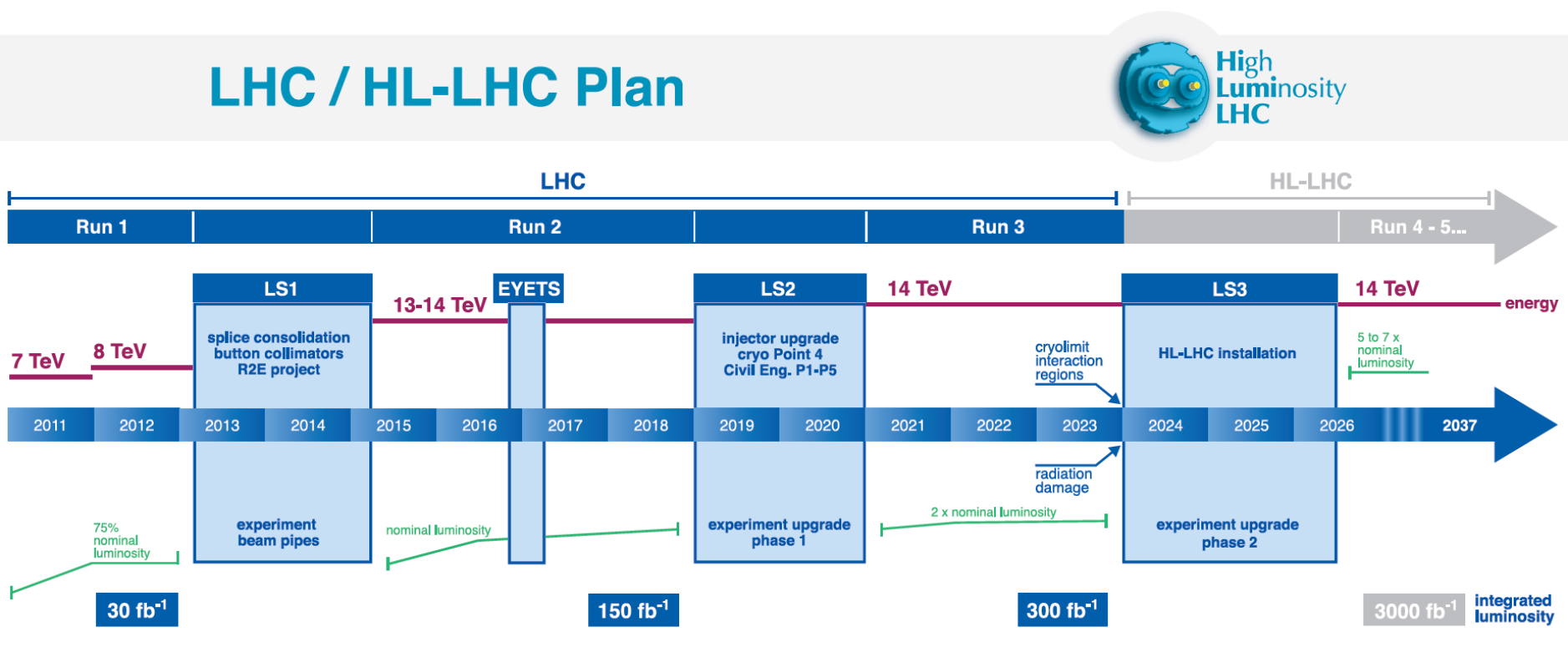
Qualification measurements of INFN-FBK 3D modules

G Alimonti[1], M Boscardin[2], **A Coccaro**[3], G F Dalla Betta[4], G Darbo[3], E Fumagalli[3], G Gariano[5], A Gaudiello[5], C Gemme[3], M Meschini[6], A Messineo[6], R Mendicino[4], H Oide[3], S Ronchin[1], A Rovani[3], E Ruscino[3], D M S Sultan[4], D Vazquez Furelos[7], N Zorzi[2]

[1]INFN Milano, [2]FBK/TIPFA, [3]INFN Genova, [4]University of Trento and TIPFA Trento, [5] University and INFN Genova, [6] University and INFN Pisa, [7] IFAE Barcelona

