ATLAS High Granularity Timing Detector (ATLAS实验高颗粒度时间探测器)

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High Granularity Timing Detector (HGTD)

- 把粒子到达时间的测量精度提高2个数量级(数纳秒→30皮秒)
- 解决高亮度LHC对撞事例堆积问题
 - 6.4平方米的硅探测器, 30皮秒的时间分辨
 - 毫米级的颗粒度, 超过三百万个读出通道
 - 能承受2.5×10¹⁵ n_{eq} /cm²的等效中子通量的辐照
- 中国组主导探测器研制(高能所,科大,南大,山大,上海交大)
 - 45%探测器组装
 - >34%抗辐照高时间分辨传感器
 - 100%前端电子学, 50% ASIC测试, >16% 高压电子系统





ATLAS高时间分辨探测器: 重要管理职位

- 中国组在ATLAS高颗粒的时间探测器项目(HGTD)中起主导作用
 - -高能所Joao担任HGTD项目经理,ATLAS实验Level-1管理职位
 - 中国组首次在LHC实验子探测器担任项目经理
 - -3人担任探测器Level-2召集人 (梁志均,赵梅,吴雨生)
 - -2人担任探测器Level-3召集人 (张杰,樊磊)

HGTD项目的管理架构





Low Gain Avalanche Detectors (LGAD) 低增益雪崩硅传感器

- > LGAD是近年出现新型硅传感器,可以高精度测量时间(20-30皮秒)
- Compared to APD and SiPM, LGAD has modest gain (10-50)
- High drift velocity, thin active layer (fast timing)
- High S/B, no self-triggering

 $\sigma_{jitter}^{2} = \left(\frac{t_{rise}}{S/N}\right)^{2}$ Modest gain to increase S/N
Need thin detector to decrease t_{rise}
Conventional PiN diode





LGAD





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Latest prototypes produced by different vendors

- Lots of prototypes R & D in LGAD in last few years, active vendors includes:
 - IHEP-IME (China), USTC-IME (China), IHEP-NDL(China), FBK (Italy), CNM (Spain), HPK (Japan) ...
 - 高能所和科大分别独立设计传感器版图和工艺,在微电子所8寸晶圆工艺流片





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Full size LGAD sensor prototype

- Good uniformity of full size LGAD prototype (15*15 channels)
 - IHEP-IME, USTC-IME, HPK, FPK, CNM has produced good full-size LGAD prototype.



LGAD sensor after Irradiation (LGAD传感器辐照后硼掺杂移除)

- After irradiation, Boron doping in gain layer became less active (Acceptor removal)
- Carbon-enriched LGAD is more radiation hard
 - Carbon "stabilized" boron doping
- IHEP-IME/FBK/USTC-IME LGAD with carbon
 - Significantly lower acceptor removal ratio
 - Significantly more radiation hard



carbon enriched

wafers

高能所传感器、科大研发传感器



LGAD Single Event Burnout effect (单粒子烧毁)

- RD50, CMS and ATLAS confirmed Single Event Burnout (SEB) effect in testbeam
- The key to avoid burnout effect is to operate at low HV
 - Operate volage needed to be <550 V (assuming 50um thick EPI layer)
- HGTD performed test beam at CERN recently
 - LGADs with HV on in 120 GeV high intensity proton beam
 - Good performance for Carbon-enriched LGAD
 - 高能所传感器辐照后,在高亮度质子流中全部通过测试,无一烧毁





Performance of various LGAD prototypes at 2.5e15 cm⁻² fluence

- Carbon enriched LGADs fulfil HGTD requirements (高能所,科大,意大利FBK)
 - 30-50皮秒的时间分辨率,4fC以上的电荷收集,工作电压低于550V(避免烧毁)
- Carbon-enrichment allows the sensors to be operated at much smaller voltages
 - 高能所 LGAD可以工作在300V的较低电压下,并有4fC以上足够电荷收集



时间分辨率 vs 偏置电压

电荷收集 vs 偏置电压

Performance of irradiated LGAD prototypes at testbeam

- Carbon enriched LGADs fulfil HGTD requirements (高能所,科大,意大利FBK)
- Close to 100% hit efficiency for irradiated LGAD at DESY/CERN test beam





ALTIROC : Fast Timing ASIC

- 225 front-end channels in ALTIROC, each channel has
 - A preamplifier followed by a discriminator:
 - Two TDC (Time to Digital Converter) to provide digital Hit data
 - Time of Arrival (TOA) : Range of 2.5 ns and a bin of 20 ps (7 bits)
 - Time Over Threshold (TOT) : range of 20 ns and a bin of 40 ps (9 bits)
 - One Local memory: to store the 17 bits of the time measurement until L0/L1 trigger (~ 1 MHz)

CHIPS

1EGA

Laboratoire de Physique des 2 Infinis Institute of High Energy Physics

Time walk

Edge Threshold Discriminator

Time

Time Walk

• 高能所参与ASIC中数字电路部分的设计



EXPERIMENT

ALTIROC R & D



- ALTIROC0 preamplifier + discriminator waveform sampling on the oscilloscope
- ALTROC1– 5x5 array with complete analogue front end (discriminator + TDC)
- ALTIROC2– 15x15 array with almost complete functionalities
 - Full-size ASIC prototype ~2x2 cm² with 225 readout channels
 - Large amount of digital data, limited power consumption (1.2W/ASIC \rightarrow 5.3 mW/ channel)
 - data serializers @ up to 1.28 Gb/s,
 - ALTIROC1 and testboad



