ATLAS High granularity timing detector activity at IHEP/NJU

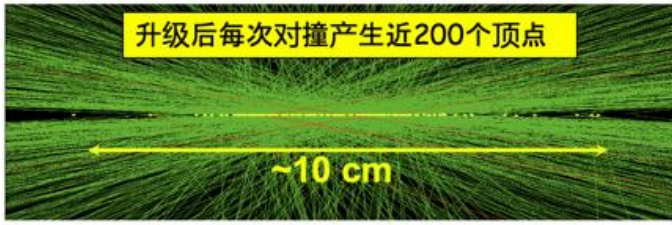
CLHCP2022

Yunyun FAN on behalf of IHEP HGTD group

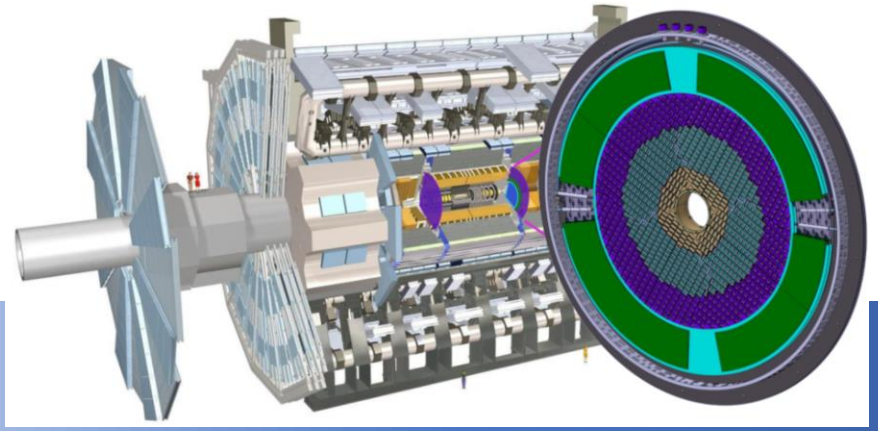
IHEP

High Granularity Timing Detector (HGTD)

- **Time resolution for particle 2 orders of magnitude up （ns→30ps）**
- **Reduce the pile-up in HL-LHC**
  - **Detector area: 6.4 m^2， time resolution：30ps**
  - **mm granularity，3 million readout channels**
  - **Radiation hardness：2.5×10^{15} n_{eq}/cm^2**



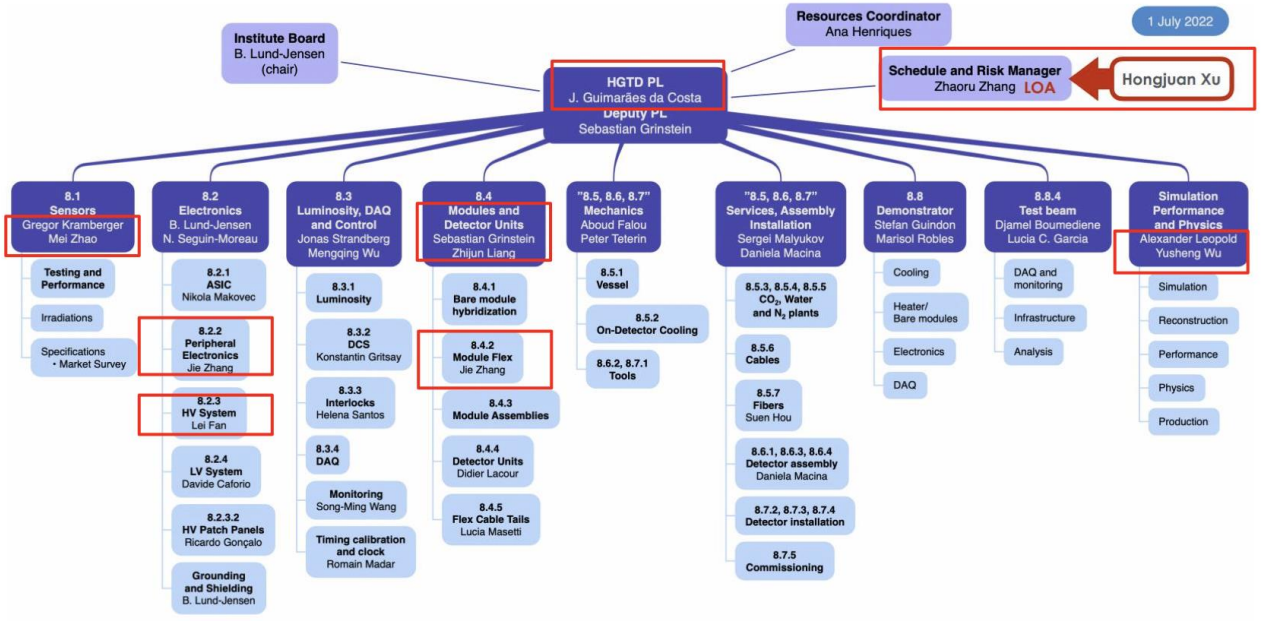
- **Chinese group make a major contribution to the HGTD** （IHEP，USTC，NJU，SDU，SJTU）
  - 45% detector assembly
  - >34% radiation harness LGAD sensors
  - 100% peripheral electronics，50% ASIC tests，>16% high voltage electronics

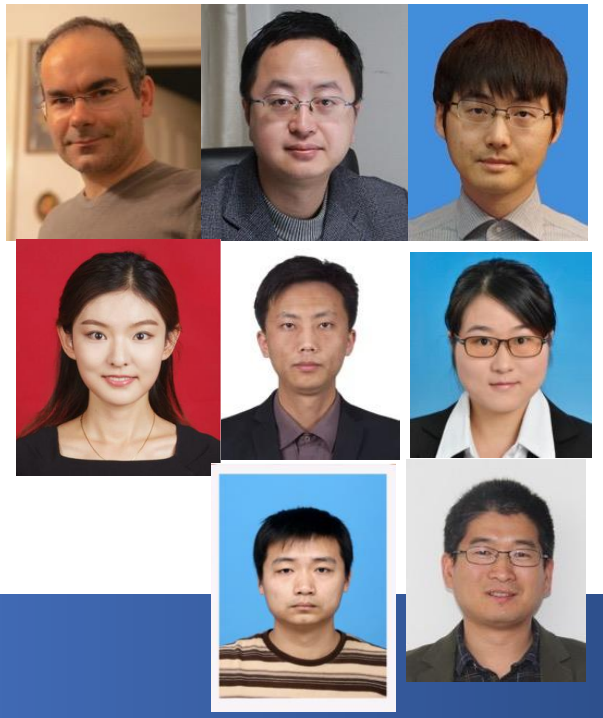


ATLAS HGTD： Management position

- Chinese group leads the ATLAS HGTD project
  - **IHEP Joao is the HGTD project leader， ATLAS Level-1**
    - First time, the Chinese group leader was the LHC detector project leader
  - 4 Level-2 convenors（梁志均，赵梅，张照茹、吴雨生）
  - 2 Level-3 convenors （张杰，樊磊）

Management architecture of HGTD projects

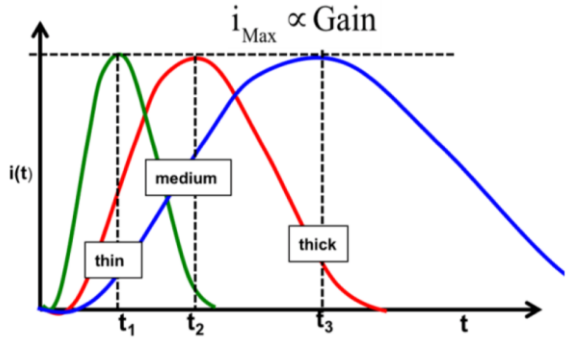




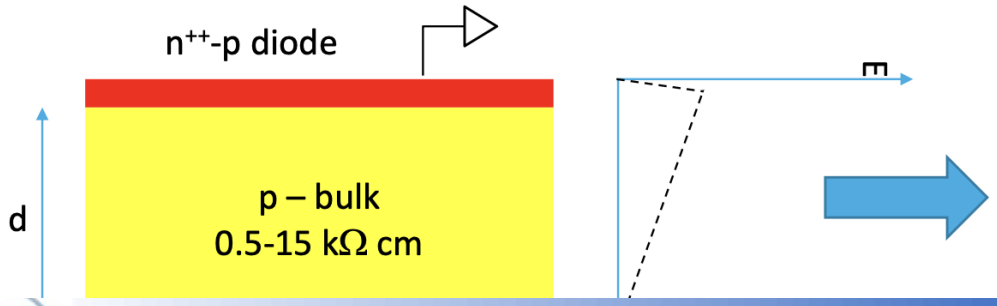
Low Gain Avalanche Detectors (LGAD)

- **LGAD is a new technology developed recently, that could measure the particle time at ps precision（20 - 30ps)**
- **Compared with APD and SiPM, LGAD has moderate gain (10-50)**
  - High S/N，no self triggering
  - Thin depleted region（漂移区）decrease t_{rise} ， increase the electric field and electron drift velosity

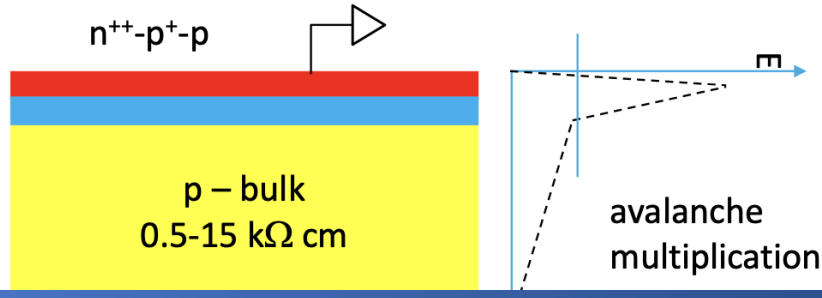
$$\sigma^2_{jitter} = \left(\frac{t_{rise}}{S/N}\right)^2$$



