IJC/IN2P3

KEK Tsukuba HEP

2023 Joint workshop of TYL/FJPPL and FKPPL

Project of FJPPL (D_RD_23): Project since 2021

Development of precision timing silicon detector (LGAD) for future collider experiments

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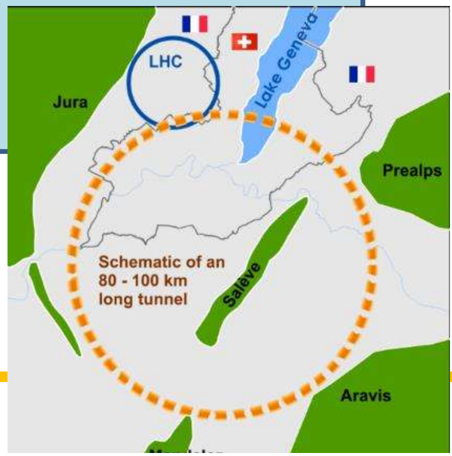
Next Generation Collider Experiments

New: "Higher Luminosity" and/or "Higher Energy"

- ***High Luminosity LHC (HL-LHC)***
  - 20 times more data (~3000-4000 fb^{-1}) at **14TeV**
  - Plan : Start in 2029
- ***High Energy LHC (HE-LHC)***
  - Use super conducting magnets with higher field (16T)
  - **28TeV** collider in the LHC tunnel.
- ***Future Circular Collider (FCC-hh)***
  - Use super conducting magnets with higher field (16T)
  - **100TeV** pp collider in 100km tunnel at CERN.
- ***International Linear Collider (ILC)***
  - 250GeV e+ e- collider in Japan

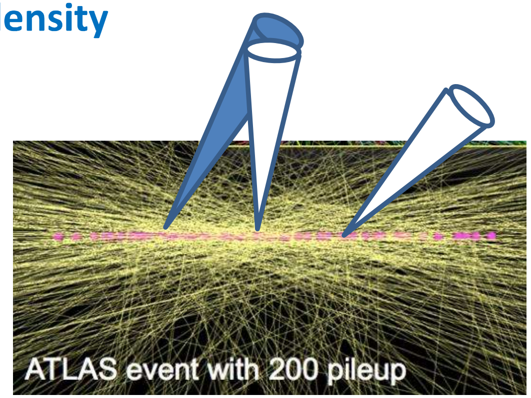
Detectors under construction
Replacements foreseen



Inner Tracking system

In very high particle density

140 pileups @ HL-LHC
1500 pileups @ FCC-hh

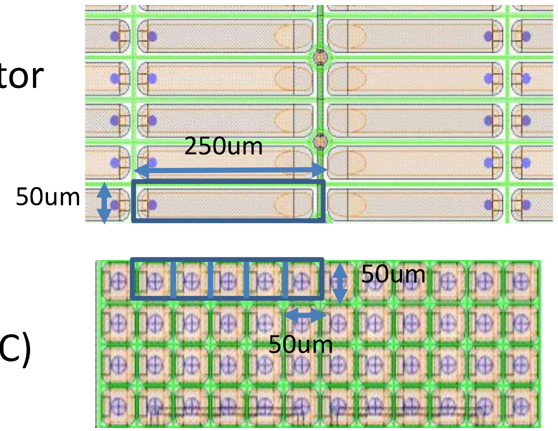


solved this so far…

finer pixel pitch

Current detector
(ATLAS IBL)

New detector
(Pixel @HL-LHC)



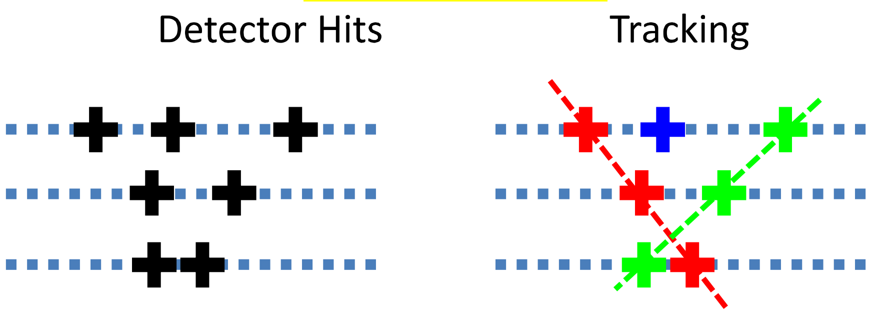
Semiconductor Tracking Detectors in future

- **Further finer pitch ?→ limited by FE Electronics/bump bonding (min : 50x50um^2)**
  - In addition to spatial resolution, **Timing resolution helps!**
  - **→Sensor with good timing information is a candidate for future tracker!**
- **Tentative Requirements:**
  - **30ps timing resolution (1cm at *c*)**
  - ***O*(10)um spatial resolution**
  - **(hadron collider) ~$O(10^{16}) n_{eq}/cm^2$ radiation tolerance**

✓ K+ π+ separation

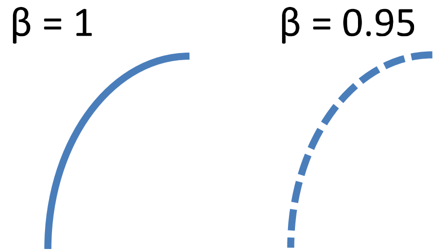
✓ Mass measurement of long lived e.g. chargino

4D tracking !