ALTIROC2 wafer



ALTIROC2 test bench setup

ALTIROC1 testing



- Very demanding requirement of <70 ps time resolution @ 4 fC
 - LGAD collected charge >15 fC (>4 fC) before (after) irradiation
- Charge injection self-calibration test in ALTIROC
 - Thresholds can be as low as 2 fC full efficiency reached at ~3 fC
 - ~15 ps jitter @ 15 fC, better than 70 ps jitter@ 4 fC





ATLAS

ALTIROC1 mini-modules performance at test beam

- 5*5 channels Mini-modules (ALTIROC1+LGAD) was tested at testbeam
 - 46ps timing resolution after time walk correction



ALTIROC1 mini-modules @ test beam





ALTIROC2 full-size hybrid

- IFAE already made 15+ bare module prototype (ALTIROC2 + HPK LGAD)
- IHEP worked made 40+ bare module prototype by far
 - ALTIROC2 + IHEP-IME v2 LGAD sensors
- AEMtec (Germany) company made 30 prototype
 - ALTIROC2 + FBK LGAD sensors



ALTIROC2 + HPK LGAD



X-ray image of full-size hybrid







Module assembly

- •HGTD项目总共需要8032个探测器模块
- •6个模块组装生产中心
 - 高能所,科大,德国,法国,西班牙,摩洛哥
 - 高能所是最大的生产中心,组装34%的模块
- 高能所与国内公司研制国产自动组装系统
 - 有高分辨图像系统, 做芯片图像识别
 - 自动芯片组装、点胶
 - 位置组装精度达到微米级







Picking flex

Picking tool Picking dummy sensor Placing dummy sensor



Hybrid functional test

Sr-90 Source tests

- Very collimated, it was moved to cover the whole area
- pixels with more hits just indicate that the area was exposed for longer time
- So far hybrids fully tested, and they are all operational

探测器模块: 放射源测试的hit maps





Peripheral electronics board (PEB)

- •高能所、南大承担100%前端电子学研制
- Work on the characterization of all individual components, prototypes under production:
 - Detailed testing of the DC/DC converter (bPOL12V), different options under consideration
 - need to fulfil space constraints, power efficiency
 measured
 - Started tests on IpGBT with evaluation board
 - VTRX+: successfully tested 2.56G/10.24G communication, bit error rate (<10⁻¹²), passed eye diagram test
 - MUX64: analogue multiplexer (for monitoring of ASIC power supply and temperature)

→ basic functionality confirmed, On-resistance larger than expected (further investigations necessary)







DC/DC converter





lpGBT eval. board

VTRx+ eval. board



MUX64 in QFN88



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Heater demonstrator

Demonstrator

- Heater demonstrator
 - 19 silicon heaters mounted on a single stave
 - Representing modules dissipating heat
 - on the cooling plate (CO2 cooling)
- DAQ demonstrator
 - Minimum system for full chain readout, from module emulator boards to FELIX board
 - Support up to 14 modules with two lpGBTs and one VTRx+
 - Timing
 - Up to 3 modules @ 1.28Gbps
 - Up to 7 modules @ 640Mbps
 - Up to 14 modules @ 320Mbps
 - Luminosity
 - 7 modules @ 640Mbps



DAQ demonstrator (高能所,南大研制)





Summary: HGTD detector for ATLAS phase II upgrade

- Good progress in LGAD design fulfilling the the radiation hardness requirements
 - Carbon enriched LGADs fulfil HGTD sensor requirements up to 2.5x10¹⁵ N_{eq} /cm²
- ALTIROC 2 (full size ASIC) on schedule, under study, so far all blocks functional
- Concrete implementation of Peripheral electronics components are under test
- full-size hybrids are in production and showed good results in functional tests
- Demonstrator activities ramping up
- Next milestones:
 - 2022: HGTD Demonstrator completed
 - 2023: Peripheral electronics boards and LGAD sensors production started
 - 2024: ASICs, Modules and detector units production started
 - 2026-2027: HGTD detector Integration at CERN, installation



Backup: High Granularity Timing Detector (HGTD)

- High precision timing (per-track resolution of 35-50ps up to 4000 fb-1) to mitigate pileup effects and improve the ATLAS performance in the forward region (2.4 ≤ |η| < 4.0)
- Provide online and offline luminosity measurements by transmitting N_{Hits} per ASIC at 40MHz in outer region
 - 2 disks (one per endcap) outside of ITk volume, upstream of the fwd. calorimeters, consisting of 2 doublesided layers each
 - Very limited space in z-direction → overall thickness of 12.5 cm for each disk
- Silicon sensor technology (LGAD)
- Max expected fluence in "3-ring layout" is 2.5e15 neq/cm² and sets the radiation hardness requirements for the sensors and electronics





Beta source tests: LGAD timing resolution measurements

- Sr⁹⁰ Beta telescope test (collected charge, gain, time resolution)
- UCSC boards with commercial amplifier and analog readout by Oscilloscope
 - Less constraints with respect to the ASICs exploring the limits of the sensors.
- Two UCSC boards with two LGAD
 - One LGAD is device under test (DUT)
 - Another LGAD is used to trigger electrons events from Sr⁹⁰





LGAD

LGAD Single Event Burnout effect (HV stability in the beam)





Peripheral board (PEB)

>PEB connects FE to the DAQ system, provides LV&HV to the modules





Detector units

- Modules are installed and glued on support units (PEEK)
 - Challenges :machining or 3D printing of PEEK (flatness <200μm)</p>

Loading modules on support units



Different color represents different support units.



Loading modules on support units



Module

Support units metrology



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