13th "Trento" Workshop on Advanced Silicon Radiation Detectors

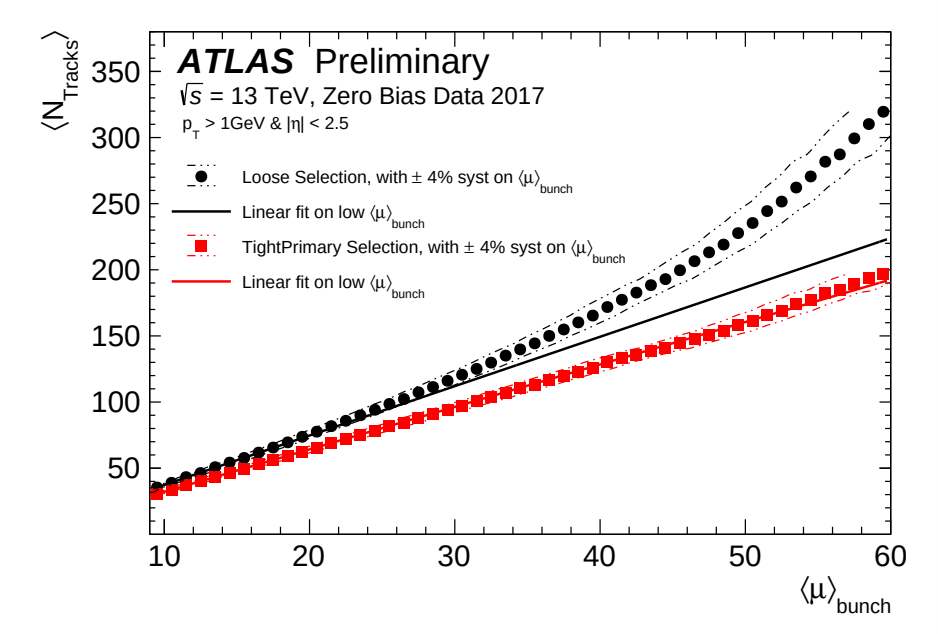


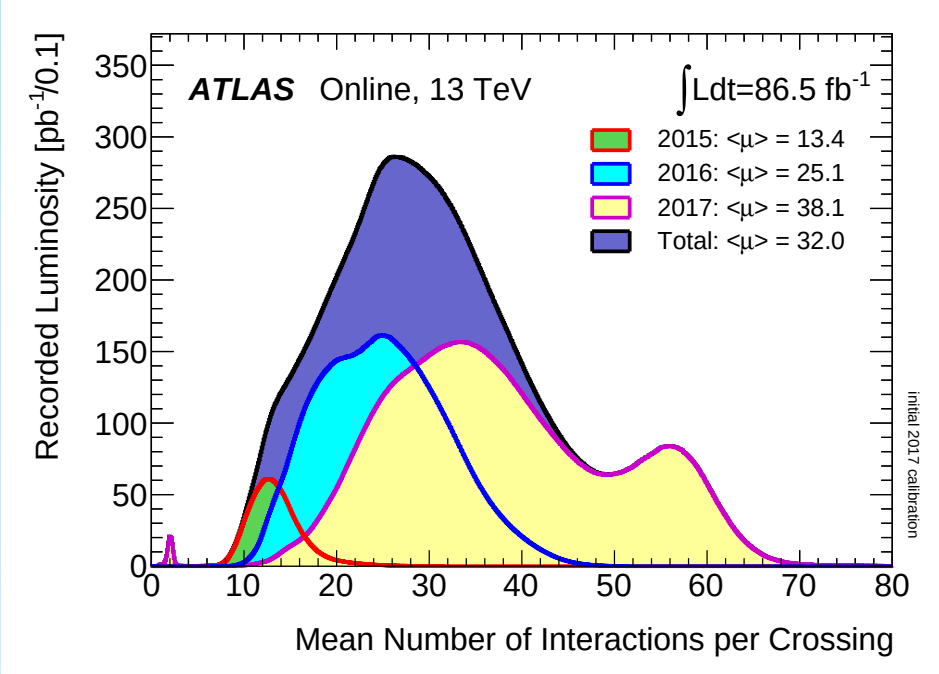
- peak instantaneous luminosity $7.5 \cdot 10^{34}$ cm^{-2} s^{-1}
- x40 integrated luminosity as of today
- ATLAS ITk pixel project to cope with the HL-LHC conditions, i.e. 14 TeV pp collisions at $\langle \mu \rangle \sim 200$ and $2 \cdot 10^{16}$ MeV n_{eq}/cm^2
- must be ready for installation in 2025

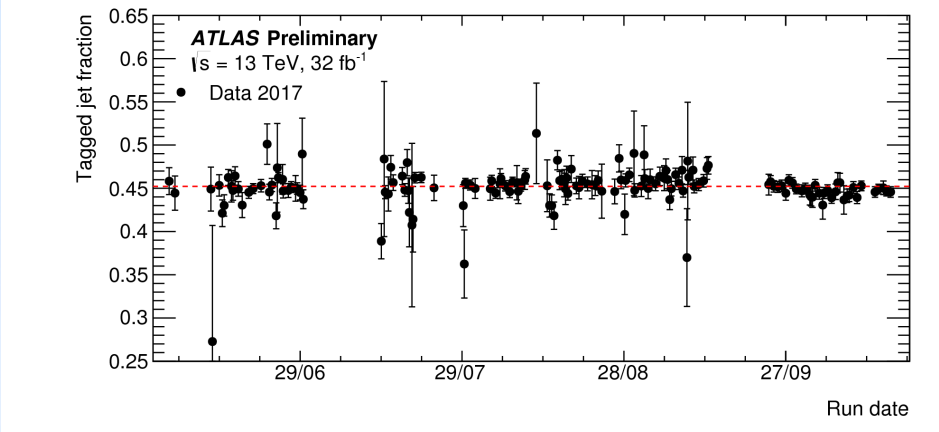
Pile-up

A costant challenge

- current pixel detector has been proven to work very reliably
- "pile-up is the word of the year" K. Jacobs in Dec 2017







3D pixel sensors

‘

Brief history

- originally proposed in NIM 395 (1997) 328-343
- the ATLAS IBL is the first implementation in a hadron collider

Main concept

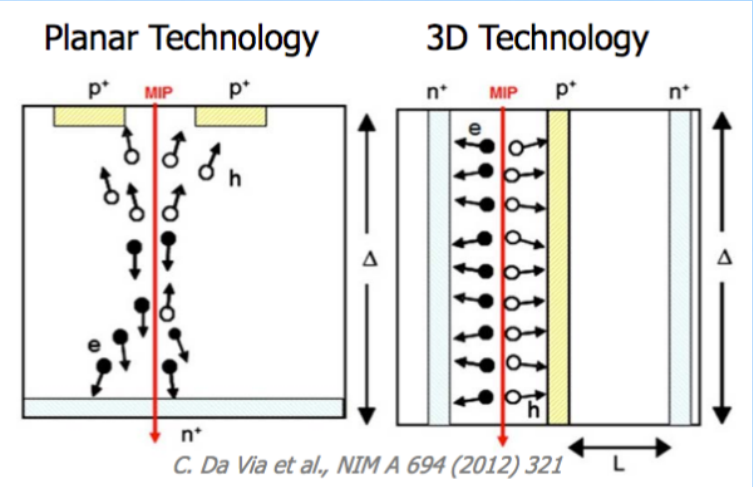
- 3D array of electrodes
- minor collection distances and times compared to planar technology