Silicon pixel detector :PIN



LGAD:P+ gain layer on top of PIN diode



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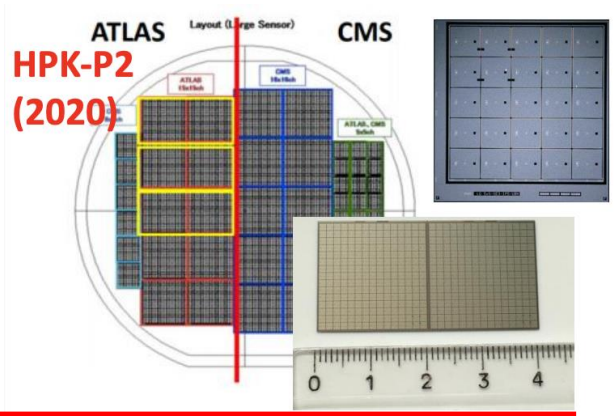
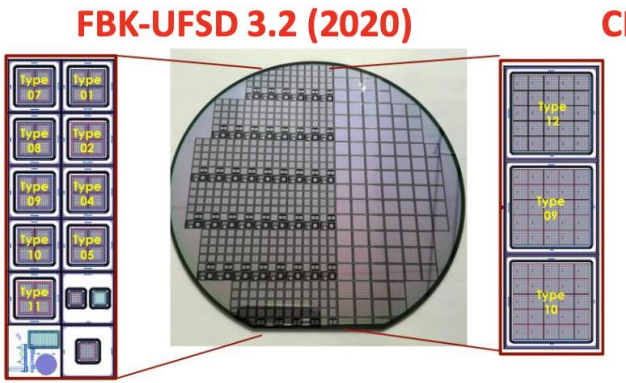
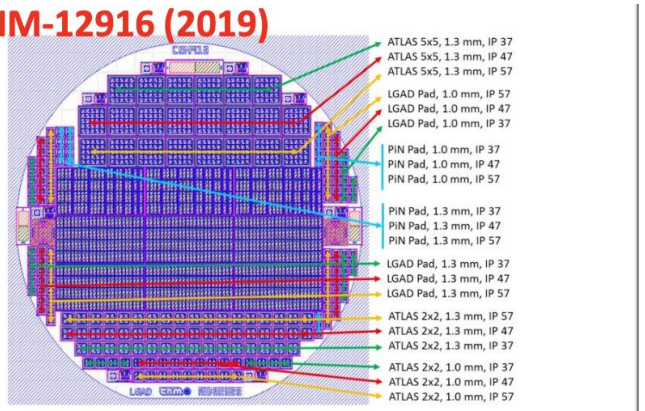
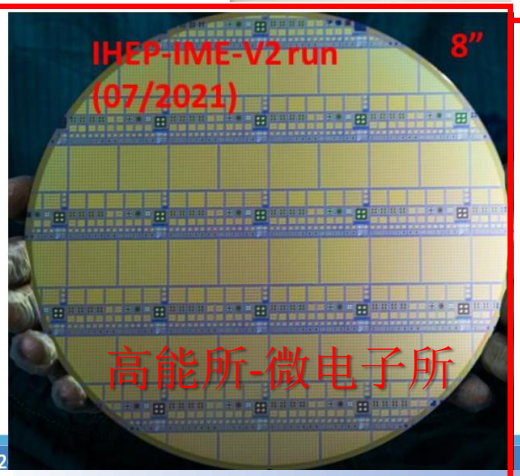
Foundries of the LGAD

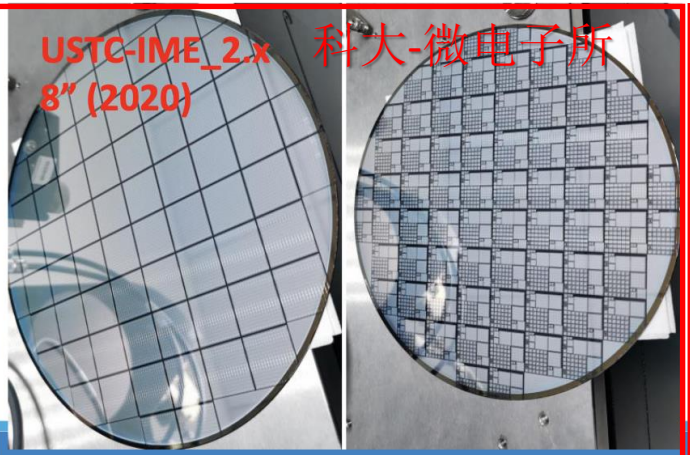
- Recently， many institutes and foundries start to develop the LGAD
  - In China： IHEP-IME (高能所-微电子所), USTC-IME (科大-微电子所), NDL(高能所-北师大)
  - Abroad： 滨松HPK (Japan)， FBK (意大利), CNM (西班牙）…
  - 高能所和科大分别独立设计传感器版图和工艺，在微电子所8寸晶圆工艺流片

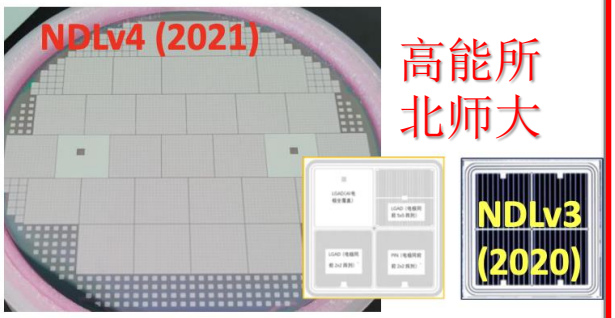








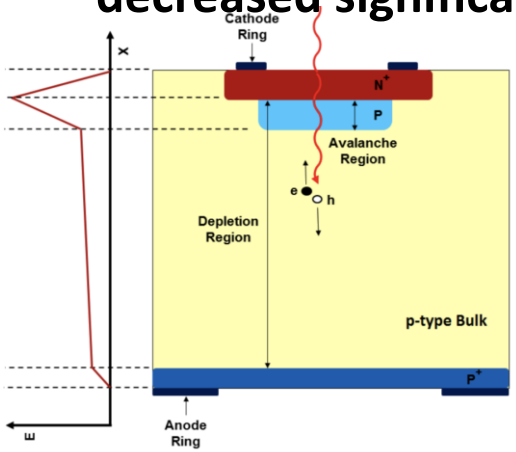


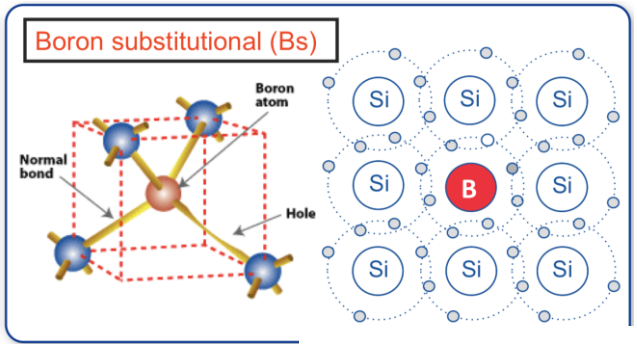


PLANAR TECHNOLOGY – more vendors
(e2V, BNL, Micron …)

Acceptor removal of LGAD

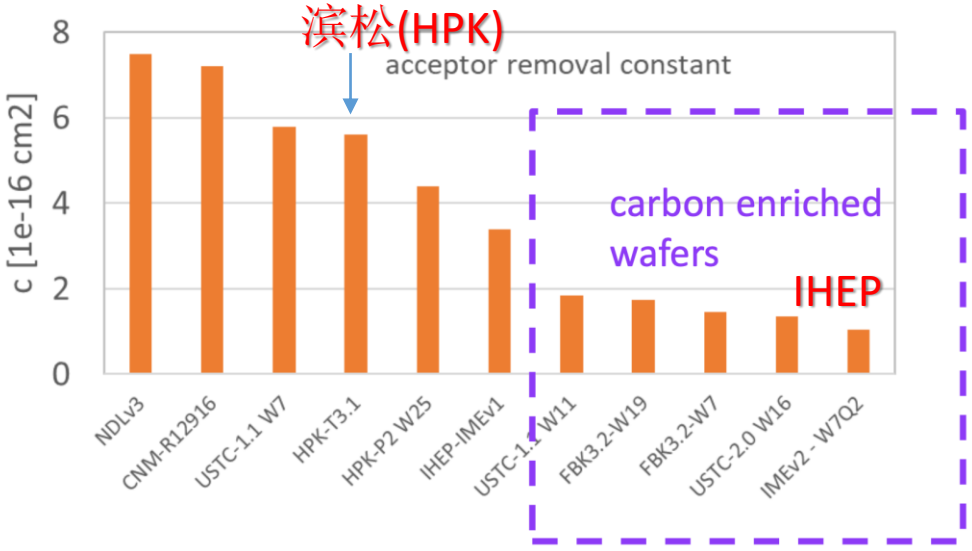
- **After neutron/proton irradiation， effective boron was removed， gain of LGAD decreased significantly (Acceptor removal)**





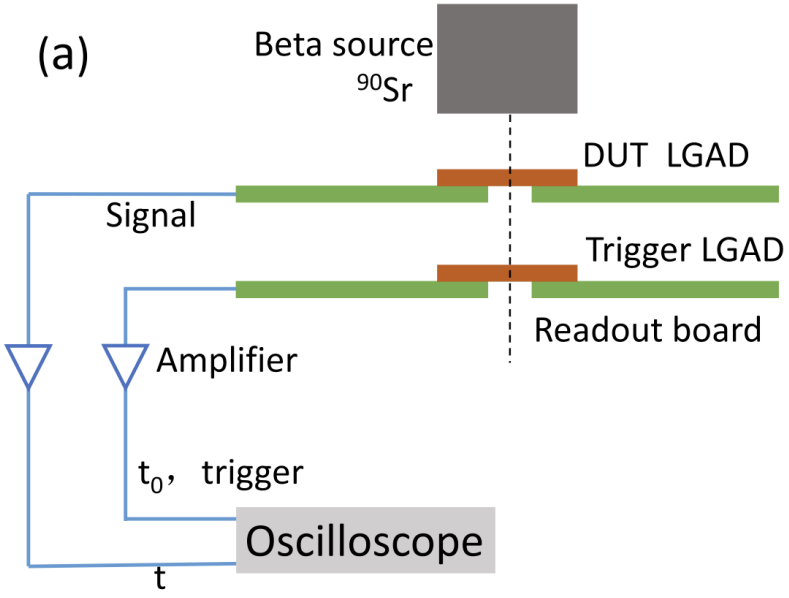
- **IHEP implanted the Carbon onto the gain of LGAD**
  - ✓ Decrease the acceptor removal rate of the boron
  - ✓ Significantly increase the radiation hardness
  - ✓ Radiation hardness better than HPK

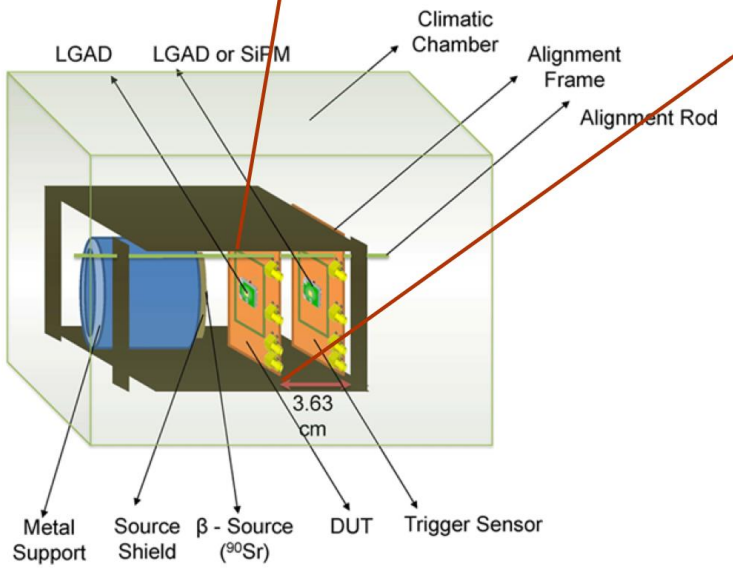
IHEP-IME LGAD most radiation hardness



Time resolution test of the LGAD

- **Sr^{90} Beta source test (time resolution、collected charge）**
- 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 Sr^{90}

