



The CMS Tracker upgrade for HL-LHC

ALESSANDRO ROSSI FOR CMS COLLABORATION









- High Luminosity upgrade after LS3
- Peak Luminosity ~7.5x10³⁴ cm⁻²s⁻¹
- Expected Pile-up ~200
- Higher rates and radiation dose wrt Run3



Hardware commissioning/magnet training



High Luminosity Requirements



- Increased granularity: In order to ensure efficient tracking performance with a high level of pileup
- **Reduced material in the tracking volume**: The exploitation of the high luminosity will greatly benefit from a lighter tracker
- **Contribution to the level-1 trigger:** The selection of interesting physics events at the first trigger stage becomes extremely challenging at high luminosity
- **Extended tracking acceptance**: The overall CMS physics capabilities will greatly benefit from an extended acceptance of the tracker
- Radiation tolerance: The upgraded tracker must be fully efficient up to a target integrated luminosity of 3000fb⁻¹
 - Outer layers "far away" from interaction point will see >10¹⁴MeV neutron equivalent fluence
 - more than innermost strip tracker layers at 20 cm for today's trackers after 10 years of LHC running





Why change the current Tracker



- Radiation damage at the end of Run3
 - A big part of current strip tracker will become completely inoperational due to either leakage current or full depletion voltage limitations at 1 ab⁻¹
 - Pixel detector need to handle a factor 6 higher hit rate (from 0.58 to 3.2GHz/cm²) and need an higher granularity
- Full tracker replacement needed for HL-LHC program





INNER TRACKER

Phase-2 CMS Inner Tracker



- **TBPX** : **T**racker **B**arrel **P**i**X**el • 4 Layers, no crack at z=0
- **TFPX** : **Tracker Forward PiXel** • 8 small double-disks on each side
- TEPX : Tracker Endcap PiXel
 4 large double-disks on each side

Extended coverage up to |η|= 4 (actual detector 2.4)
Innermost modules located at r=2.75cm form the beamline (actual detector 2.9cm) INFN

Modules



- Two types of Pixel Modules
 - 1x2 and 2x2 readout chip
- 3892 module plus spares (1156 1x2, 2736 2x2)
 - 2 Billion pixel (124 million in current detector)
- Read Out Chip (ROC) only active element on module













Modules inside the Detector







Barrel Layer1 with 3D sensors



- Sensors
- Intese R&D program carried out
- 25x100µm² pixel cells with 150µm active thickness
- 2 different technology will be adopted
 - n-in-p planar sensors
 - Bitten implant, no punch-through bias dot
 - Hit efficency >99% after 2x10¹⁶ n_{eg}/cm²
 - 3D pixel sensors on Barrel layer1 Ο
 - Better power consumption
 - Stable hit resolution performances up to $10^{16} n_{eg}/cm^2$













- ASIC based on CMOS 65nm technology (CERN RD53 project)
 - Radiation tolerant up to 1 Grad
 - Strongly protected against SEU effects
 - Low power consumption < 1 W/cm2
 - At CMS Level1 trigger rate of 750 kHz
 - Serial powering via on-chip shunt-LDO regulators (1 for analog, 1 for digital sections)
- CMS flavor of RD53 ROC : C-ROC
 - Full size ASIC: 432x336 channels
 - Analog FE linear architecture
 - 4 bit digital readout with selectable 6-to-4bit dual slope ToT mapping for charge compression (elongated clusters, heavy ionizing particles)
 - First Prototypes modules built with CROC
 - Several beam test already perfomed







Read out architecture



- Comunication electronics hosted on dedicated board:
 - Portcards optoelectronic service card
- Portcard houses 3x lpGBTs and VTRx+ links, powered via cascaded DC-DC converters
- Up to 6 electrical up-links at 1.28 Gb/s → module to lpGBT
 o Rates reduction achived with data formatting
- One electrical down-link at 160 Mb/s \rightarrow <u>lpGBT to module</u>
 - clock, trigger, commands, configuration data to modules
- 28 Data Trigger Control boards required for inner tracker





Powering scheme





- Supply the needed 50 kW with a limited mass of the power cables \rightarrow SERIAL POWERING
 - Modules grouped in 576 serial power chains, up to 12 modules in a chain
 - • Modules powered in series, chips within each module powered in parallel
 - A shunt-LDO (SLDO) on each chip provides voltage regulation for each chip while maintaining a constant current
 - Chips in a module in parallel (4A for 1x2 modules, 8A for 2x2 modules)
 - Sensor bias following the serial power chains with single return line
- Single power supply module: current source (SP), HV for sensor (0-800V), LV for portcards and pre-heaters required by CO2 cooling

INFN



- Light Carbon Fiber structures with embedded cooling pipes
- Disks with flat geometry (unlike turbine in current detector)
- Improved fiber routing which reduces radiation induced attenuation
- Cooling based on evaporative CO_2 (T=-35°C) distributed in 1.8 mm outer diameter stainless steel pipes (168 cooling loops)







OUTER TRACKER

Phase-2 CMS Outer Tracker



- **TBPS** : **T**racker **B**arrel with **PS** modules
- **TB2S** : **T**racker **B**arrel with **2S** modules
- **TEDD** : **T**racker **E**ndcap **D**ouble **D**isk

