOTEM Precision Proton Spectrometer (CT-PPS) allows the measurement of proton trajectories in the very forward regions on both sides of CMS in standard LHC running conditions, taking advantage of the machine magnets to bend the protons.

Tracking and timing detectors are installed in Roman pots between 205 and 220 m from the CMS IP.
γγ → μ+μ- measurement

CT-PPS already took data in 2016 with an ‘accelerated program’. Silicon strip and diamond detectors from the TOTEM experiment were installed in the CT-PPS Roman Pots.

A public analysis document has been recently published on the semi-exclusive dimuon production in proton-tagged events. Dataset: ~10 fb⁻¹ of the ~15 fb⁻¹ collected during the 2016 runs.

Background: Double proton dissociation or Drell-Yan + protons pile-up events.

By matching the ξ measured by the muons with that of the proton the background is suppressed [1.47 ± 0.06 (stat.) ± 0.52 (syst.) events].

12 events have been observed: Significance of 4.3σ
The CT-PPS hardware
Roman pots (RP)

Each station includes 3 RPs (1 horizontal and 2 vertical for alignment runs only).

The tracking RPs are equipped with a thin window 150 μm thick toward the beam.

New cylindrical design to host larger detectors and reduce the impedance.

The timing RPs are equipped with a 300 μm thick window towards the beam. The thickness is required to compensate the pressure gradient on the larger window.

No vertical stations needed, the alignment is done by propagating tracks from the tracking stations.

The CT-PPS RPs are inserted at ~15σ from the LHC beam in standard high lumi fills.
TOTEM strip detectors

Micro-strip silicon detectors with edgeless technology:
- 512 strips per plane, with ± 45° orientation
- Strip pitch = 66 µm
- Inactive edge = 50 µm
- Resolution ~20 µm
- Lifetime up to an integrated flux of $5 \times 10^{14}$ p/cm²
- Binary readout provided by 4 VFAT2 (128 channel each). VFAT2 has trigger capability, currently not integrated in the CMS L1 trigger system

Each station is composed of 10 planes.

Hit/track reconstruction using consolidated TOTEM algorithms fully integrated in the CMS official software since 2016.
Tracking system with pixel 3D

- **Requirements:**
  - **Sustain high radiation levels:** for 100 fb⁻¹, proton flux up to 5x10¹⁵/cm² in tracking detectors, corresponding to ~1-3 x 10¹⁵ nₑq/cm².
  - **Small inefficient area at the edge of the sensor** towards the beam.
  - **Tracking resolution of ~10 and 30 μm** along x and y directions, respectively.

- **Baseline design:**
  - **3D sensor** technology chosen for its intrinsic high radiation hardness and the possibility to implement slim edges.
  - **Two stations per side, each with 6 detector planes tilted by 18.4°** to increase the cluster size and improve resolution.
  - **Readout chip and front-end electronics as for CMS Phase I pixel upgrade.**
  - Mechanics and cooling adapted from TOTEM tracking system.
  - **Run at -20°C and in a vacuum** (pressure < 20 mbar) to avoid condensation and stress of the Roman pot thin window.
CT-PPS pixel detector

Each plane is equipped with a sensor bump-bonded to the psi46dig ReadOut Chip (ROC) developed for the CMS Phase I upgrade of the CMS pixel tracker. The detector is precisely glued on a Thermal Pyrolithic Graphite (TPG) layer that provides the thermal contact with the sides of the package connected to the cooling pipes.

Modules are wire-bonded to the flex circuits which are connected to the RPix portcard.

The RPix portcard interfaces the front-end electronics with the detector planes. Concept: TOTEM board (to fit the RP space constraints) with components from the CMS Phase I forward pixel readout.

Front-end boards for data (FED) and control (FEC) are the same as those of the Phase I CMS pixel tracker.
3D sensors for CT-PPS

3D sensors produced in double-sided not-fully-passing-through technology by CNM
Baseline design:
• **2E pixel** configuration (2 readout columns)
• 200 μm **slim edges** with column fences
• 3x2 sensors (6 ROCs each)
**1E and 2x2 sensors as backup solution**

Specifications to qualify the devices:
Define: $V_{op} = V_{depl} + 10V$ where $V_{depl}$ and $V_{op}$ are the full depletion and operation voltages, respectively.