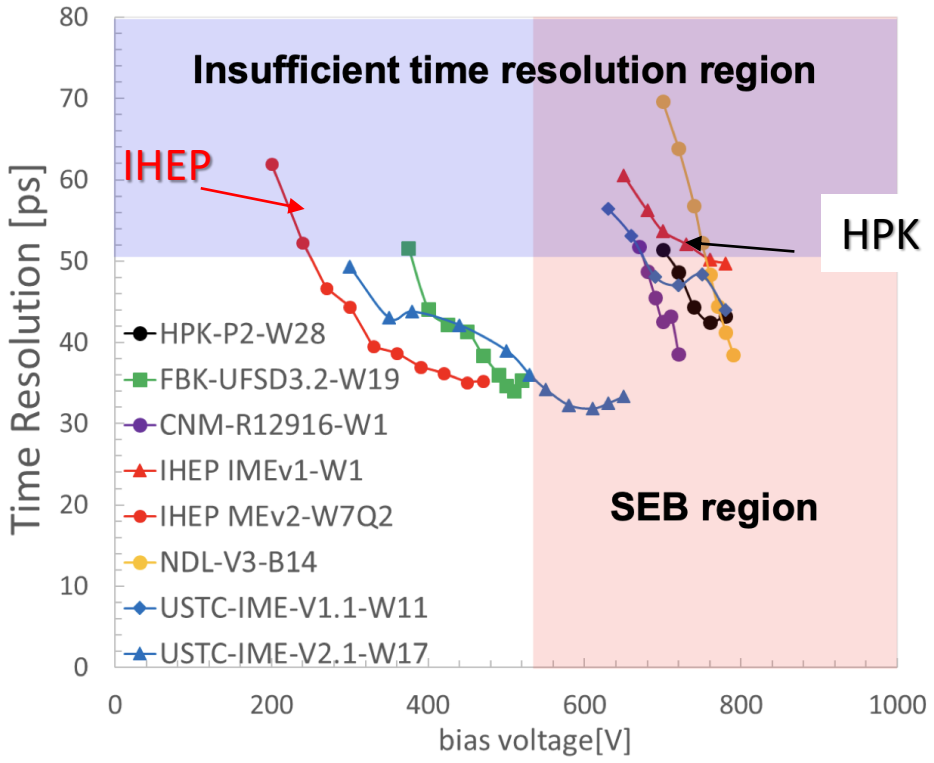




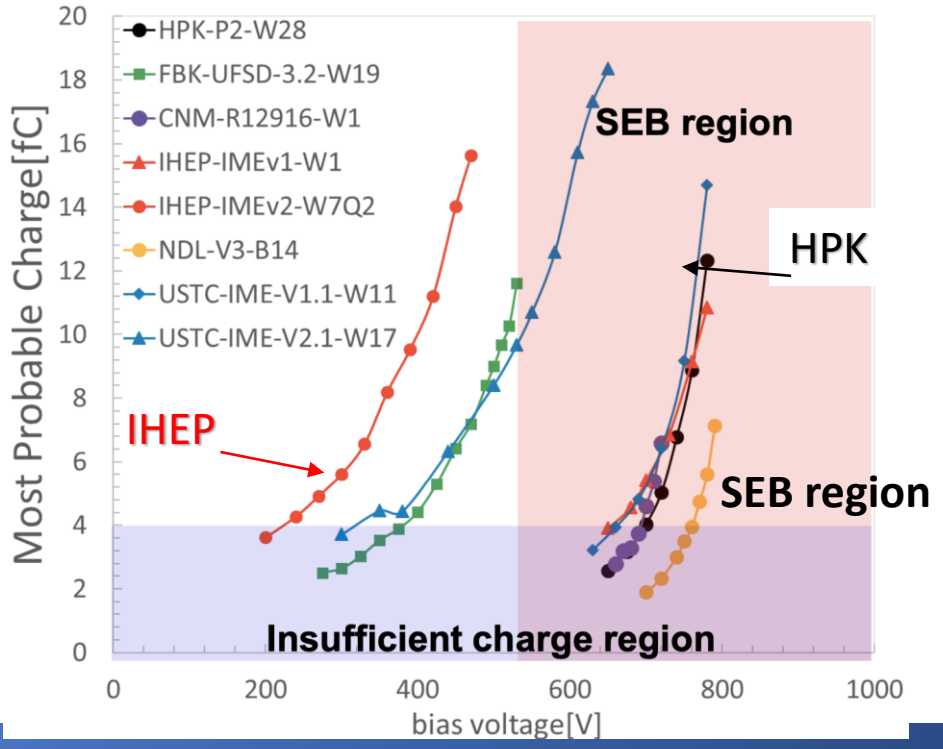
Performance of LGAD after 2.5e15 cm^{-2} neq radiation

- Carbonated IHEP-IME LGADs satisfied the requirement of the HGTD ATLAS
  - Time resolution: 30-50 ps， collected charge > 4fC， work bias voltage < 550V（avoid the SEB）
  - IHEP LGAD work below 300V

Time resolution vs bias voltage



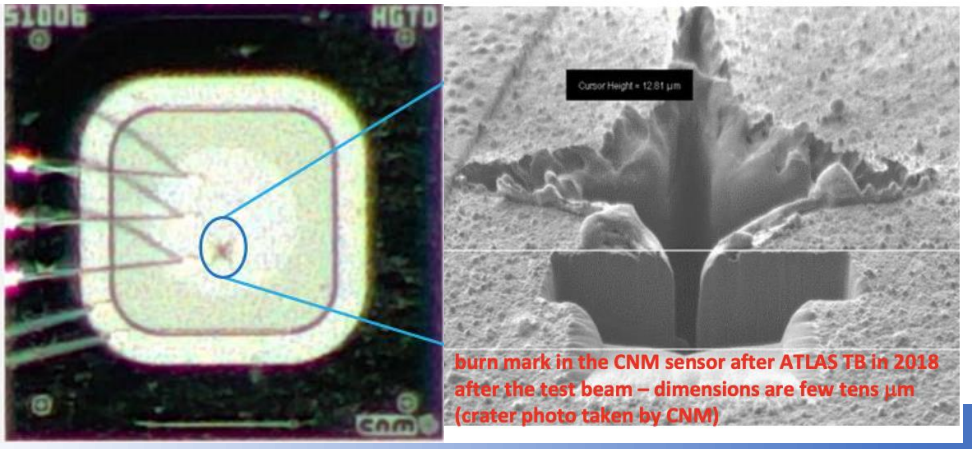
Collected charge vs bias voltage



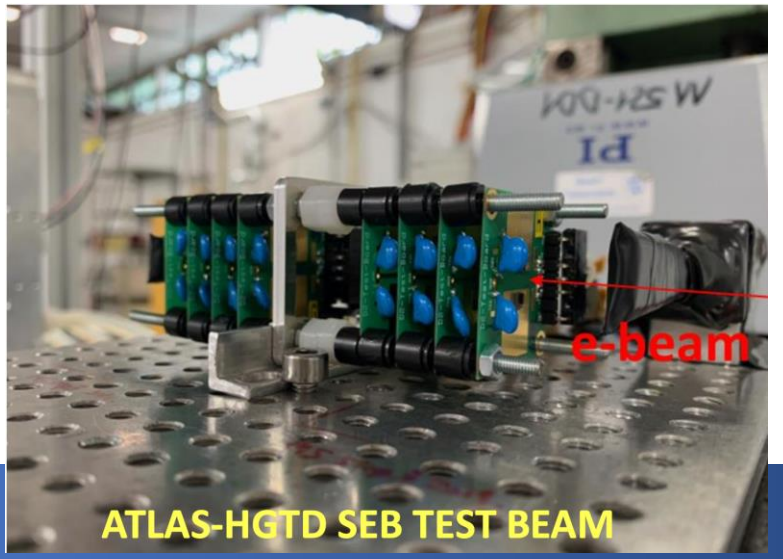
Single Event Burnout (SEB) of the LGAD

- **RD50, CMS and ATLAS found the SEB of LGAD at 2021**
  - High bias voltage and electric field in LGAD could induce the SEB,
  - To avoid the SEB, the bias voltage of 50 um LGAD should <550 V
- **ATLAS has done the test beam with 120GeV proton at CERN**
  - After 2.5e15 neq/cm2，8 IHEP-LGAD sensors didn't burnout at the test beam
  - Carbonated IHEP-IME LGAD could avoid the SEB since the low work bias voltage radiation hardness