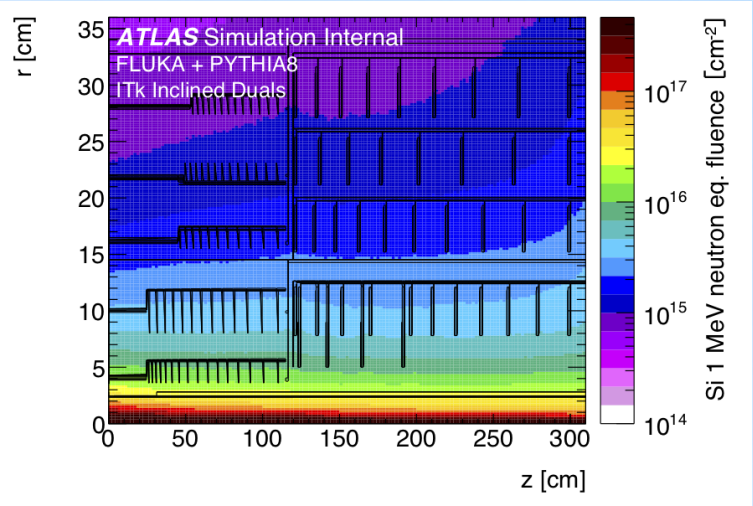
Baseline technology for the ITk innermost layers

- power dissipation and radiation hardness

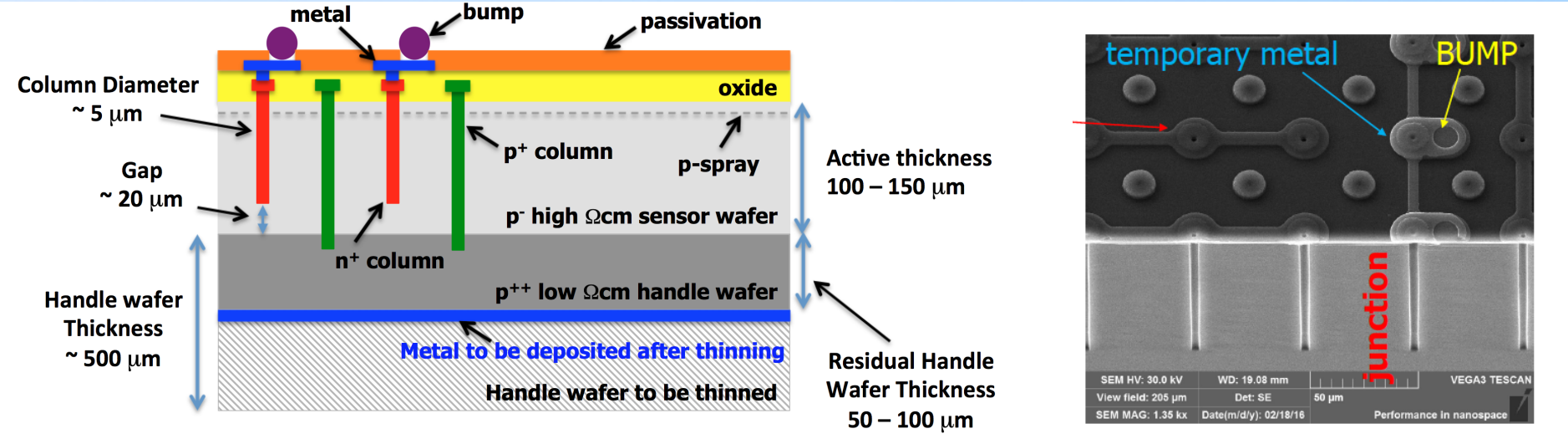
Where we stand?

- ATLAS ITk pixel TDR sent to LHCC
- sizes of 50×50 or 25×100 μm^2 being considered
- final geometry and area tickness not fully decided
- optimal electrode configuration for 25×100 being further studied