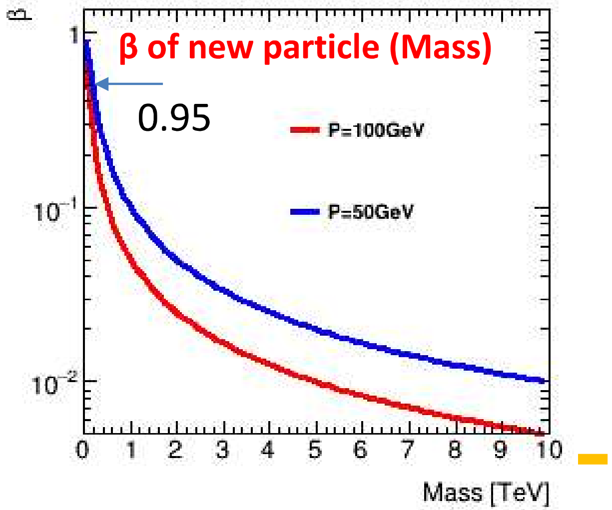


Solve pileup: **correct assignments faster reconstruction**

Timg of flight



150ps difference at R=1m

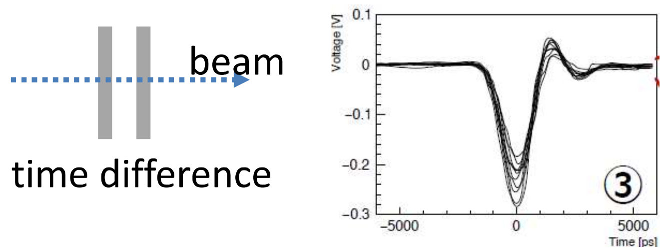


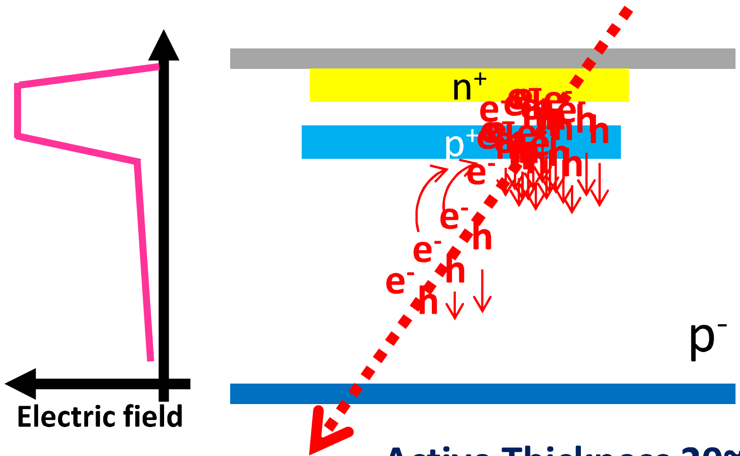
Low Gain Avalanche Diode (LGAD)

- Low Gain Avalanche Diode (LGAD)

  n+-in-*p* type sensor with *p*+ gain layer under *n*+ implant, creating high electric field in localized region: avalanche→ Good timing resolution.

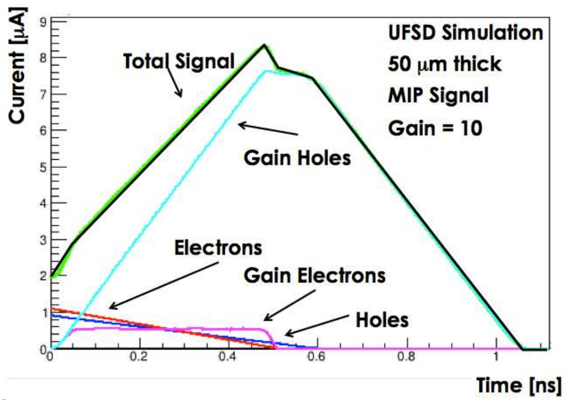
  - **30ps timing resolution already achieved**
  - R&D on
    - **Finer pitch electrodes for spatial resolution**
    - **Understanding the timing resolution**
    - **Radiation tolerance**