Single event burnout of the LGAD

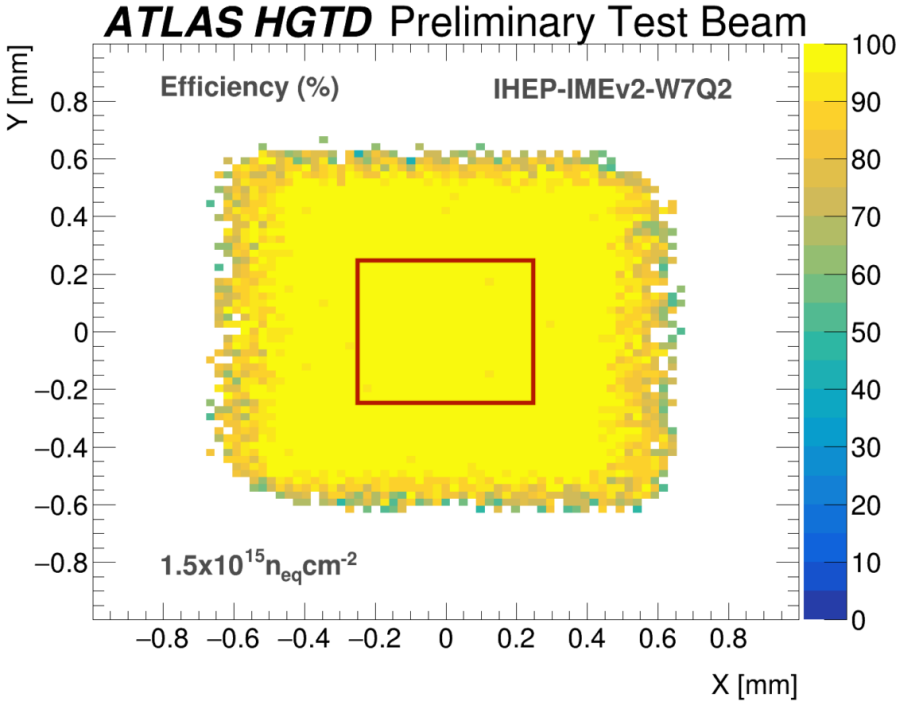


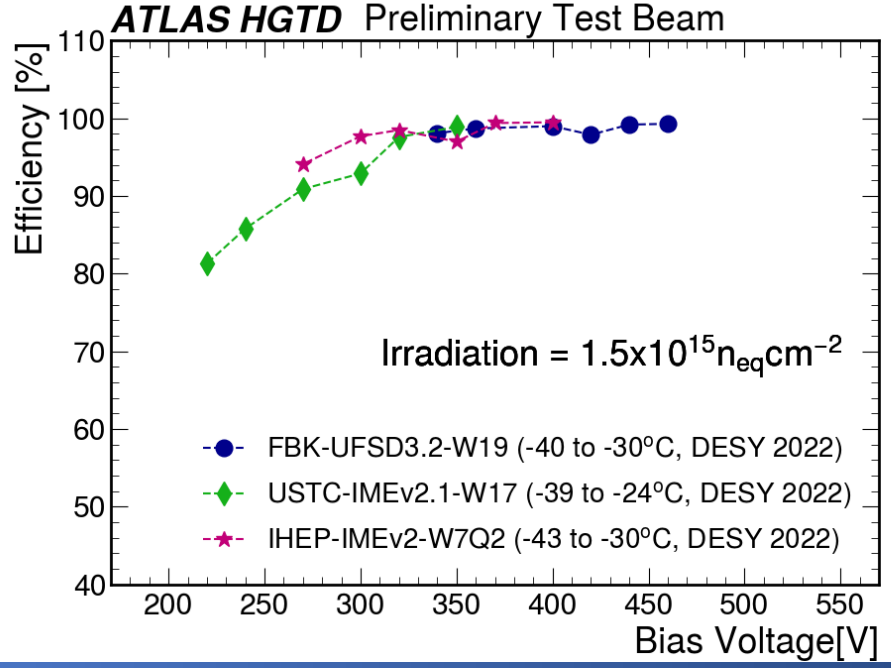
CERN test beam: 120 GeV 质子束流



Performance of the LGAD after irradiation at the test beam

- After irradiation， IHEP-IME LGAD achieved **100% detecting efficiency** at the test beam
- IHEP-IME LGAD has passed the Market Survey of CERN
  - **The domestic silicon sensor firstly is used in LHC**

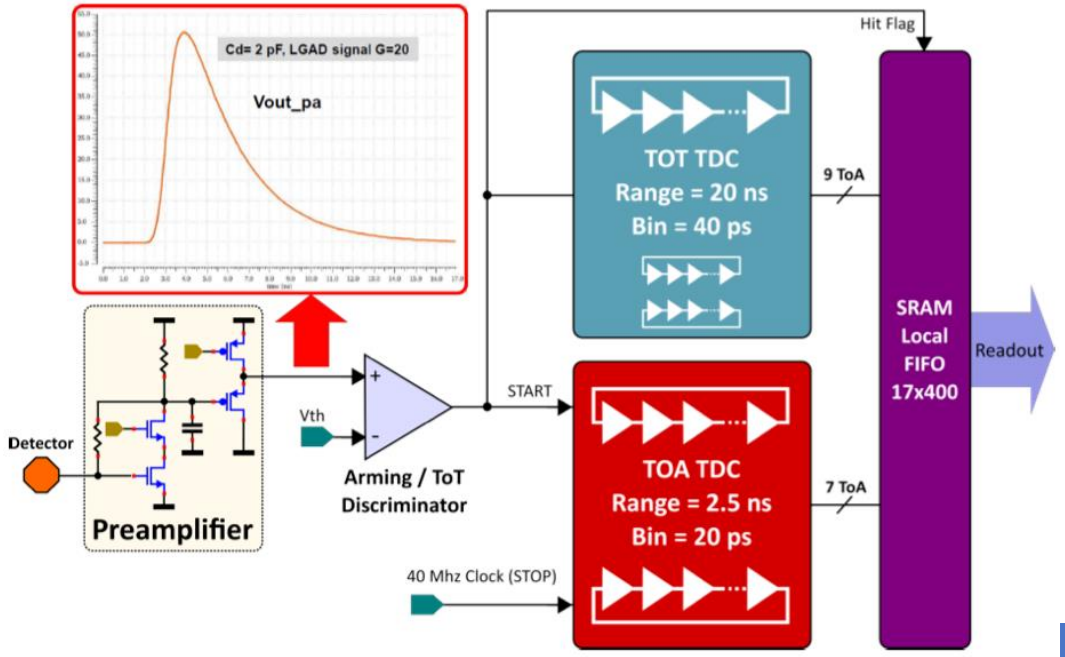




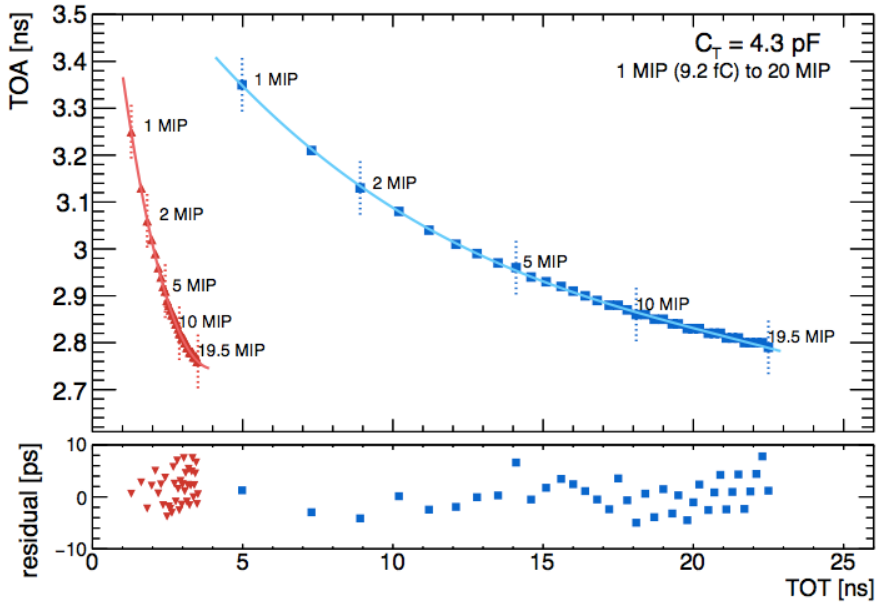
ALTIROC : fast readout ASIC

- ATLAS fast readout ASIC chip， many institutes cooperated to design
  - IHEP would do the digital circuit part of the ASIC， will finish 50% wafer level test
- 225 channels per chip， Amplifier, discriminator and two TDC per channel
  - 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)

ALTIROC timing ASIC in nutshell



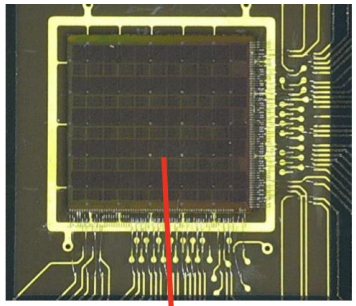
Time walk correction with TOT

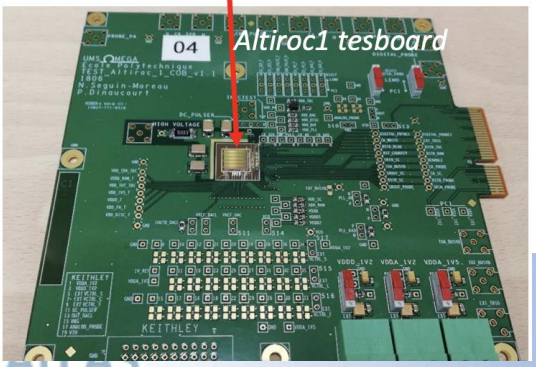


Fast readout ASIC

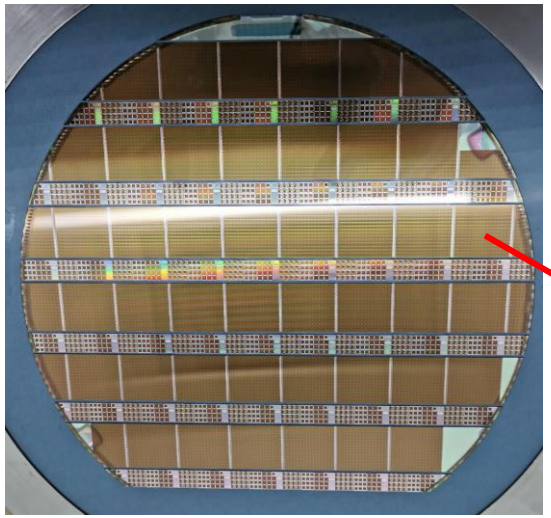
- Produced by the 130nm process of the 台积电（TSMC）
- ALTROC1– 5x5 array with complete analogue front end (discriminator + TDC)
- ALTIROC2– 15x15 array with almost complete functionalities
  - Full-size ASIC prototype ~2x2 cm^2 with 225 readout channels
  - Large amount of digital data, limited power consumption (1.2W/ASIC → 5.3 mW/ channel)
  - data serializers @ up to 1.28 Gb/s,