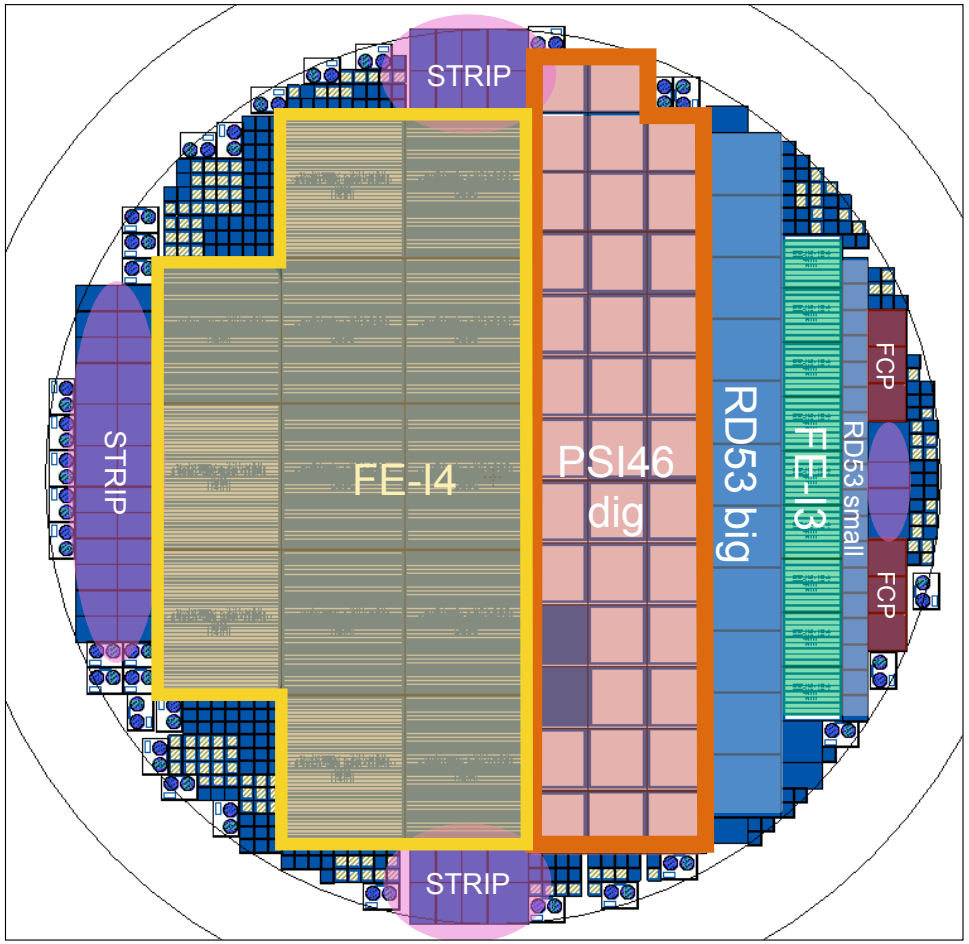


FBK 3D pixel sensors prototype concept



- in partnership with FBK in Trento
- target fluence $\Phi \sim 2 \cdot 10^{16}$ MeV n_{eq}/cm^2
- 100 to 150 μm active sensor tickness with single-sided column processing
- column of $\sim 5\mu$m diameter with and without poly-caps options for p^+ columns
- n^+ columns shorter than active tickness by $\sim 20\mu$m to avoid early breakdown
- p^+ columns longer than active tickness and touching the p^{++} handle wafer for biasing

First batch wafer layout - produced in 2015-16



- FE-I4
  - 50x250 (2E) — std.
  - 50x50(1E)
  - 25x100(1E and 2E)
  - 25x500 (1E)

  } 13 sensors in total → ATLAS R&D
- FE-I3
  - 50x50 (1E)
  - 25x100 (1E and 2E)
- PSI46dig 38 sensors in total → CMS R&D
  - 100x150 (2E and 3E) — std.
  - 50x50 (1Eand2E)
  - 50x100, 100x100 (2E and 4E)
  - 50x100, 100x150 (2E and 6E)
  - 25x100(1E and 2E)
- FCP
  - 30x100 (1E)
- RD53
  - 50x50(1E)
  - 25x100 (1E)
  - 25x100 (2E)
- Other test structures

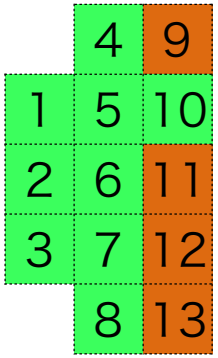
10 wafers of 130µm-thicknes with optional variations produced in 2015-2016*.

* one of them got broken at the very last step, but still could be measured.

ATLAS R&D with FBK modules

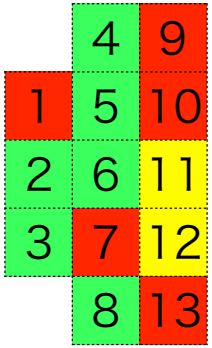
Wafer ID 76

9/13 modules assembled



Wafer ID 78

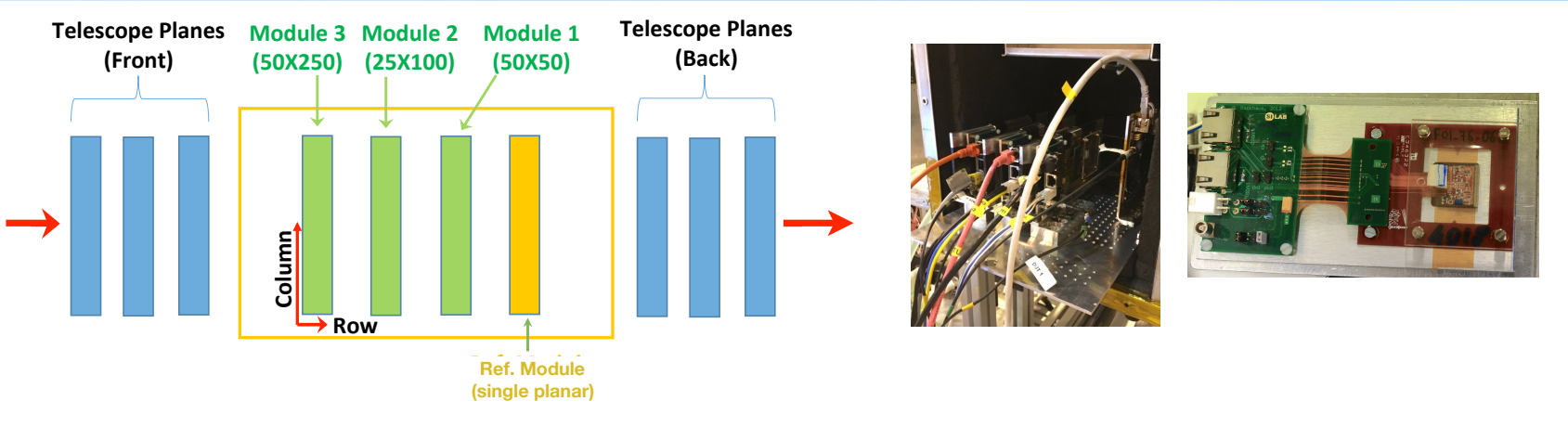
8/13 modules assembled



Wafer	FEI4	Geometry	2016 TB	irrad	Fluence	2017 TB
76	1	25x100(1E)		KIT+IRRAD	5.2e15 + 4e15	July
	2	25x500				
	3	50x250				
	4	50x450/ 50x50				
	5	50x50				
	6	50x50	✓	KIT+IRRAD	5.2e15 + 6.6e15	July, October(2)
	7	25x100(1E)	✓	IRRAD	9e15 (max)	N/A
	8	50x250	✓			
	10	50x50				
78	2	25x500				
	3	50x250		IRRAD	9e15 (max)	July
	4	50x450/ 50x50				
	5	50x50		IRRAD	9e15 (max)	July
	6	50x50				
	8	50x250		KIT+IRRAD	3.8e15 + 4e15	October(1)
	11	50x50				
	12	25x100(2E)				