The following specifications, taken at room temperature (20-24 °C), qualify a device as functioning correctly:
• $V_{depl} < 20$ V
• Breakdown voltage: $V_{bd} > 35$ V
• $[I(25V)/I(20V)] < 2$
• Current at operation voltage:
  - **Class A** \( I(V_{op}) < 2uA \) per tile
  - **Class B** \( 2uA < I(V_{op}) < 10uA \) per tile
  - **Class C** \( I(V_{op}) > 10uA \) per tile
CNM production results

Sensor IV curves have been measured on wafer before bump-bonding by means of a temporary metal deposition to short all the pixels.

First batch of 12 wafers completed in December 2015.
In general good quality sensors but low yield, in particular of the class A ones.

<table>
<thead>
<tr>
<th>Pixel configuration</th>
<th>Class A</th>
<th>Class B</th>
<th>Class A + B</th>
<th>2E + 1E</th>
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<tbody>
<tr>
<td>3x2 2E</td>
<td>3</td>
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<tr>
<td>2x2 1E</td>
<td>6</td>
<td>5</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

Second batch production completed in May 2016.
A problem, probably with the p-stop implantation, caused values of breakdown voltage too low to allow using the sensors.
In order to recover the production a low-dose neutron irradiation is under study.

Third batch production completed in June 2017.
Sensors showed a large leakage current that would classify all the modules as class C. After discussing with the psi46dig designers it has been decided to relax the current limit above the ROC specifications and accept sensors with a leakage current up to 400 μA per tile -> further ~50 modules available.
Module assembly and installation

Two tracking stations have been assembled and fully tested in lab and in the expected conditions of secondary vacuum and cooling. Each station has 5 3x2 + 1 2x2 modules.

The detectors were installed in the Roman pots along the LHC at the end of March and connected to services and power.
The pixel modules have been tested and optimised in the Torino and Genova laboratories during the module selection phase, with the same procedure used for the CMS Phase I ones.

The calibrations and tests are made by means of the internal calibration circuit present in the psi46dig ROC.

The obtained register values have been used as a starting point for the detector optimisation in the LHC tunnel.

A calibration campaign has been carried out.
Pixel calibration - II

Module maps for sector 45 installed on LHC beam-pipe 2

Module maps for sector 56 installed on LHC beam-pipe 1

Very low number of bad pixels (eff<90%) = 129 (<0.05% of all channels)

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Timing detectors

The average pile-up is expected to reach up to 50 interactions per bunch crossing.

A resolution of $\sim 10$ ps on the proton arrival time allows to determine the vertex $z$ position with $\sigma_z \sim 2$ mm ("z-by-timing" measurement $z = c (t_1 - t_2) / 2$).

Each timing station hosts 3 scCVD diamond ($\sigma_t \sim 80$ ps) and one Ultra-Fast Silicon Detector ($\sigma_t \sim 35$ ps) planes.

Digitization is done with NINO chip + HPTDC.

**Precise clock distribution (few ps jitter)** is obtained with a design adapted from the "Universal Picosecond Timing System" (optical network) or with RF-feedback with low-loss coaxial cable.
Four 4x4 mm² diamond sensors per plane, with different pad patterns to match the particle rate as a function of the distance from the beam. Single sensors are mounted with a different order and rotation to improve the spatial resolution to \(\sim 150 \, \mu\text{m}\).

Intrinsic radiation hardness \(\rightarrow\) to withstand overall integrated flux of \(5 \times 10^{15} \, \text{p/cm}^2\).

Triple stage amplification by SMD components on the TOTEM hybrid.

Allow for high granularity (wrt, e.g., quartz). Time resolution \(\sim 80 \, \text{ps per plane}\).

Ultra-Fast Silicon Detectors (UFSD)

1 plane of UFSD (first installation in HEP).

Pad readout adapted to that of the diamond readout board: eight 0.5x6mm$^2$ and four 1x3mm$^2$ pads.

**Radiation hardness still an issue** → in RP environment expected lifetime $\sim 10^{14}$ p/cm$^2$ (R&D to improve rad-hardness still ongoing).

Allow for high granularity (wrt, e.g., quartz).

Double-stage amplification with modified TOTEM hybrid. **In Torino an ASIC (TOFFEE) is under development** to integrate the SMD components amplification and the NINO discrimination.

**Time resolution $\sim 35$ ps$^1$**

$^1$ N. Cartiglia et al., NIM A 850 (2017) 83
Operational experience
Alignment run procedure

- **Goal:** RP alignment with respect to the collimators, relative alignment between the RPs, alignment with respect to the beam, optics determination.
- Upstream collimators are closed to a given number of $\sigma_{\text{beam}}$ from the beam (5 - 8.5). The RPs (both horizontal and vertical) are slowly approached one at a time and when a spike is observed in the downstream Beam Loss Monitor (BLM) it means that the RP reached the same position as the collimator in terms of beam sigmas.