ALTIROC1 and testboad

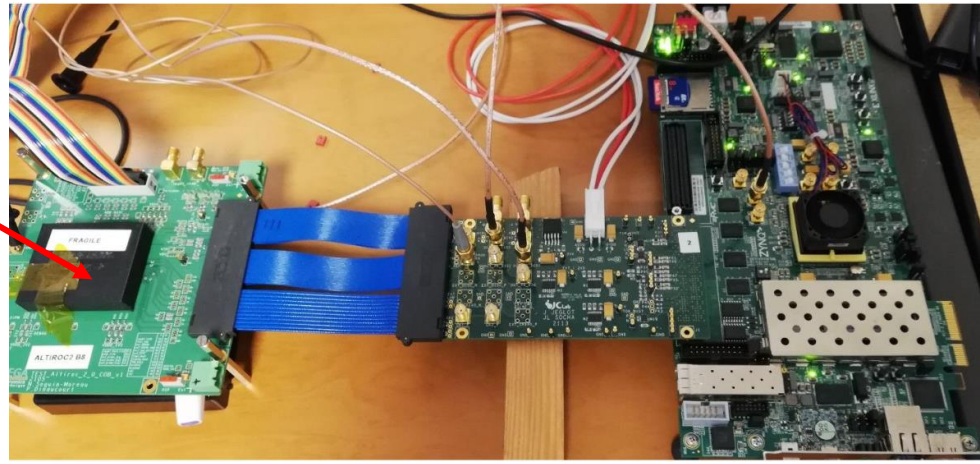




ALTIROC2 晶圆



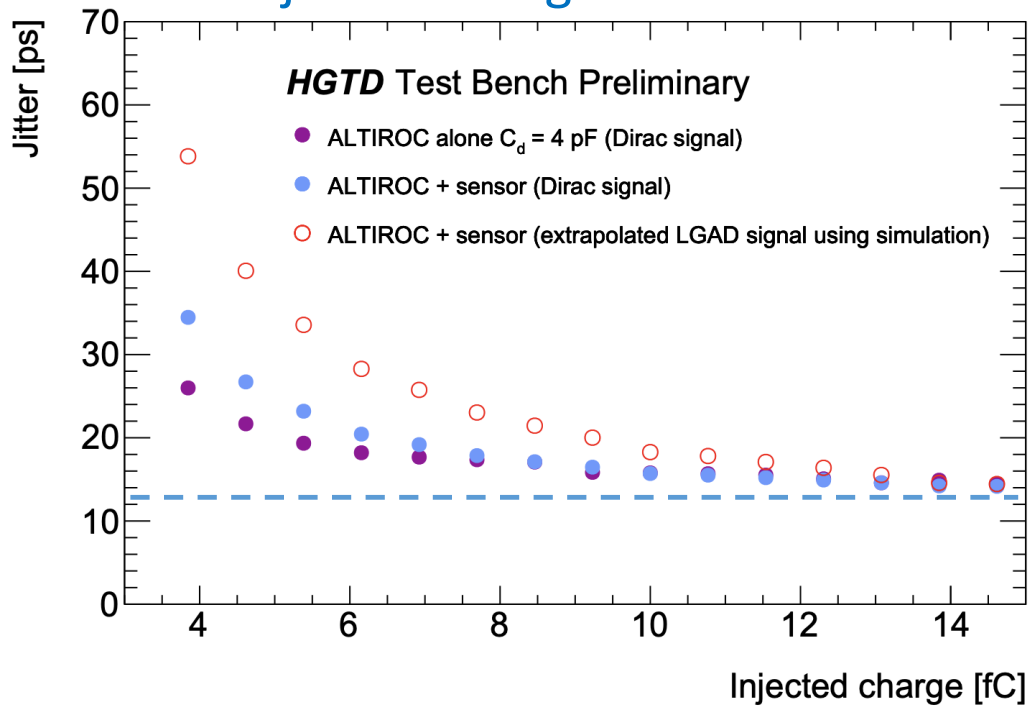
ALTIROC2 test bench setup



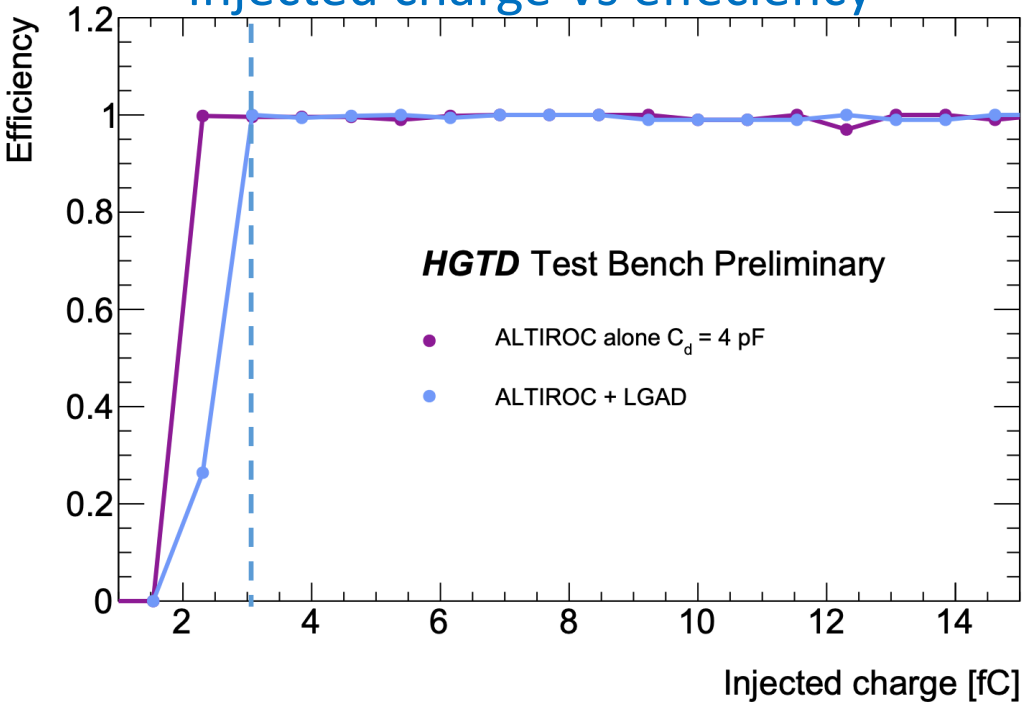
Test of the fast readout ASIC

- Requirement of the ATLAS: time resolution < 70 ps @ 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

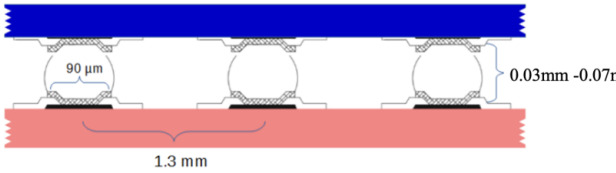
Injected charge Vs Jitter



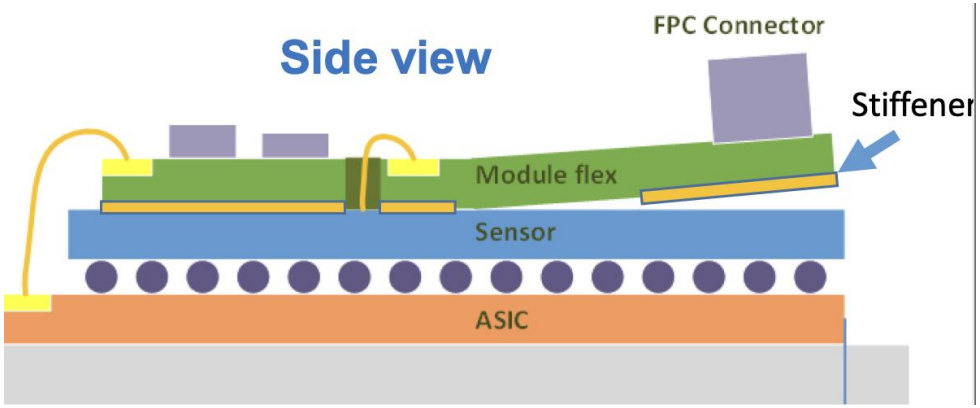
Injected charge Vs effeciency

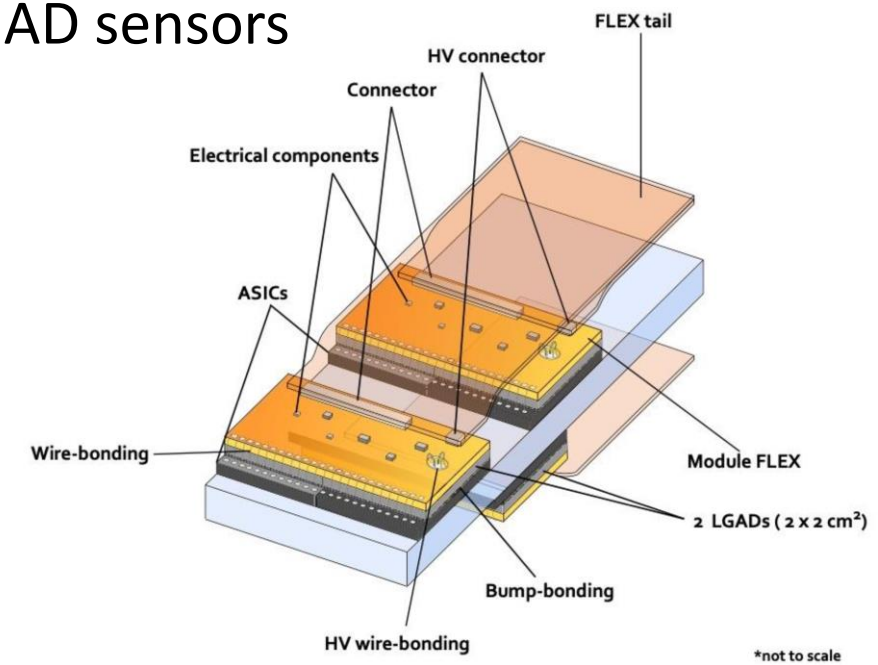


Detector module of the ATLAS HGTD



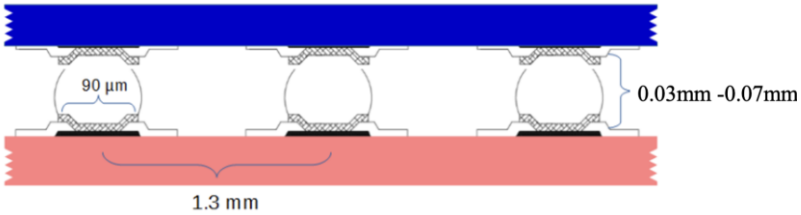
- ATLAS HGTD consists of 8032 detector modules, 3.6 million channels , 6.4 m2
- Detector module consists of 2 ASIC、2 LGAD sensors、1 flexible PCB
  - 15 × 15 pixels， mm pixel size
  - Bump bonding of the ASIC and LGAD sensors





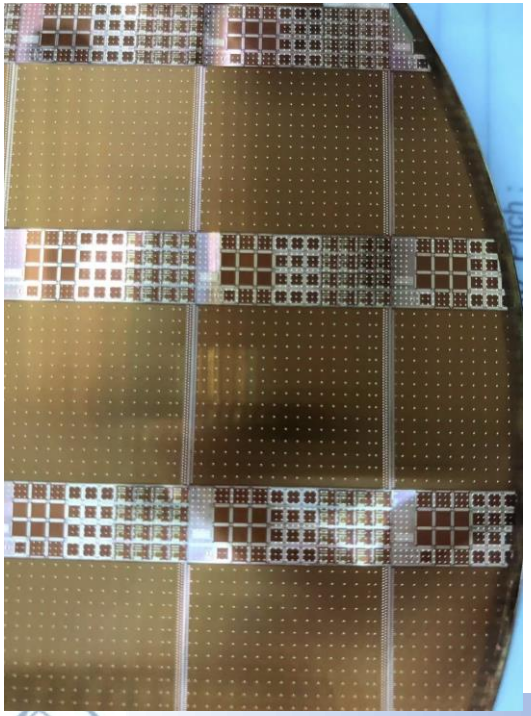
Detector module： Bump-bonding

- IHEP would finish 50% of the bump-bonding
- IHEP has finished 40+ bump-bonding modules
  - ALTIROC2 chips + IHEP-IMEP LGAD