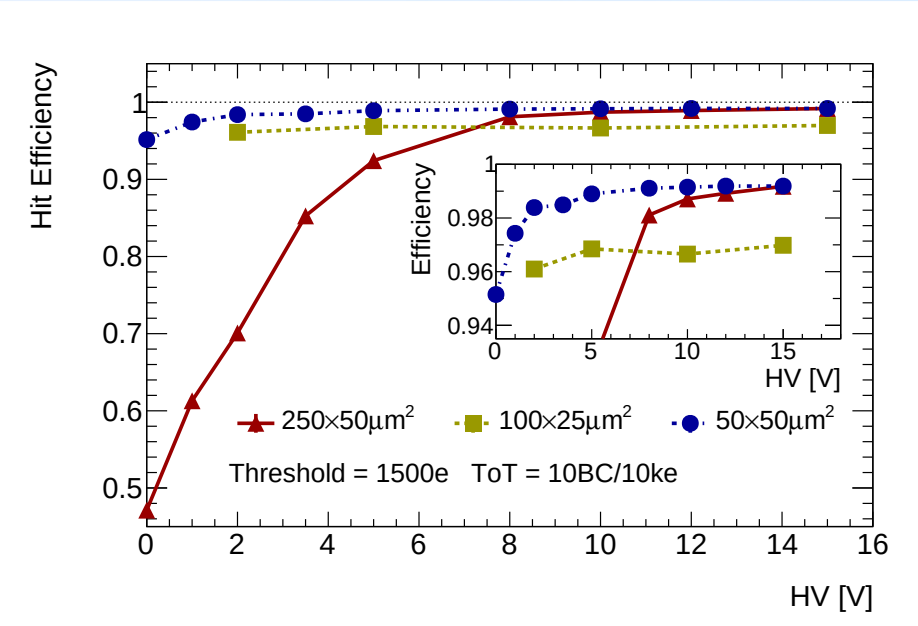
- 17 sensors out of 2 wafers were assembled as single FE-I4 modules
- 3 modules in 2016 TB unirradiated - H Oide talk at 12th Trento WS
- 6 modules, all pixel sizes, irradiated at KIT and IRRAD in 2017
- 5 irradiated modules in 2017 TB

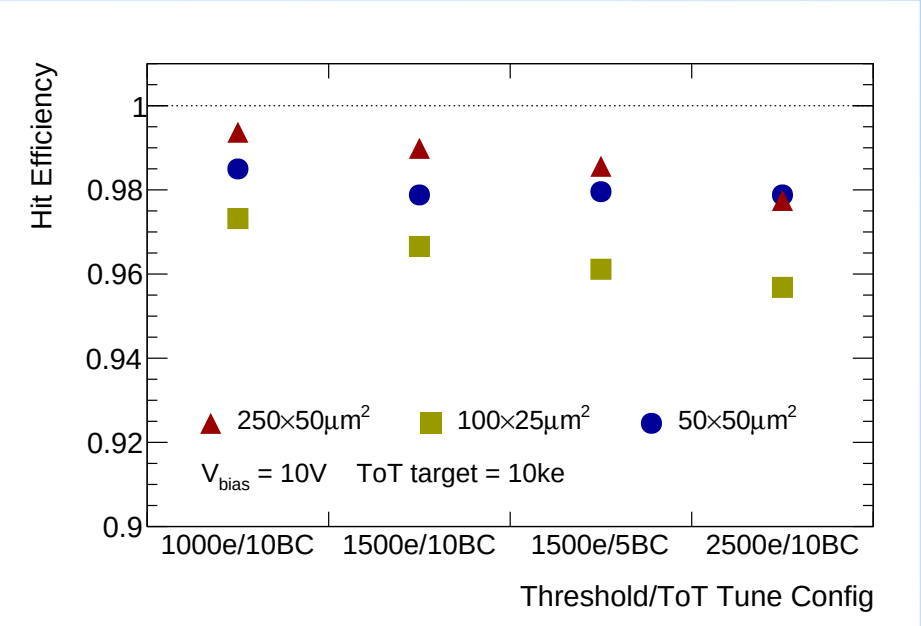
Test beam setup



- SPS H6A beam line with mainly 120 GeV pions
- Aconite telescope with Mimosa26
- 1 IBL-like FE-I4 as a reference module and then DUT
- various non-irradiated and irradiated data-taking campaigns with FBK FE-I4 sensors
- Eudaq software for data-taking and decoding
- FrecciaFocaccia light-weight package by H Oide