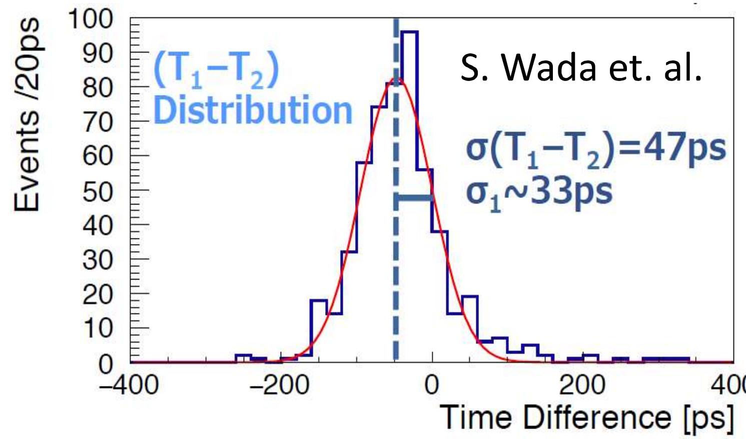




Active Thickness 20~50um

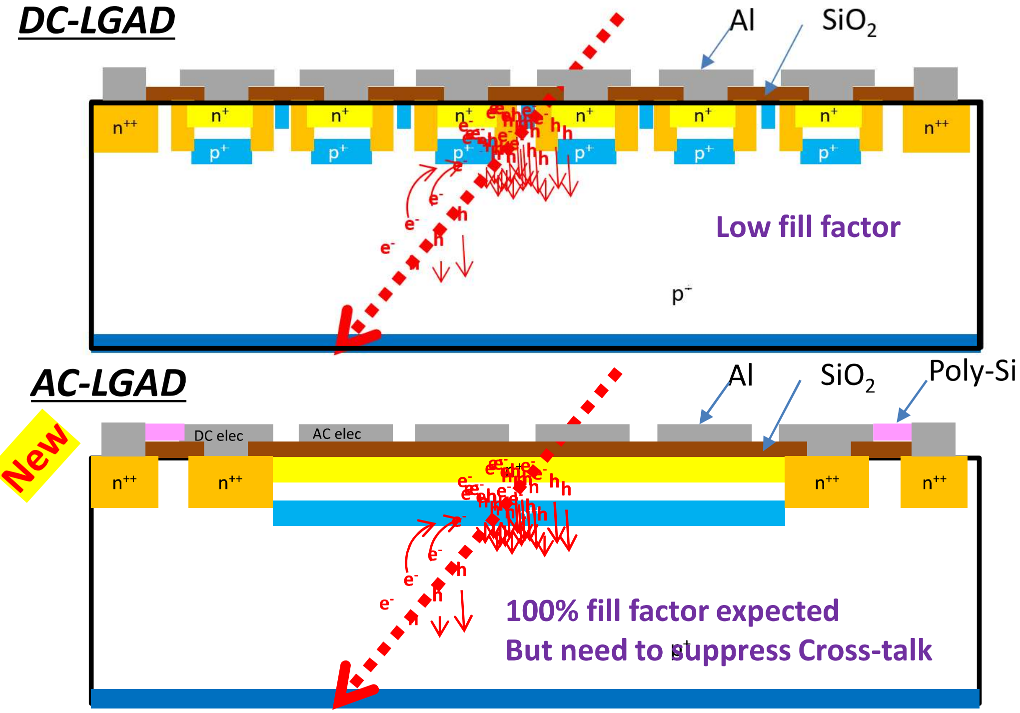
Signal drivers : **Gain Holes**

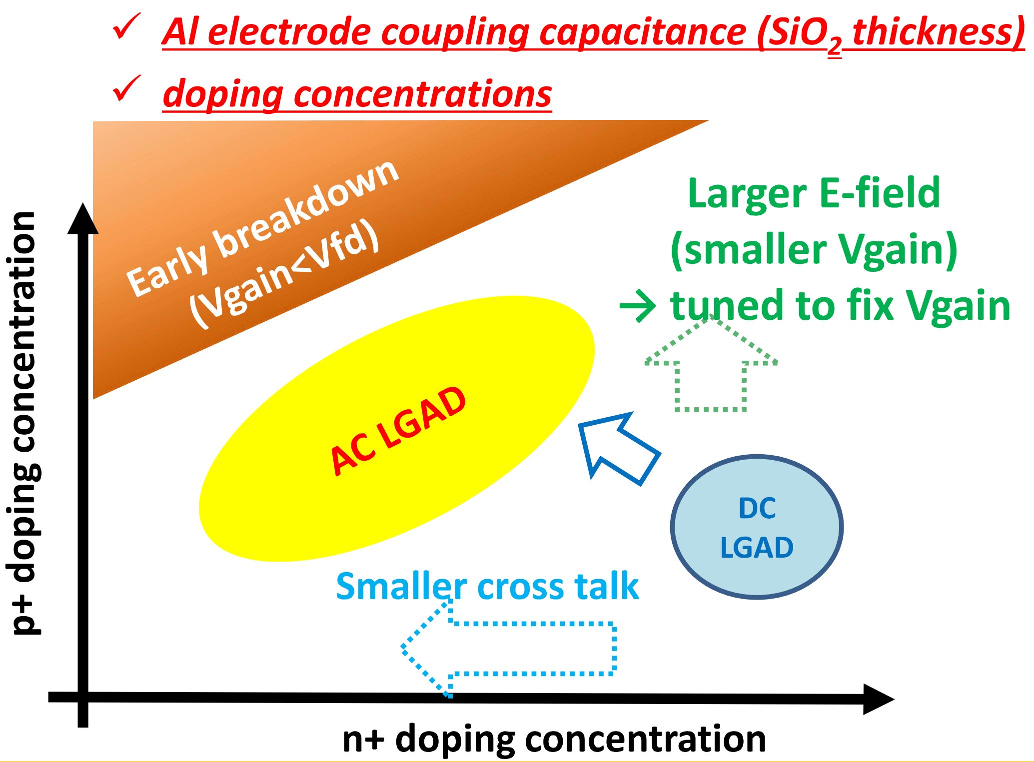




AC-LGAD with both spatial and timing resolutions

- First prototype with 80um pitch strip (DC-LGAD)→**Only 20% of area has gain**
- Common gain layer with AC-coupled readout (AC-LGAD) → **Uniform gain! and electrode segmentation possible**