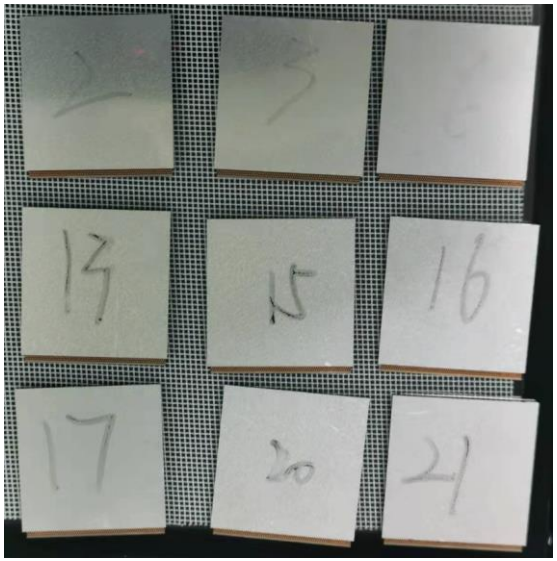


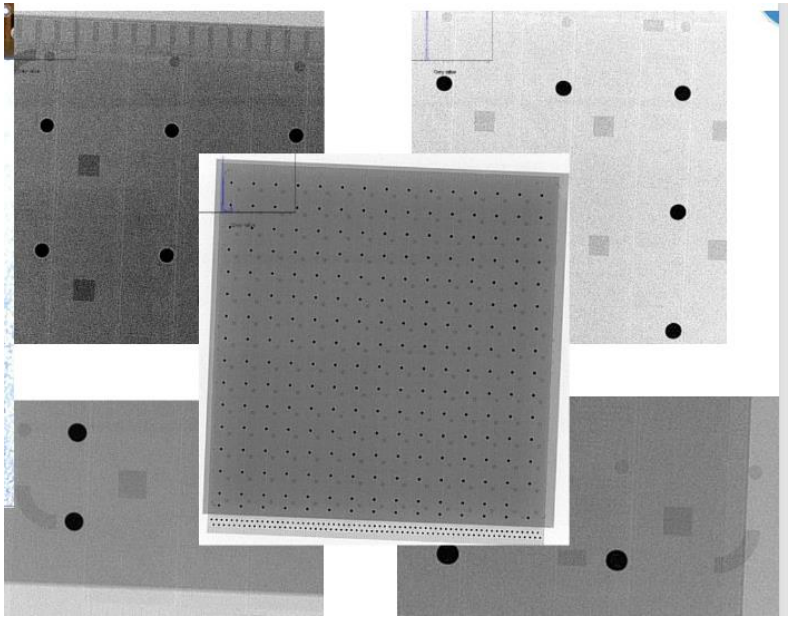
X-ray image of full-size hybrid

ALTIROC2 wafer with bump



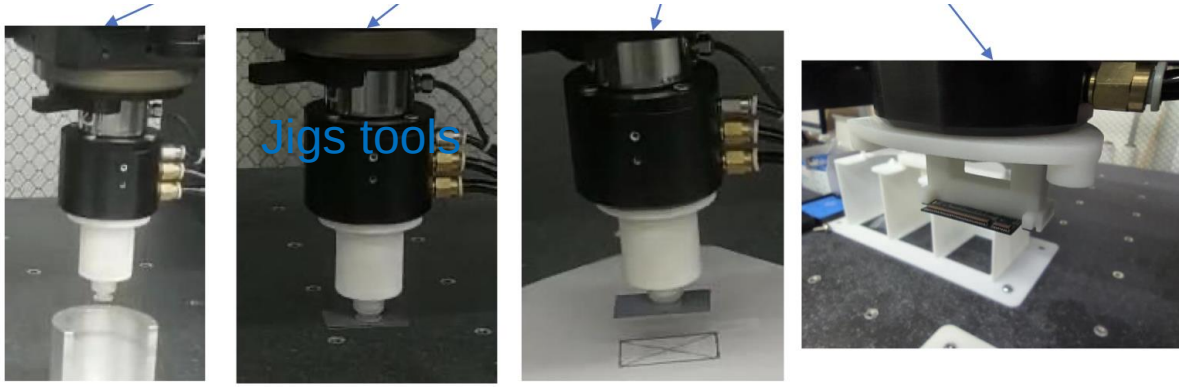
Bump-bonding modules

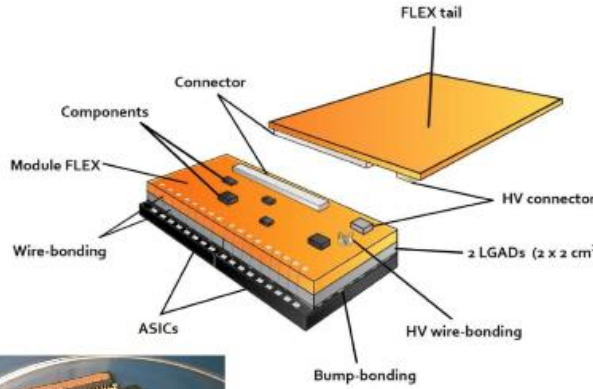


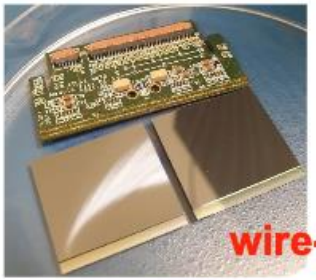


Assembly of the detector modules

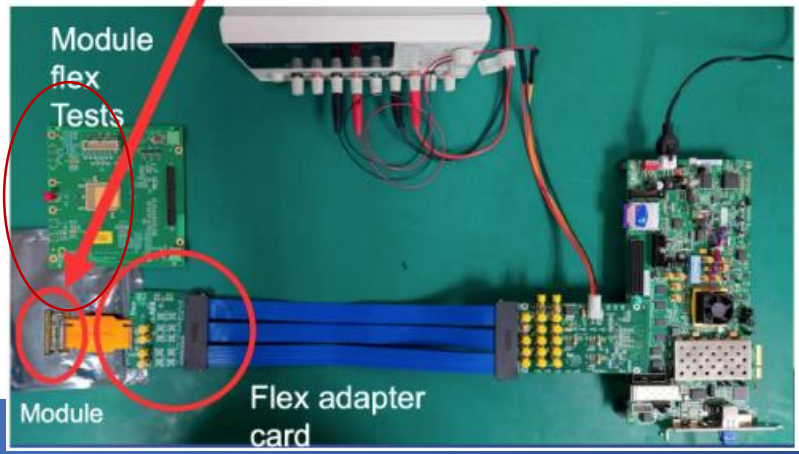
- HGTD will have 8032 detector modules
- 6 assembly centers in the world
  - IHEP, USTC, German, France, Spanish, Morocc
  - IHEP is the largest centers, will produce 34%
- Automatically gantry developed by the IHEP and Chinese company
  - ✓有高分辨图像系统，做芯片图像识别
  - ✓自动芯片组装、点胶
  - ✓位置组装精度达到微米级







glue+
wire-bonds

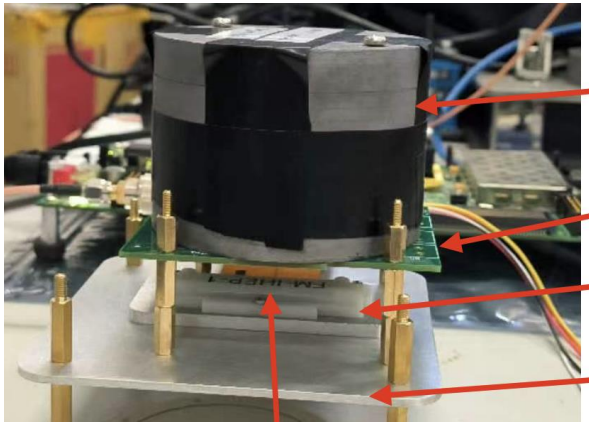


The first detector module prototype of ATLAS HGTD

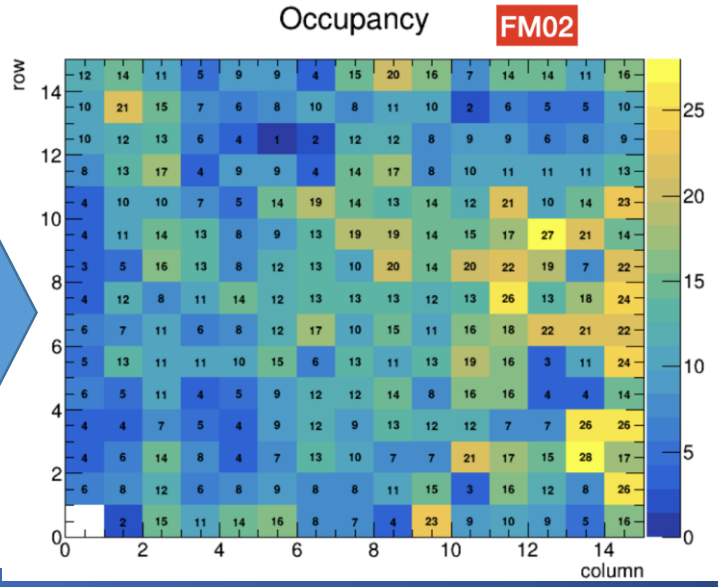
- IHEP has developed the first detector module prototype of ATLAS HGTD
- In the radiation source test, all of the 225 channels of the module work well