- Alignment with respect to the beam based on the elastic protons measured in the vertical RPs.

- **RP relative alignment**

- **Alignment wrt the beam** Based on the hit profile on the CT-PPS tracking detectors

- **Optics tuning**

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Tracking detector hit maps

Data collected during alignment run at end of May 2017

x-y coordinates relative to an arbitrary system of reference

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RP relative and global alignment

Data of alignment runs are currently under study.

A first estimation of the roman pot relative alignment and beam position is shown:
- black line: axis of elastic hits
- orange line: fit and extrapolation of hit profile in the horizontal RPs
- cyan point: intersection of black and orange line, estimate of beam position

The fine determination of the optics parameters is ongoing and requires a more refined data analysis.
Timing status

To ensure the consistency of the data collected with the timing detectors, hit maps as measured in the strips are plotted requiring a coincidence with timing detectors. Colours indicate the different channels. **A clear correlation is observed. Timing system being commissioned.**
Status of the data taking

- The Roman pots have been inserted during the LHC intensity ramp-up up to the maximum 2017 luminosity with ~2556 bunches. They have been certified for the 2017 data taking and they have been **inserted in all high luminosity fills since the Technical Stop 1** (beginning of July).

- **The CT-PPS detector is running stably** with very low impact on the CMS data taking.

- Up to now detectors have been inserted close to the beam for more than 13 fb$^{-1}$.

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**CMS Integrated Luminosity, pp, 2017, $\sqrt{s} = 13$ TeV**

Data included from 2017-05-23 14:32 to 2017-09-04 09:08 UTC

- LHC Delivered: 20.49 fb$^{-1}$
- CMS Recorded: 17.77 fb$^{-1}$

**Delivered lumi with RP inserted 2017**

- Non-official numbers estimated error ~10%
Summary and conclusions

• 2016 CT-PPS installation with an “accelerated program”: silicon strips + diamond detectors → **15 fb⁻¹ collected**. First data analysis: CMS-PAS-PPS-17-001

• **2017 CT-PPS installation completed in April 2017**, 4 different detector technologies
  • silicon strips for tracking
  • 3D silicon pixels for tracking (**first installation in CMS**)
  • scCVD diamonds for timing
  • Ultra-Fast Silicon Detectors for timing (**first installation in a HEP experiment**)

• All detectors successfully integrated in the CMS central DAQ already from the first 2017 LHC fill.

• Commissioning of tracking detectors completed. Commissioning of timing system in progress.

• The analysis of the alignment data is ongoing, the relative and global alignments are being finalised; efforts are ongoing to determine the LHC optics parametrisation.

• **More than 13 fb⁻¹ of data have been collected so far at √s = 13 TeV in 2017**. Much more are expected to be collected up to the end of 2018.
Backup
Physics motivations

QCD: LHC as gluon-gluon collider with tagged proton
- Exclusive two and three jet events
- Test of pQCD mechanism of exclusive production
- Gluon jet samples with small component of quark jets

EWK: LHC used as photon-photon collider
- Measurement of $\gamma\gamma \rightarrow W^+W^-$, $e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$
- Search for anomalous quartic gauge couplings (AQGCs) with high sensitivity

Beyond Standard Model:
- Clean events (no underlying event)
- Independent mass measurement by pp system
- JPC quantum numbers 0++, 2++
LHC beam optics

Proton kinematics at the detector is determined by optics and proton kinematics at IP.

\[ \theta^*_y = \frac{y_{RP}}{L_y} \]

Mass and rapidity acceptance

\[ y = \frac{1}{2} \ln \frac{\xi_1}{\xi_2} \]

2017 Optics Preview
ATS Option 3bis, \( \beta^* = 0.4 \) m
\( \alpha_s = 300 \, \mu \text{rad} \)

\[ M^2 = \xi_1 \xi_2 \]

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Detector setup in 2016

Sector 45 (left arm) - Sector 56 (right arm)

- CT-PPS
- CMS
- TCL6 collimator installed to suppress debris from RPs
- 2 new horizontal pots (only 1 during LS1)
- 2 horizontal pots for tracking detectors equipped with Faraday cages (RF shields)
- Cylindrical RP for timing detectors to reduce impedance and increase available space
- Timing detector for PU rejection

2016: 4 planes of segmented diamond detectors
R&D: UFSD and QUARTIC

2016: 3D silicon pixel detectors, 6 planes per station
2016: TOTEM silicon strip
3D detectors - Efficiency

10 single-ROC sensors (2 1E and 8 2E) from the first production have been bump-bonded at IZM to the ROC and have been tested at FNAL on beam. Sensors selected of both class A and B.