  - **Increase n^+ implant resistivity to suppress cross talk via n^+ implant**
  - **Larger Ccpl for larger signal**

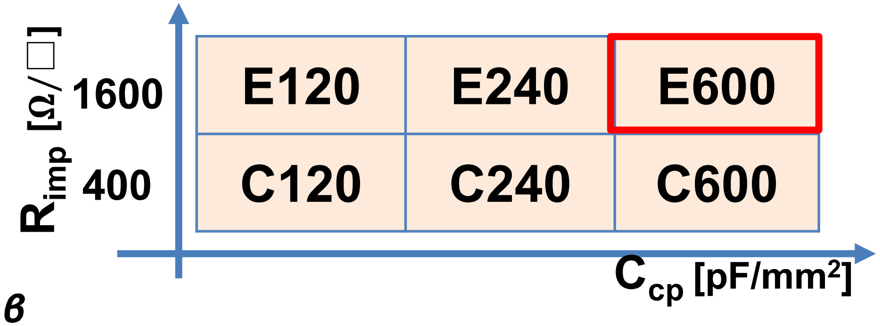




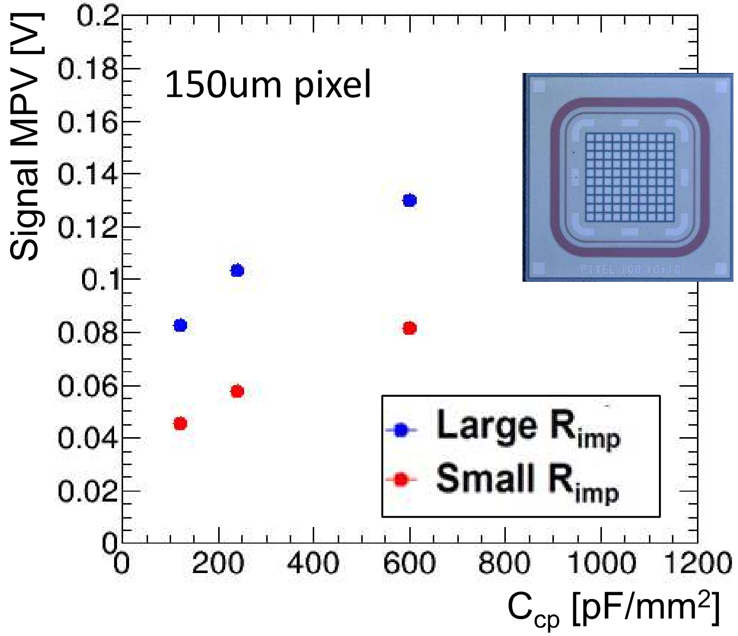
Electrode segmentation (spatial resolution)

(left) Compared signal height MPVs of 6 C_{cp}/R_{imp} settings
- Two n+ resistivities and three Ccpl (150um pixel)