Results for non-irradiated samples





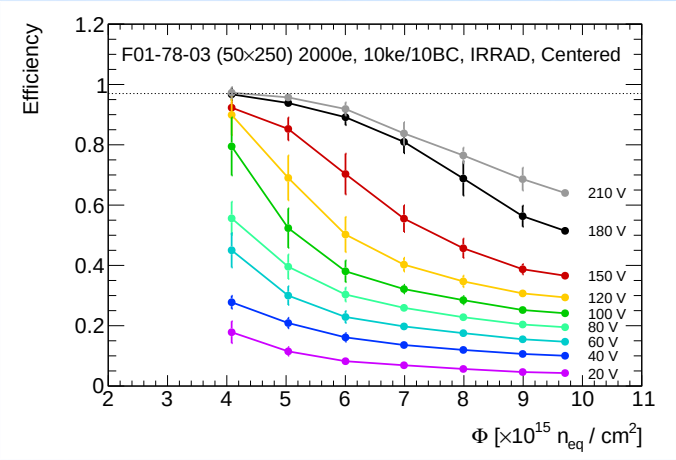
HV scan

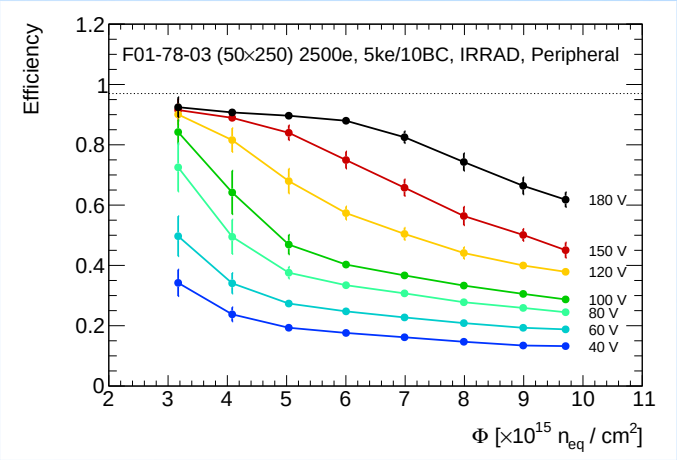
- $250 \times 50\ \mu m^2$: efficiency is $> 99\%$ above $\sim 10V$
- $50 \times 50\ \mu m^2$: almost flat efficiency at 98% in $2 < HV < 15$ then slight increase
- $100 \times 25\ \mu m^2$: similar trend of $50 \times 50\ \mu m^2$

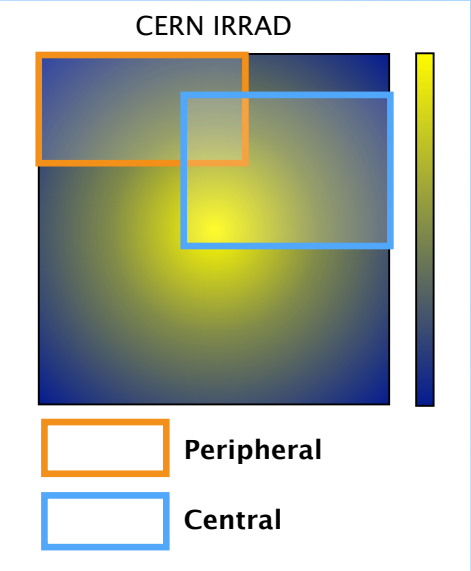
Tuning scan

- a gradual change of efficiency of $1 - 2\%$ versus tuning

Results for irradiated $50 \times 250\ \mu m^2$ samples

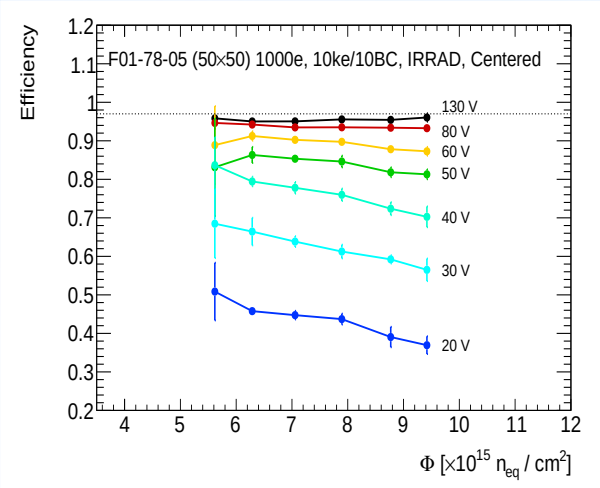


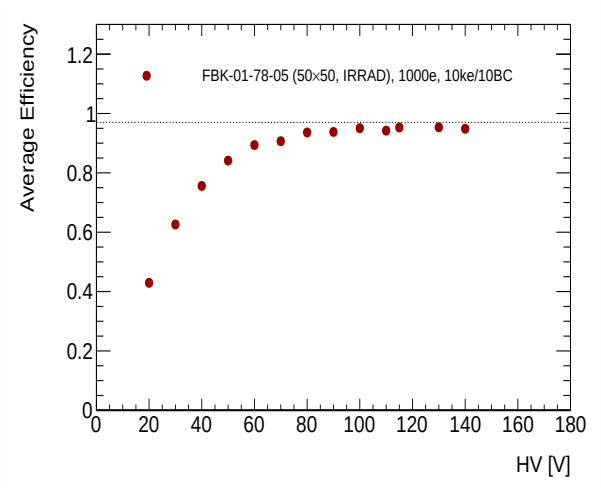


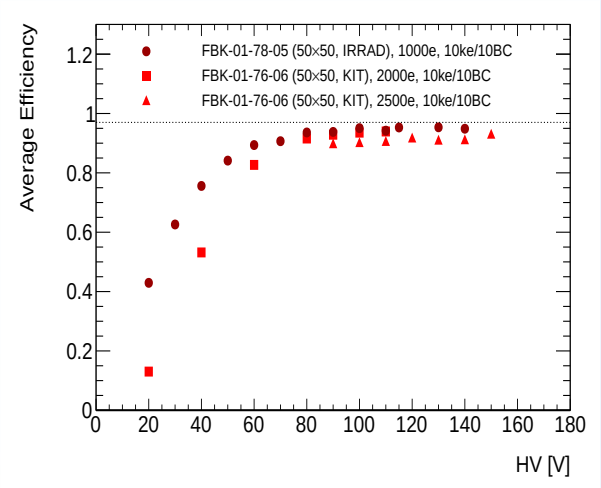


- improvement of efficiency versus HV
- degradation of efficiency versus fluence
- uncertainty due to fluence measurement misalignment
- threshold effect inducing a higher efficiency for 2000e compared to 2500e
- $> 95\%$ efficiency for $\Phi < 5 \cdot 10^{15}$ MeV n_{eq}/cm^2