First Detector Module Prototype

Beta test

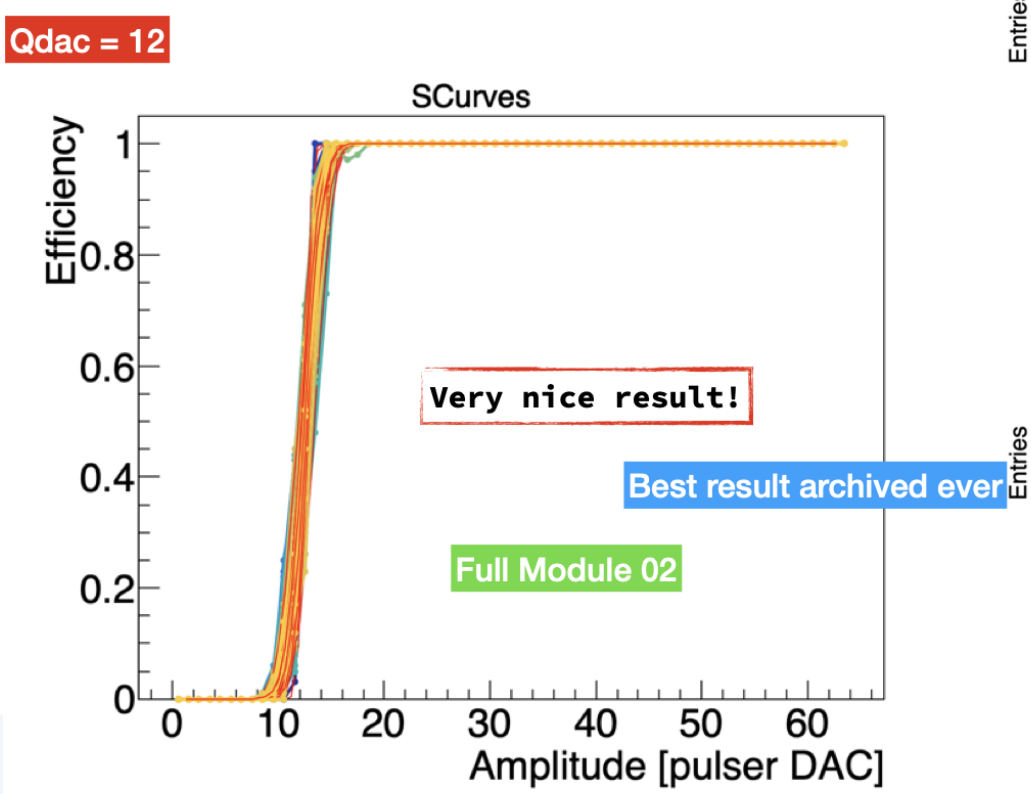


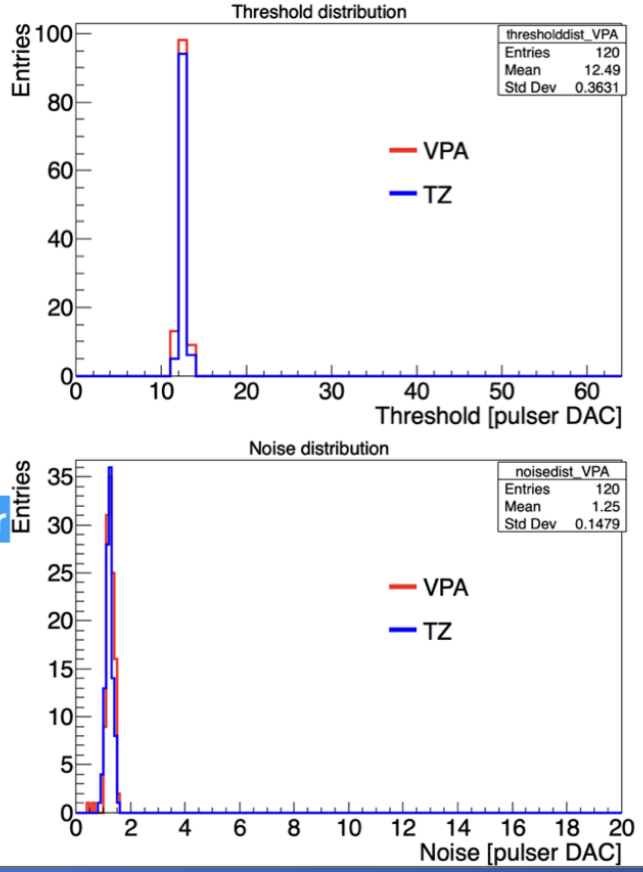
Hit maps of 225 channels



The first detector module prototype of the HGTD

- IHEP has developed the first full-size detector module prototype for the HGTD of ATLAS
  - The lowest threshold of ASIC is 4.8fC, verly close to the design goal 4fC,
  - the uniformities of the noise and the threshold of 225 channels are good



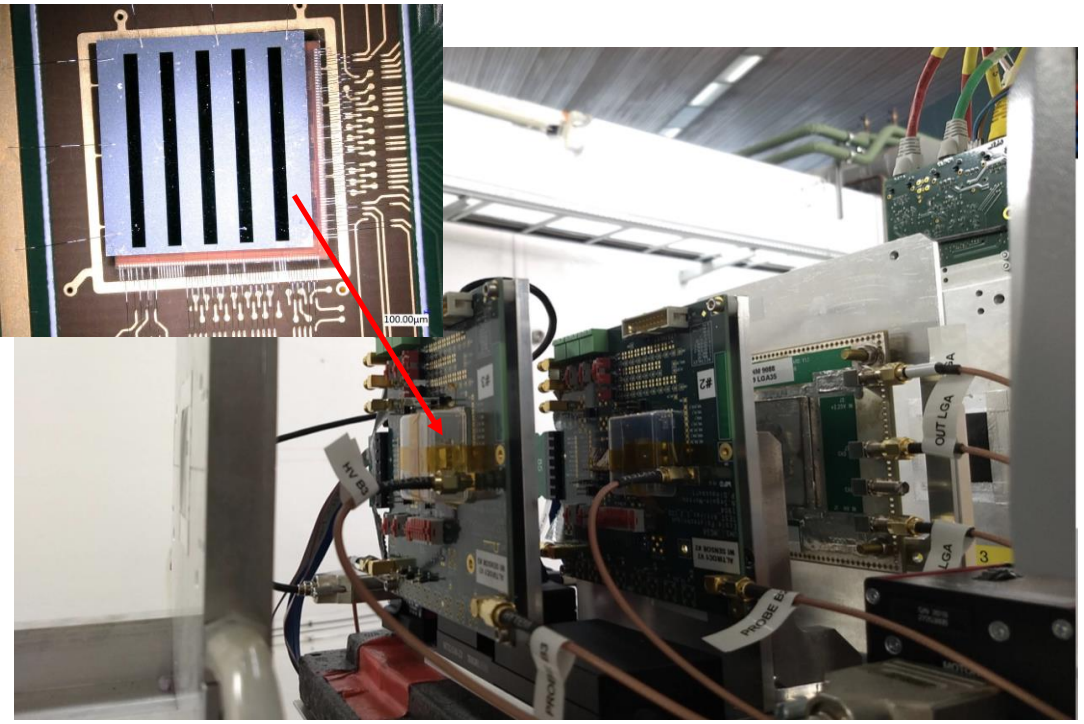


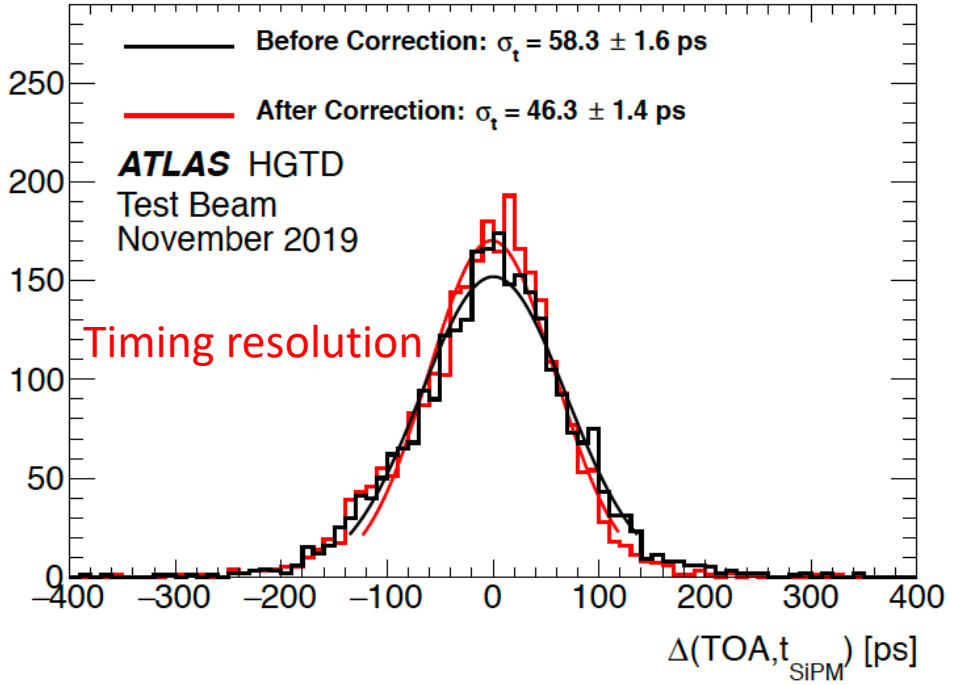
Detector Module Testbeam at IHEP

- The test beam of the 5x5 array detector module (ALTIROC1+LGAD)
  - Time resolution of the module: ~46 ps

LGAD Landau	25 ps	the reason for part of the high jitter found **26 (known reasons)**
Jitter+system/internal clock+time walk residual	37 ps	
TDC clock	7 ps	Total resolution: 36 ps (likely achievable for 20 fC)/ 70 ps for (4 fC)
Per hit total	46 ps	

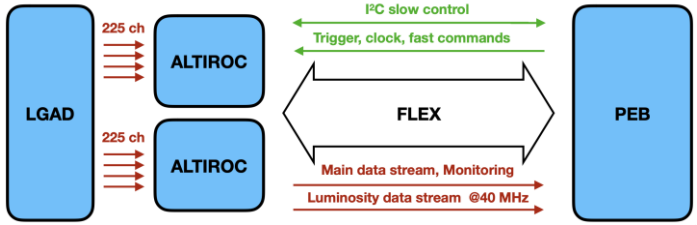
ALTIROC1 mini-modules @ test beam



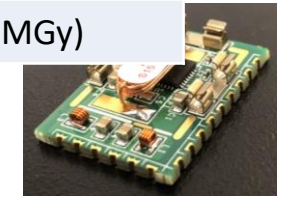


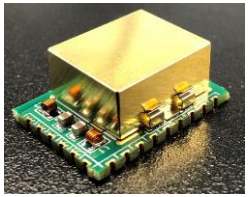
Peripheral electronics board (PEB)

- IHEP and NJU developed 100% PEB
  - Space limit、radiation hardness, high-speed readout ASCI



	From simulation	Safety factor	Design requirement
Fluence	< $1x10^{15}$ neq /cm^2	1.5	≥ $1.5x10^{15}$ neq /cm^2
TID	< 20 Mrad (0.2M Gy)	1.5 x 1.5 (1)	≥ 45 Mrad (0.45 MGy)