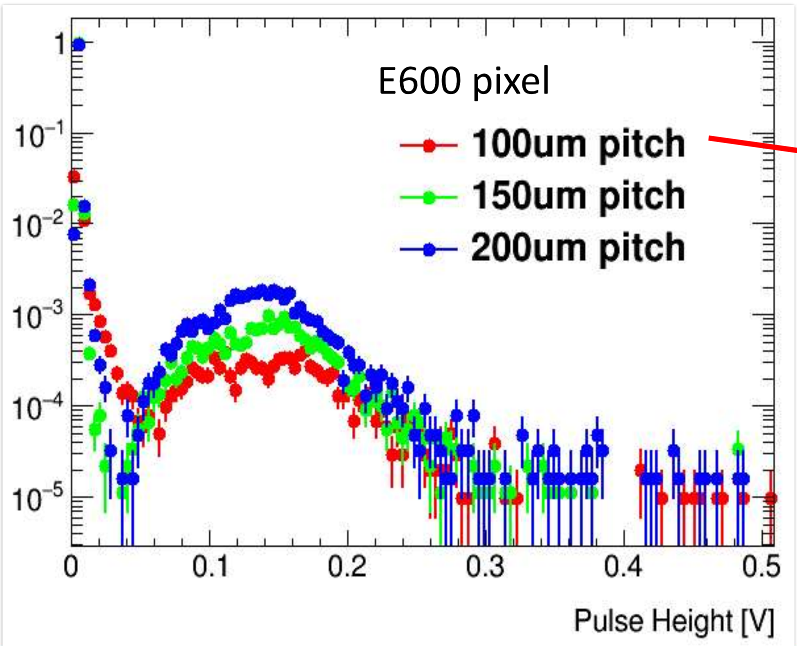
(right) Compared signal distributions of 3 pixel pitches
- 100/150/200um pitches (E600 type)



Signal height MPVs for β



Signal height distributions for β



Signal MPV for β : 122.4±5.5mV

Noise: 2mV (typ.)

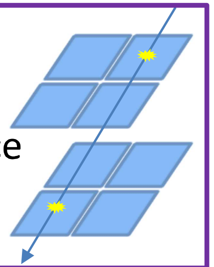
100um pitch pixel successfully developed with good S/N

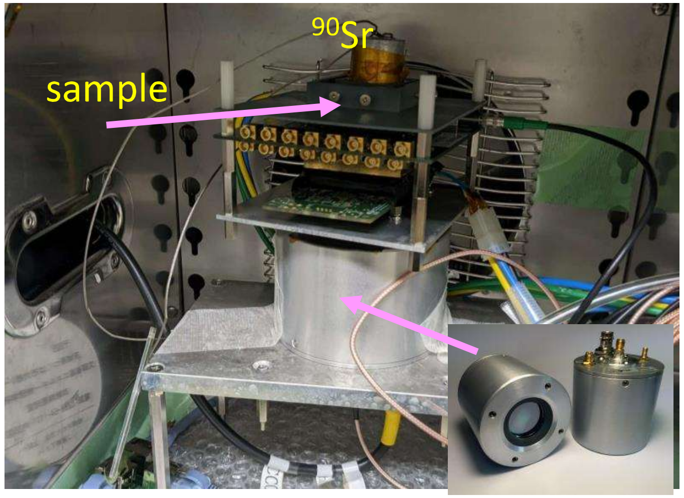
Measurement/understanding of timing resolution

In beam

2 layer coincidence

→ $\sigma_t = \sigma_{\Delta t}/\sqrt{2}$

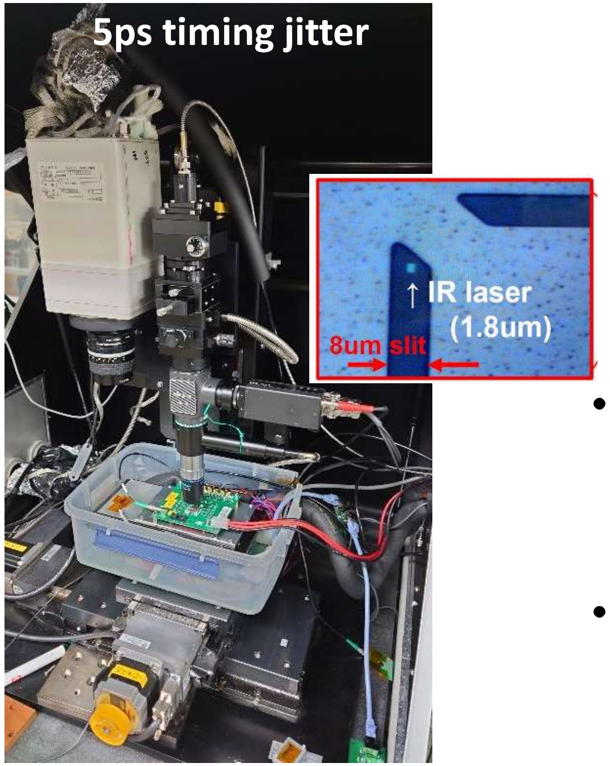




Photek PMT 240

~9ps timing resolution

Infra-Red (pico sec) laser



Contributions to timing resolution

$$\sigma_t^2 = \sigma_{tw}^2 + \sigma_j^2 + \sigma_L^2$$

~~σ_{tw}: Time walk~~ (constant fraction)

σ_j: Jitter (electronics) **MIP** **IR**

σ_L: Landau effect **MIP**

- Photek PMT240 (MCP-PMT)
  - timing reference to MIP signal
  - **9 ps resolution**
  - **Don't know injecting position.**
- Infra-red (pico sec) laser
  - Known injecting position(Size : 1.8um)
  - **<10 ps jitter**
  - **No landau noise**