Results for irradiated $50 \times 50\ \mu m^2$ samples







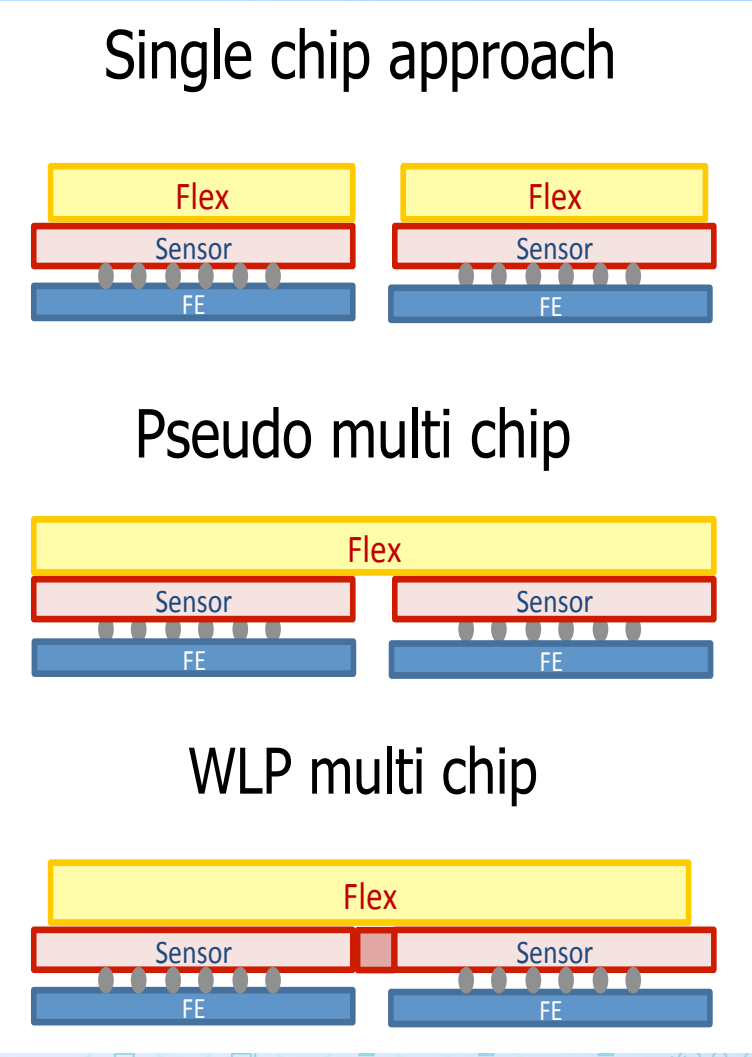
- for $50 \times 50\ \mu m^2$ the calculation of the efficiency takes into account the region with no readout
- efficiency at $\sim 95\%$ for HV $>\sim$ 80V up to $1 \cdot 10^{16}$ MeV n_{eq}/cm^2
- KIT versus IRRAD comparison is actually with different thresholds
- threshold at 2k e^- when modules on flex and at 1k e^- when modules on board

Multiple-chip 3D modules

Pixel tracker layout foresees single, duals and quads modules

- multiple-chip layout has the potential to greatly simplify the production and loading
- two approaches, pseudo and WLP, being investigated

Layer0/Ring0	*flat*	*inclined*	*ring*	***Total***
n-chip type	2	1	4	
Modules	**192**	**512**	**128**	**832**
Fes	384	512	512	1408
Surface [cm2]	1536	2048	2048	5632
Layer1/Ring1	*flat*	*inclined*	*ring*	***Total***
n-chip type	4	4	4	
Modules	**240**	**520**	**484**	**1244**
Fes	960	2080	1936	4976
Surface [cm2]	3840	8320	7744	19904