2E (1E) sensors reach the full efficiency already at bias voltages of ~3 V (5 V). No difference in efficiency is seen between class A and B sensors.

Thanks to the not-fully passing-through columns and the well optimised thresholds, high efficiency is obtained even without rotating the sensors.

Efficiency greater than 99.4% at 20°. (CT-PPS tracking detector angle = 18.4°)
Efficiency at the edge of the sensor fitted with a S-curve. Error bars represent the width of the S-curve.

At a bias voltage of 40 V up to 150 μm can be gained at the edge of the sensor with the 2E layout.

2E detectors allow to gain ~60 μm more than 1E ones at a bias of 40 V thanks to the n⁺-electrode closer to the sensor edge.
3D detectors - Resolution vs angle

Detector resolution is evaluated by fitting residuals separately for clusters of size 1 and 2. After subtracting the telescope resolution, the **global resolution is obtained as average of the two values weighted by the cluster size probability**.

Since electrodes are closer to the pixel geometrical edge, **2E sensors have more clusters of size 2 and therefore a better resolution with respect to 1E ones**.

Considering a resolution per single plane between 22 and 25 μm, **the target resolution of ~10 μm can be achieved** considering the 6 planes per station.

CNM single-ROC sensors demonstrated to fulfill the CT-PPS requirements.
Module testing

Detectors characterised and optimised in Torino and Genova by a temporary wire-bonding and gluing with gel-pak film on flex hybrid:
- IV curve
- ROC calibration and optimisation
- Threshold trimming to ~ 1800 e⁻
- X-ray to check bump-bonding quality

No damage due to flip-chip observed, based on sensor IV curve comparison and ROC performance before and after bump-bonding.

Good quality of bump-bonding
Torino X-ray setup

module

DTB

X-ray tube

DAQ PC

module

DTB

module
### Status of module production - batch 1

#### 3x2 module

<table>
<thead>
<tr>
<th>Module</th>
<th>Layout</th>
<th>Class on wafer</th>
</tr>
</thead>
<tbody>
<tr>
<td>3x2_b1w1d2</td>
<td>2E</td>
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</tr>
<tr>
<td>3x2_b1w1d3</td>
<td>1E</td>
<td>B</td>
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<td>3x2_b1w2d4</td>
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#### 2x2 module

<table>
<thead>
<tr>
<th>Module</th>
<th>Layout</th>
<th>Class on wafer</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x2_b1w1d1</td>
<td>2E</td>
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<tr>
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</tr>
</tbody>
</table>

#### Color code:
- **Green** → Ok
- **Light green** → few defects but still good
- **Light blue** → timing issue, maybe usable but still under investigation
- **Orange** → quite serious problems, better not to use it
- **Red** → not usable

All red modules have been broken during handling or wire-bonding at the beginning of testing campaign.

### Status of 3x2:
Tested 22/22  
Good sensors 16/22 (7 2E)

### Status of 2x2:
Tested 22/24  
Good sensors 18/22 (10 2E)

For the 2017 data taking only 2 pixel stations (one per each side) have been installed.

Mainly green 3x2 modules have been selected for the final station assembly.
CT-PPS pixel tracker DAQ

- The DAQ and calibration software for the CT-PPS pixel detector is based on the CMS Phase I Pixel Online Software (POS).
- **The software has been adapted to the CT-PPS electronics.**

- The software has been fully tested in laboratory and all the standard calibration procedures have been verified.
- The tests done on the modules during their qualification provided the initial setting which have been further optimised with the DAQ software.
- The software demonstrated to be reliable.
ξ and t resolution

\[ \sigma(\xi_{\text{gen}} - \xi_{\text{reco}}) / \xi_{\text{gen}}(\%) \]

\[ \sigma(|t_{\text{gen}}| - |t_{\text{reco}}|) / |t_{\text{gen}}|(\%) \]

\[ pp \rightarrow p \oplus J \oplus p, z=204m \oplus 215m, d=15\sigma \]

Simulation
CMS-TOTEM