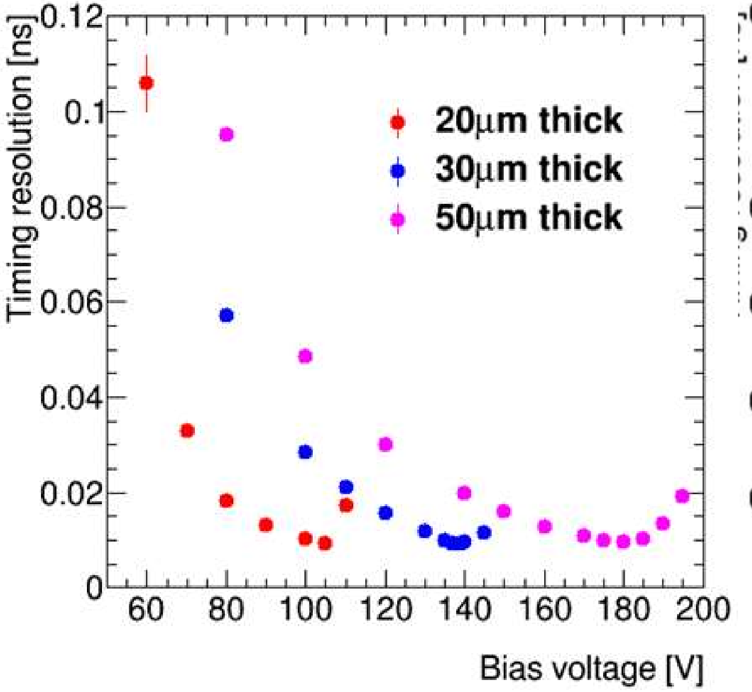
Timing Resolution

$$\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} = \frac{\sigma_n}{\left|\frac{S}{t_r}\right|} = \frac{t_r}{\left|\frac{S}{\sigma_n}\right|}$$

Timing resolution measured in two systems
(reference time jitters are not subtracted)

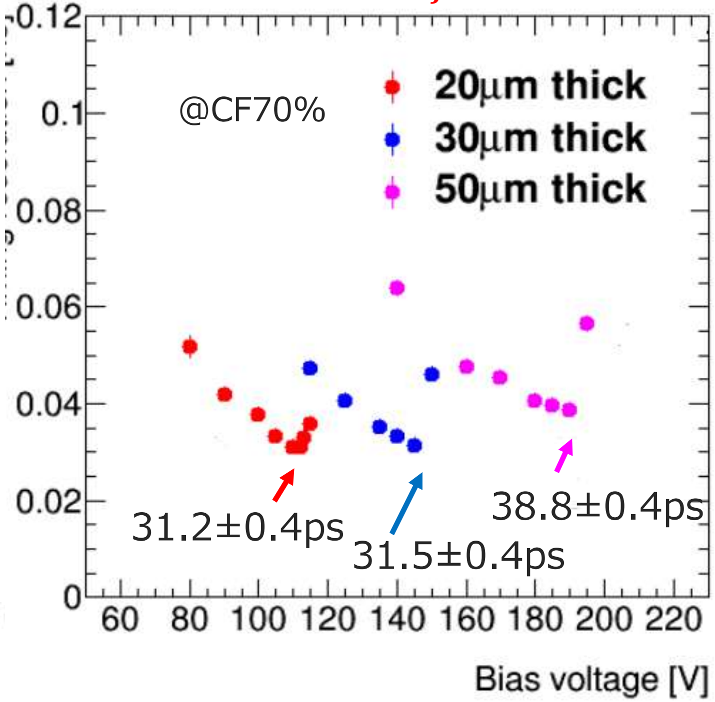
Infra-red laser (E_{dep}~ a few times MIP)

$\boldsymbol{\sigma_t^2} = \sigma_{tw}^2 + \boldsymbol{\sigma_j^2}$



Beta-ray measurement

$\boldsymbol{\sigma_t^2} = \sigma_{tw}^2 + \boldsymbol{\sigma_j^2} + \boldsymbol{\sigma_L^2}$



IR: measure jitter noise at each bias.
→ transfer it to jitter for MIP
→ evaluate Landau contribution