DC/DC converter

Design and test each sub-module circuit

- Control and data transmission module(lpGBT&VTRx+）
  - 10.24Gbps uplink
  - Joint testing with ATLAS TDAQ(FELIX)
- Power Block (bPOL12V)
  - Coreless inductor, height < 4mm
  - Optimize the output ripple
- 64-to-1 multiplexer
  - Packaging and testing
  - Pass the proton irradiation test (80MeV) at CSNS

lpGBT eval. board

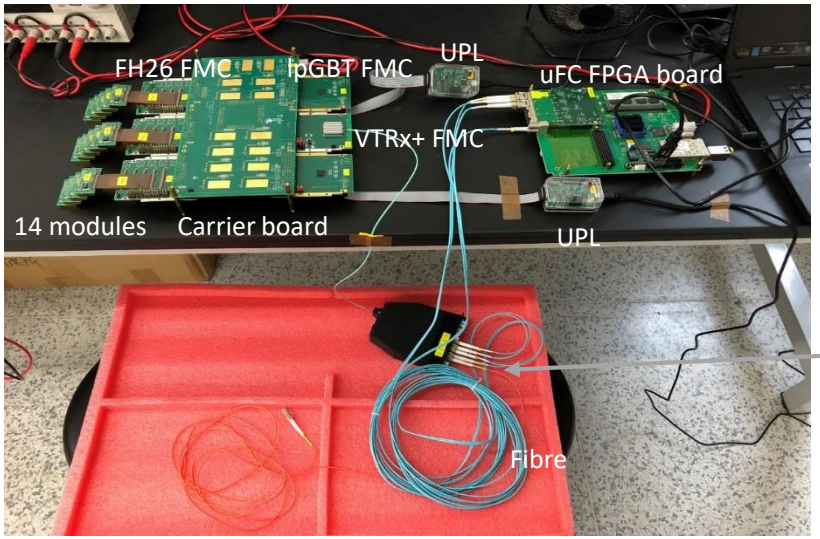
VTRx+ eval. board

MUX64 in QFN88

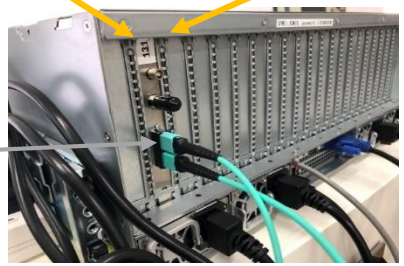
DAQ Demonstration System

- IHEP and NJU developed the DAQ Demonstration System

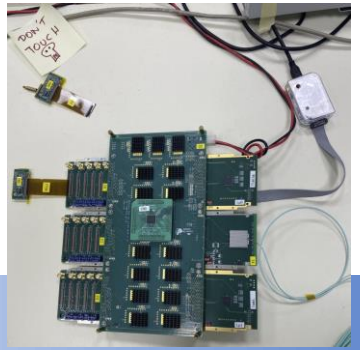
Could read out the data from 14 detector modules synchronously



@IHEP

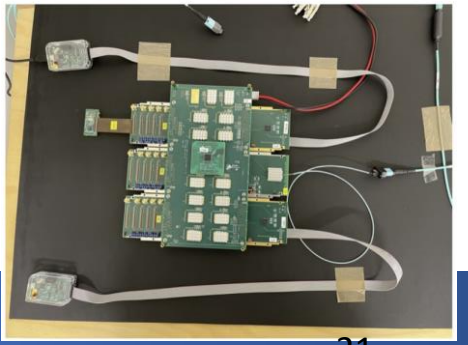


FELIX Server in IHEP



@CERN

@ Nikhef



@KTH

21

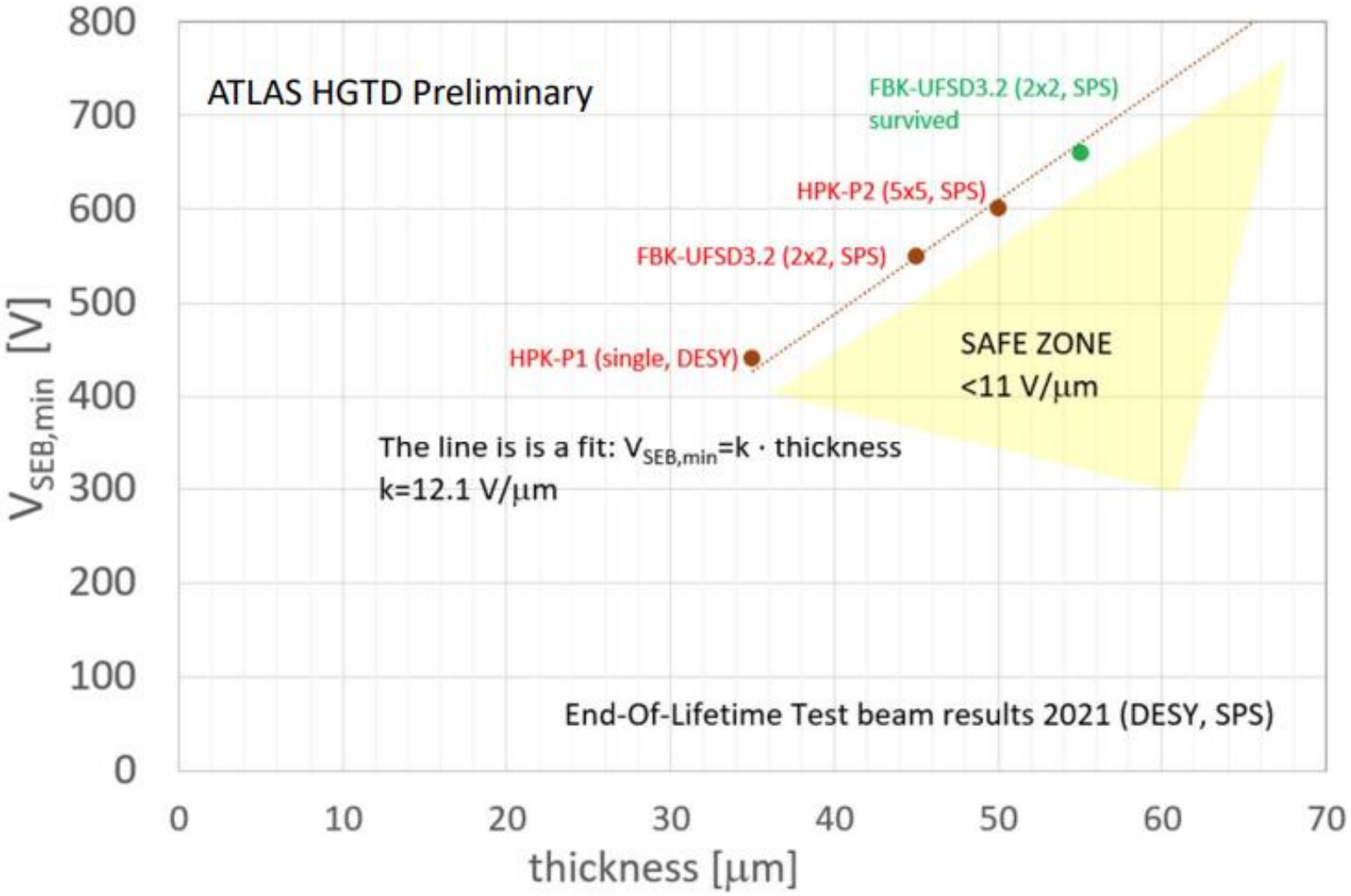
Summary: HGTD of ATLAS at IHEP/NJU

- **Chinese group make a major contribution to the HGTD,** and several members were appointed as level-1/2/3 managers.
- **Domestic LGAD sensor: IHEP designed and IME produced**
  - Most radiation hardness LGAD in the world recently
  - Time resolution is 35ps@300V, could avoid the SEB
- **Peripheral electronics board:**
  - IHEP and NJU lead the designs of the peripheral electronic
  - The prototype of the PEB has been successfully developed
- **Detector modules: first detector modules has been produced by IHEP**
  - **Chinese group leads the module production, finish ~4000 modules, 45% of the total modules**
- **fast readout ASIC chip:**
  - Chinse group will do ASIC **50%** water level test, radiation hardness test
- **High voltage supplier**
  - IHEP has developed one high voltage supplier (100nA current measurement precision)

Thank you for your attention!

backup

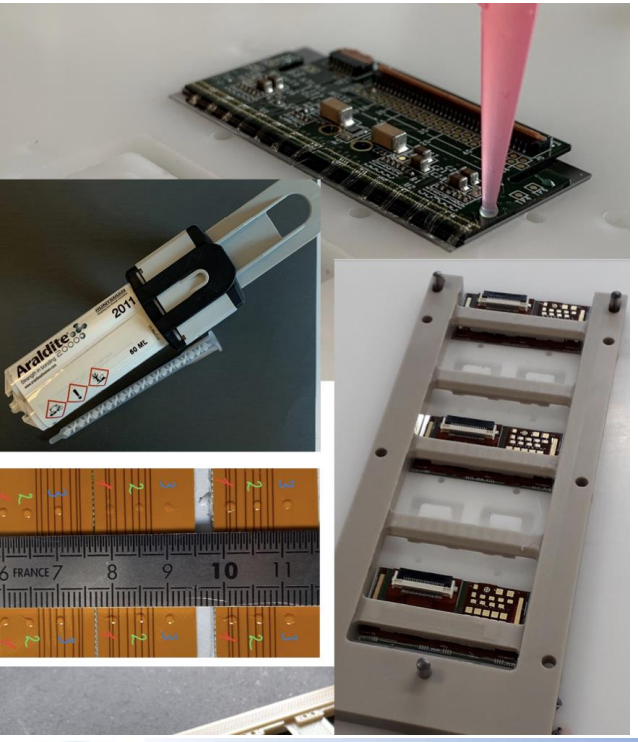
LGAD Single Event Burnout effect (HV stability in the beam)



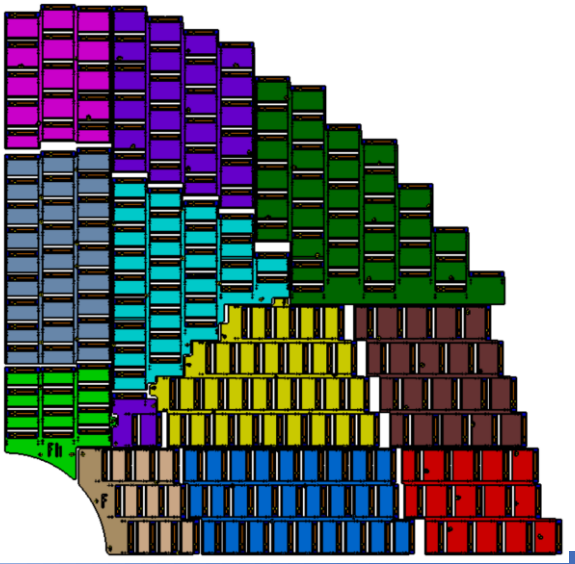
Detector units

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

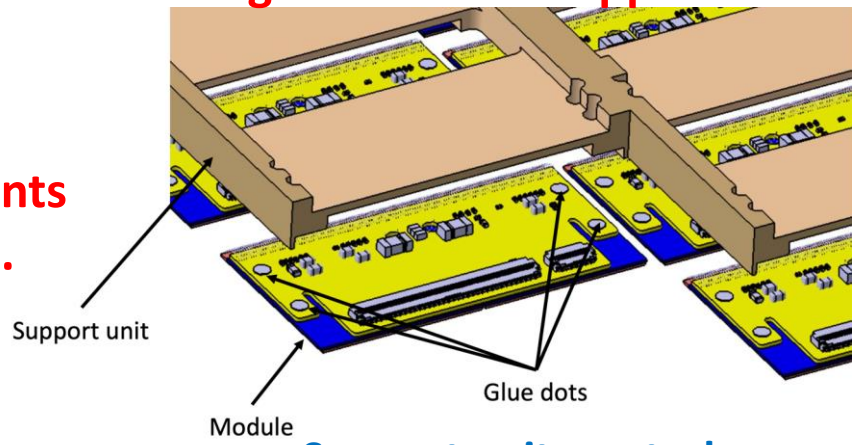
Loading modules on support units



Different color represents different support units.



Loading modules on support units



Support units metrology