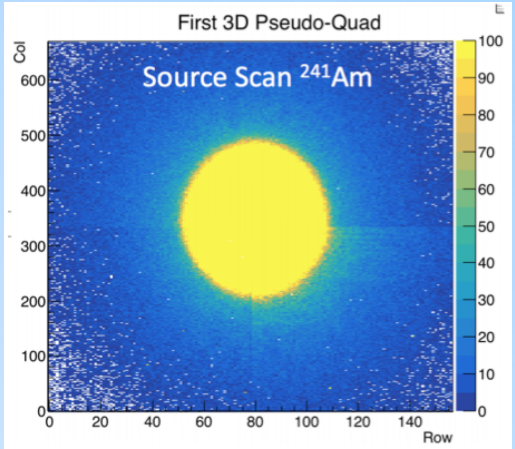


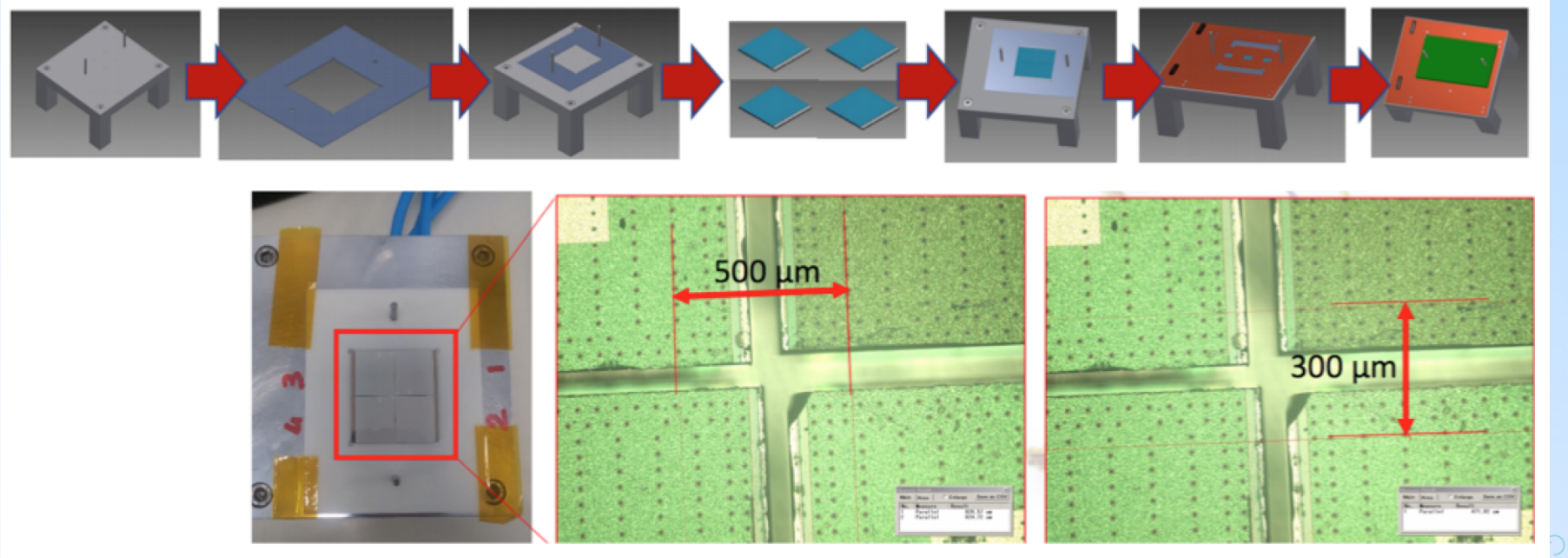
Multiple-chip 3D modules

The first pseudo quad-module has been built using single 3D tiles

- similar assembly procedure as IBL module production
- CNM sensors from AFP ATLAS detector

  Thanks to S Grinstein (Barcelona)
- interspace between most external pixels $\mathcal{O}(100 - 500)$ μm





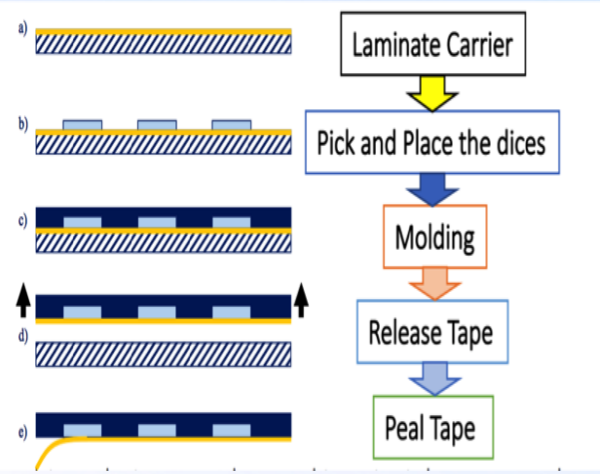
Wafer Level Packaging

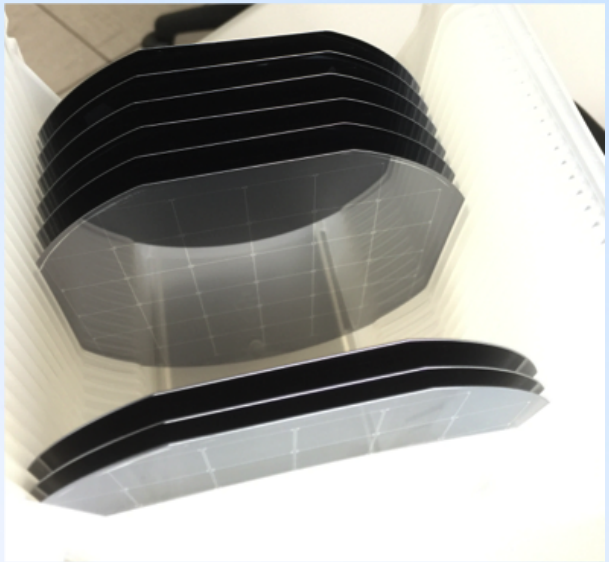
An industrial solution is being developed for wafer level packaging (WLP)

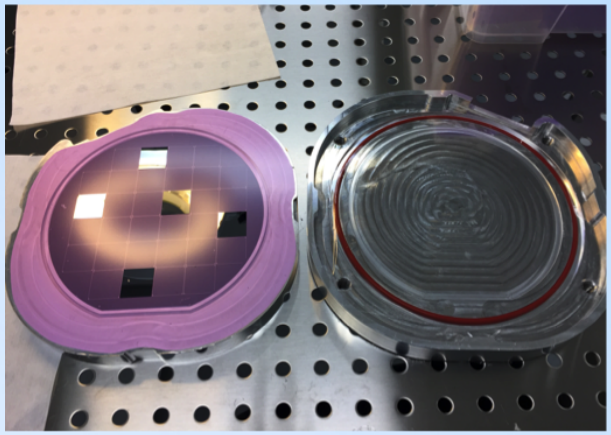
- rebuild new wafers using only good sensors diced from the standard production
- minimise the chip interspace as much as possible, i.e. $\mathcal{O}(50 - 100)$ μm

Ongoing R&D program in MicroFabSolutions

- 300 μm thick wafers with 20×20 mm^2 chips with dummy chains
- now testing chip placing accuracy and deformation of six rebuilt wafers using different resins







Courtesy of P Conci (MicroFabSolutions)

Conclusions

Characterisation of FBK phase-II 3D sensors is in full swing

2015-16 wafers

- extensive non-irradiated and irradiated tests with the FE-I4 readout
- different fluences with irradiation at KIT and/or IRRAD tested
- results inserted in the pixel ITk TDR under LHCC review
- results with irradiated modules based on TBs on July and September 2017

Multiple-chip 3D module

- first pseudo quad-module with CNM sensors
- ongoing R&D program for WLP