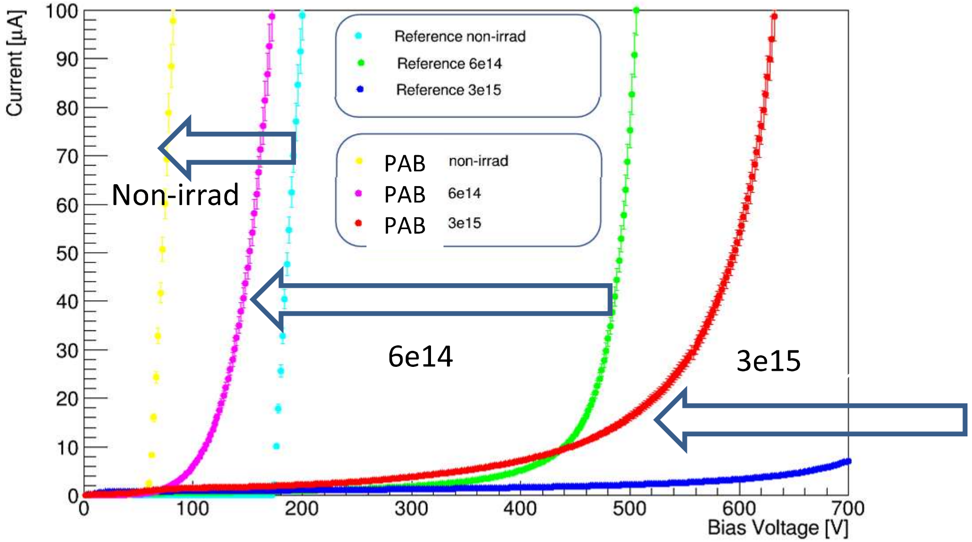
Thick	50um	30um	20um
Time resolution	38.8 ps	31.5 ps	31.2 ps
jitter	9.8 ps	11.8 ps	15.9 ps
Landau noise	**37.5 ps**	**29.2 ps**	**26.8 ps**

- ✓ 20um active thickness is better for smaller Landau noise
- ✓ expect to obtain better results in testbeam: Beta ray scattering?

Rad-hardness: New ideas of improvement

- LGAD p^+ concentration is radiation sensitive :
  - active shallow acceptors are transformed into defect complexes that are no longer acceptor. *e.g. BiOi* is donor
- New ideas
  - Carbon annealing (add *C* to capture *Oi*)
  - **Compensation method**
    - Add Phosphorus to compensate Boron doped in excess
    - doner removal expected to be slowed: turned not effective
    - Injecting carbon in addition may work
  - **Partially activated Boron (PAB)**
    - Non active *Bi* at beginning to clean up *Oi*

    (no further creation of *BiOi*)



PAB : Very promising results
First LGAD sensor surviving up to 3e15 neq/cm^2 at <600V
(non-irrad sample needs to tune properly…)

IJCLab plan/contribution

- Characterisation measurements of LGAD sensors with IR laser
  - Gain measurement
  - Study of charge sharing between channels
  - Front-end electronics should be already coupled to the detector
    - Perspective: possible evolution towards a generic system to measure “stand-alone” detectors

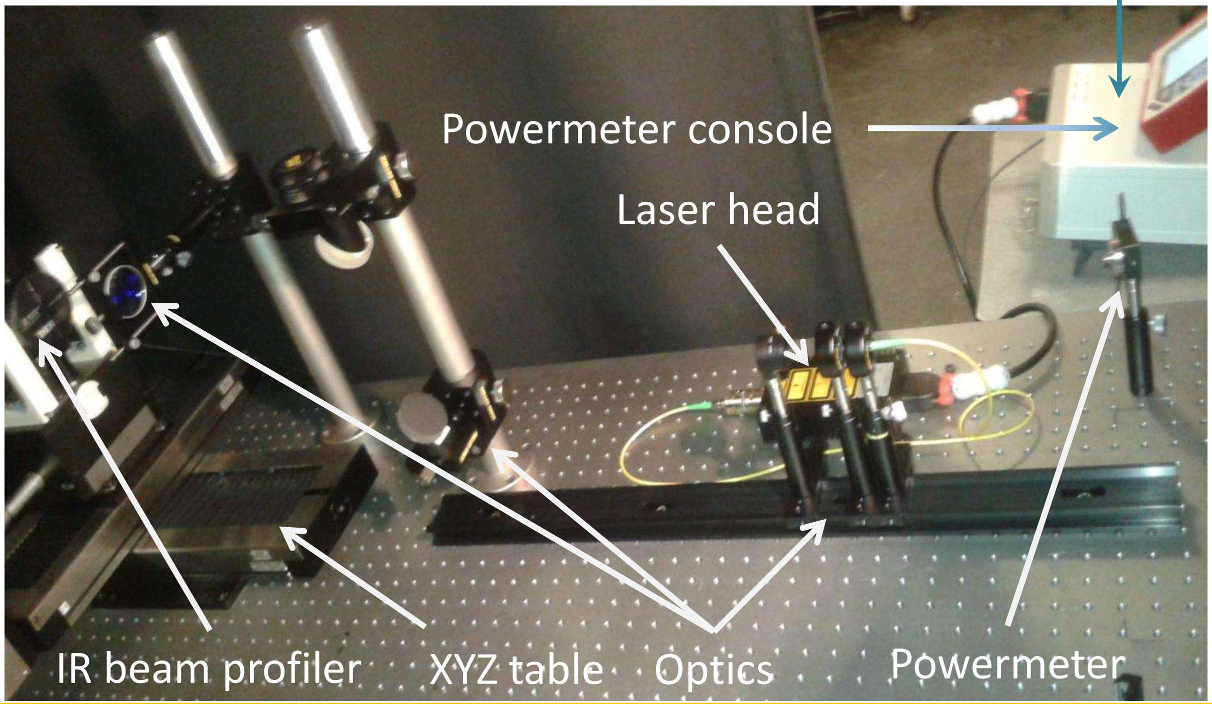
- SIMS measurement of doping profiles
  - Compact SIMS tool (Hiden analytical Ltd.) able to achieve a sensitivity of 10^{17} at/cm^3
    - Perspective: possibility of accessing a system with 10^{14} at/cm^3 sensitivity (U. Versailles) under study