CMS

INFŃ



Phase-2 CMS Outer Tracker



- TBPS : Tracker Barrel with PS modules
- **TB2S** : **T**racker **B**arrel with **2S** modules
- **TEDD** : **T**racker **E**ndcap **D**ouble **D**isk



- **TBPS** : Tracker Barrel with **PS** modules
- TB2S : Tracker Barrel with 2S modules
- TEDD : Tracker Endcap Double Disk

Phase-2 CMS Outer Tracker



- Outer Tracker coverage up to η~2.5
 Tracking up to η~4 thanks to InnerTracker
- Two different type of technology: micro-strips and macro-pixels
- Tilted barrel geometry
 - Better trigger performances
 - Reduction on number of modules

CMS

INFN

Tracks for L1 Trigger

- HL-LHC will deliver an high instantaneus luminosity with a high PileUp
 - It's fundamental to be more selective at L1 trigger in order to keep data rate under control



- Most of charged particles have low p_T
- Perform a p_T selection at readout level in order to reduce the L1 tracking input data size



- Two silicon sensors with small spacing in a module
- Flex hybrid in order to get data from both sensors to one ASIC → Select track «stubs»
- Different sensor spacing for different detector region
- Tunable correlation windows







Tracks for L1 Trigger



► x



Phase-2 Tracker Modules





- Two type of modules:
 - o 2S Modules
 - 2 different spacing : 1.8mm & 4mm
 - 2 micro strip sensors with 5cm x 90µm strips
 - Sensor dimension are 10cm x 10cm
 - o two column of 1016 strips

- PS Modules
 - 3 different spacing : 1.6mm & 2.6mm & 4mm
 - One strip sensor: 2.5cm x 100µm strips
 - One macro Pixel sensor : 1.5mm x 100μm pixels
 - Sensor dimension 5cm x 10 cm
 - two column of 960 strips
 - o <u>32x960 pixels</u>



Phase-2 Tracker Modules







Modules ReadOut



- 2S Module ASICs
 - CMS Binary Chip (CBC) for readout and stub finding for L1
 - both sensors read out by same chip
 - o 254 channels per chip
 - 127 from each sensor
 - Implemented in 130 nm technology
- PS Module ASICS
 - Macro-Pixel ASIC (MPA) and Short-strip ASIC (SSA) for readout of sensors
 - Stub finding performed by MPA
 - SSA sends cluster and L1 information to MPA to enable match in space and time
 - Both chips done in 65 nm technology
- Common ASIC:
 - CIC concentrator chip Receives L1 information and readout data
 - "Data hub" to service hybrid
 - Done in 65 nm technology



Tracker Back-end

Stubs only

Outer Tracker Front-end

CMS DAQ

CMS







- DTC (Data, Trigger and Control) boards readout and control module
 - ACTA standard
- Each Module equipped with a lpGBT and a VTRx+
- Bi-directional optical links
 - 2.56 Gb/s DTC \rightarrow Module
 - clock, trigger, fast-commands and programming
 - \circ 5.12 or 10.24 Gb/s Module \rightarrow DTC
 - L1 and DAQ data
- L1 data at 40 MHz
- DAQ data (after L1) at 750 kHz





Powering & Cooling



Large Area + High Granularity High Power Budget : <u>Outer</u> <u>Tracker ~100kW</u>

Parallel Powering with onmodule conversion (DCDC converters)



Powerful cooling system:

- (4+1) x 50W cooling plants
- based on two-phase CO₂ cooling system (-35°C set point)
- small pipes



Material Budget



 Material budget much reduced wrt Phase0/1 detector despite an increase in the number of channels





- DCDC converters
- Fewer layers
- Lighter materials
- Optimized service routing
- CO2 cooling
- Inclined geometry

CMS

INFN

CMS

ÍNFŃ

Performances: Phase-1 vs Phase-2

- Track parameters resolution of Phase-2 tracker improve wrt Phase-1
 - Higher granularity and less material
- Significant extention at higher η



Performances: High PileUp

- High tracking efficiency (~90%) also at 200PU
 - Fake rate below 2(4)% at 140(200)PU
- Dip around ±1.2η due to Barrel/endcap transition in Inner Tracker
 - Due to an old geometry model, it has been reduced by a factor ~2 with optimized geometry





MS

Y Residuals

2000

1500

1000

500

Some highlights from beam tests

- Planar HPK Sensor with CROC and RD53A
 - \circ ϵ >99% for V_{bias}>5V before irradiation and for V_{bias}>400 after irradiation ($\Phi_{eg}=1x10^{16}cm^{-2}$)

Ehit [%]

100

Mean= -1.76

Fit results

Mean= -1.79

Std dev= 9.94

v residual (um)