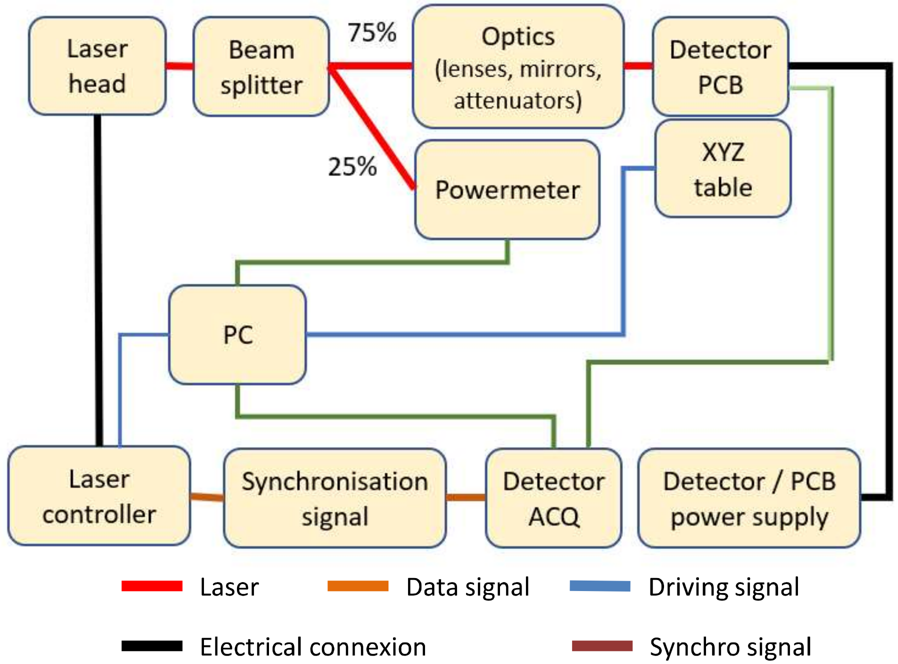
Optical test bench@IJClab (preliminary)

IR laser test bench built to characterise AC-LGAD sensors for EIC

- Picosecond pulsed diode laser
- λ = 1056.4 ± 7.4 nm
- 0 – 40 MHz
- 150 mW peak intensity
- 35 ps pulse width (FWHM)
- 10.8 ps jitter
- Expected spot size ~ 10 µm

Laser controller PILAS





2022 activity: Visit to IJClab

Japanese team visited IJClab

- Discussed SIMS for implant profile analysis
- Discussed LGAD sensor testing setup
- Discussed ATLAS HGTD ALTIROC ASIC status

visited U Geneva group:

- Learned operation of Si-Ge based ASIC (obtained one set for test @ KEK)

R&D list

- Improvement of radiation tolerance (con’t)
  - Tune Partially Activated Boron procedure
  - Apply PAB to AC-LGAD
  - Re-try Compensation with Carbon rich wafer.
- Large area prototype
  - Gain uniformity in larger sensor is to examine
    - Fabricate samples using KEK R&D and EIC prototype masks
    - Flip-chip 20mm x 20mm sensors to ATLAS ITkpix chips
- ASIC development
  - Need high speed ASIC with “not-too-high power consumption”
    - Target: less than 0.5W/cm^2 power consumption
  - Collaborating with OMEGA and Si-Ge ASIC (Uni. Geneva)
  - ATLAS/CMS/EIC will produce their own ASICs for the colliders

- Will build modules suitable for future collider experiments

Large area prototype

EIC prototype
3cm length
500um pitch strip

R&D prototype
2cm x 2cm
100um pitch pixel

ASIC

Applications to Collider Experiments

Funding Request

Funding Request from France				
Description	€/unit	nb of units	total (€)	requested to
Visit to Japan	150/day	20 days	3000	IN2P3
Travel	1000	2 travels	2000	IN2P3
Total			**5000**	

Funding Request from Japan				
Description	k¥/Unit	nb of units	total (k¥)	requested to[3]
Visit to France	45/day	5 days	225	KEK
			150	KEK
Travel	150/travel	2 travels	300	KEK
Total			**675**	

Additional Funding from France		
provided by/requested to[4]	Type	€
IN2P3 pixel core funds		30000

Additional Funding from Japan		
provided by/requested to[4]	Type	k¥
JSPS	travel	2000
JSPS	Equipment	2000