Std dev= 13.87



50 50 0 50 100 150

Mean= -0.67

x residual (um

Std dev= 63.22

X Residuals

200

100



Efficiency as a function of Vbias



The efficiency is > 99.8% even with Vbias = 20V



INFN

requency

0.7

0.6

0.5

0.3

0.2

0.1

Some highlights from beam tests

- Different module prototypes tested in particle beam
 - **2**S

CMS

- Full size module and mini-module has been tested
 - Stubs finding capabilities tested
 - Magnetic bending «simulated» with module rotation
- Beam Test focus on the 40MHz stubs readout also performed
 - High intensity muon beam with Stubs line directly on disk
 CMS Phase-2 Preliminary



• **PS**

- Test on Single sensor (pixel) with MPA readout
- MPA+SSA intercommunication tested on bench
- Several beam test activity on full PS modules ongoing







Conclusions



- Ambitious upgrade project underway for the CMS Tracker for the HL-LHC running
 - Designed to maintained or improve tracking performance compared to current system even in the presence of up to 200 pile-up events
 - Tracking capabilities extended to $|\eta|=4$
 - Tracks above 2 GeV as L1 primitives at 40MHz
- Improvements result in the tracker being more performant and yet more light-weight compared to its predecessor
- Advanced layout and integration studies
- First pre-production modules foreseen by the end of the summer...a long way toward HL-LHC!



Backup



Inner Tracker insertion



- Two ladder of each Barrel Pixel layer skewed in r¢
 - This will allow the detector insertion and removal without any action on the beam pipe





Mechanics

0.4-1.1 m



• TBPS

- Flat Part: planks
- Tilted Part: rings

• TB2S

Ladder support structure

• TEDD

- Building block: DEE (half disk)
- Double-Disk to be hermetic also with rectangular modules

Module type and variant		TBPS	TB2S	TEDD	Total per variant	Total per type
25	1.8 mm	0	4464	2792	7256	7680
	4.0 mm	0	0	424	424	
PS	1.6 mm	826	0	0	826	5616
	2.6 mm	1462	0	0	1462	
	4.0 mm	584	0	2744	3328	
Total		2872	4464	5960	13296	





Modules Service Systems





- Module houses both frontend and service hybrids
- Service hybrid(s) has:
 - o lpGBT
 - o VTRx+
 - DCDC converters



 Frontend hybrids have readout chip and data concentrator



Modules Service Systems



evelopme

commor

- 1: 2S silicon sensor 2: AI-CF spacer 3: Front-end hybrid 4: Service hybrid 5: CFRP support 6: High voltage tab 7: Temperature sensor
- Module houses both frontend and service hybrids



Each module is a functional unit individually connected to:
backend power system
DTC (Data, Trigger and Control) system via Optical link
no token control rings
no intermediate power grouping

10: High voltage tab 11: Temperature sensor 12: Kapton HV isolators reauout cmp and data concentrator





- Silicon sensors will be produced by Hamamatsu
 - o n-in-p sensors
 - Showed better behavior after irradiation
- HPK lost confidence in deep diffused material as substrate for mass production
 - baseline for TDR
- Options left:
 - standard material: 320μm physical and 290μm active (FZ290)
 - same material as in the current tracker
 - thinned material with physical ~ active thickness (thFZ240)
 - same substrate as FZ290, but backside ground down to desired thickness, followed by polishing
 - more expensive







Sensors



- Irradiation campaign to study the sensors behavior and perform a technology choice:
 - Take nominal expected max. fluences for outer (2S) and inner (PS) regions after 3000fb⁻¹
 - Consider the approximate mixture of neutrons and charged hadrons





Sensors



- Irradiation campaign to study the sensors behavior and perform a technology choice:
 - Take nominal expected max. fluences for outer (2S) and inner (PS) regions



- thFZ240 barely reaches 2S limit
- FZ290 is well above

- thFZ240 only just above PS-s limit
- FZ290 comfortably above with 800V



Tilted Barrel Geometry



- Stubs generation works only if the charged particle cross the two sensors on the same halve of the same module
- This is not true for (flat) barrel peripherical modules
 - → (increasingly) Tilt peripherical barrel modules







Tilted Barrel Geometry



- Stubs generation works only if the charged particle cross the two sensors on the same halve of the same module
- This is not true for (flat) barrel peripherical modules
 - → (increasingly) Tilt peripherical barrel modules



CMS Phase-2 Simulation s=14TeV, Muons (pT>10GeV), 0 PU Sizable reduction on the number of modules Stub efficiency needed 000000000000 00000000000 \rightarrow From ~15k (flat) to ~13k (tilted) TILTED SECTION 0 FLAT SECTION 0.80 TILTED SECTION Flat barrel geometry 0.7 Tilted barrel geometry 0 0.6 0.5 0.4-2.5 -0.5 0.5 1.5 2 2.5 -1.5-1 Particle n



























Irradiated Sensors at Beam Test



- Sensor irradiated with neutron only at JSI
- CBC3 readout chip (almost final)
- Charge collection reflected in hit efficiency as a function of threshold
 FZ290 can tolerate higher thresholds
 - Only after long annealing (200 days) at ultimate 5x10¹⁴neq/cm² both materials are comparable
- dark noise occupancy was measured:
 - lower than 10⁻⁵ while expected hit occupancy is ~10⁻²
 - Scale with annealing (current) and not with thickness

