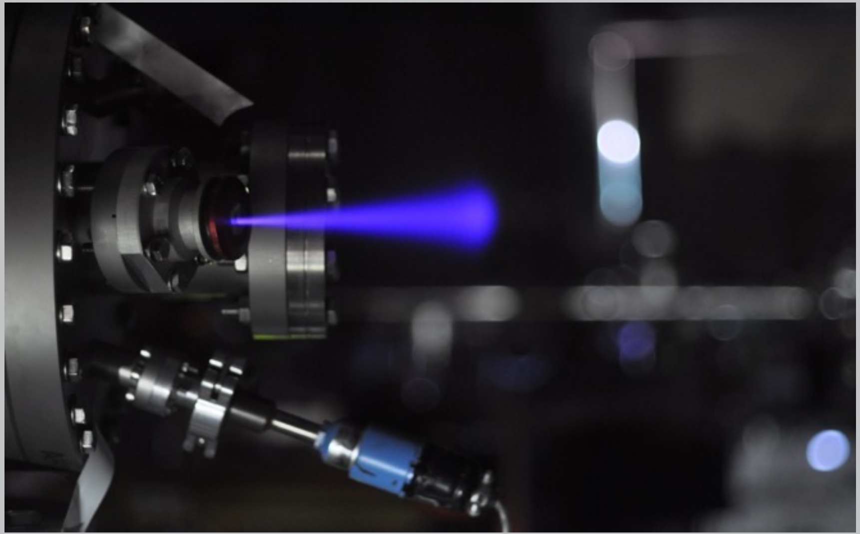
Ion microbeam studies of charge transport in semiconductor radiation detectors with three-dimensional structure



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Mauricio Rodriguez Ramos,
Georgios Provatas, Milan Vićentijević

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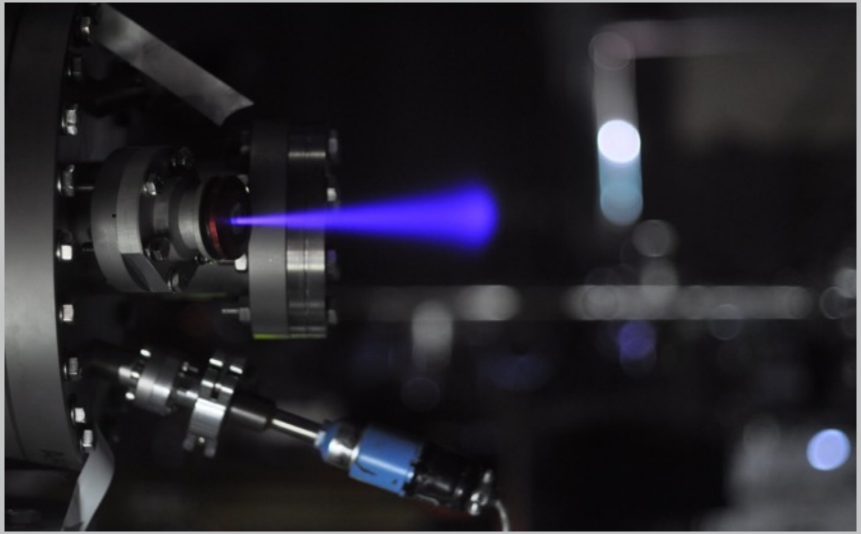
Division of experimental physics
Ruđer Bošković Institute,
Zagreb, Croatia

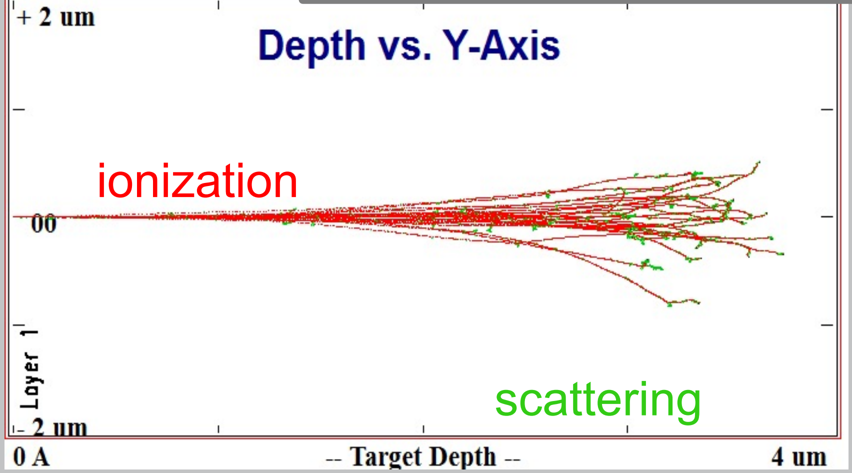
With contributions of: Gregor Kramberger (IJS, Slovenia); Natko Skukan (IAEA), Gordana Medin (Uni. Montenegro); Alex Oh (Uni Manchester); Claudio Verona (Uni Roma 2); Gennaro Conte (Uni Roma 3)

VCI
VIENNA CONFERENCE ON INSTRUMENTATION

Why (MeV) ion beams?

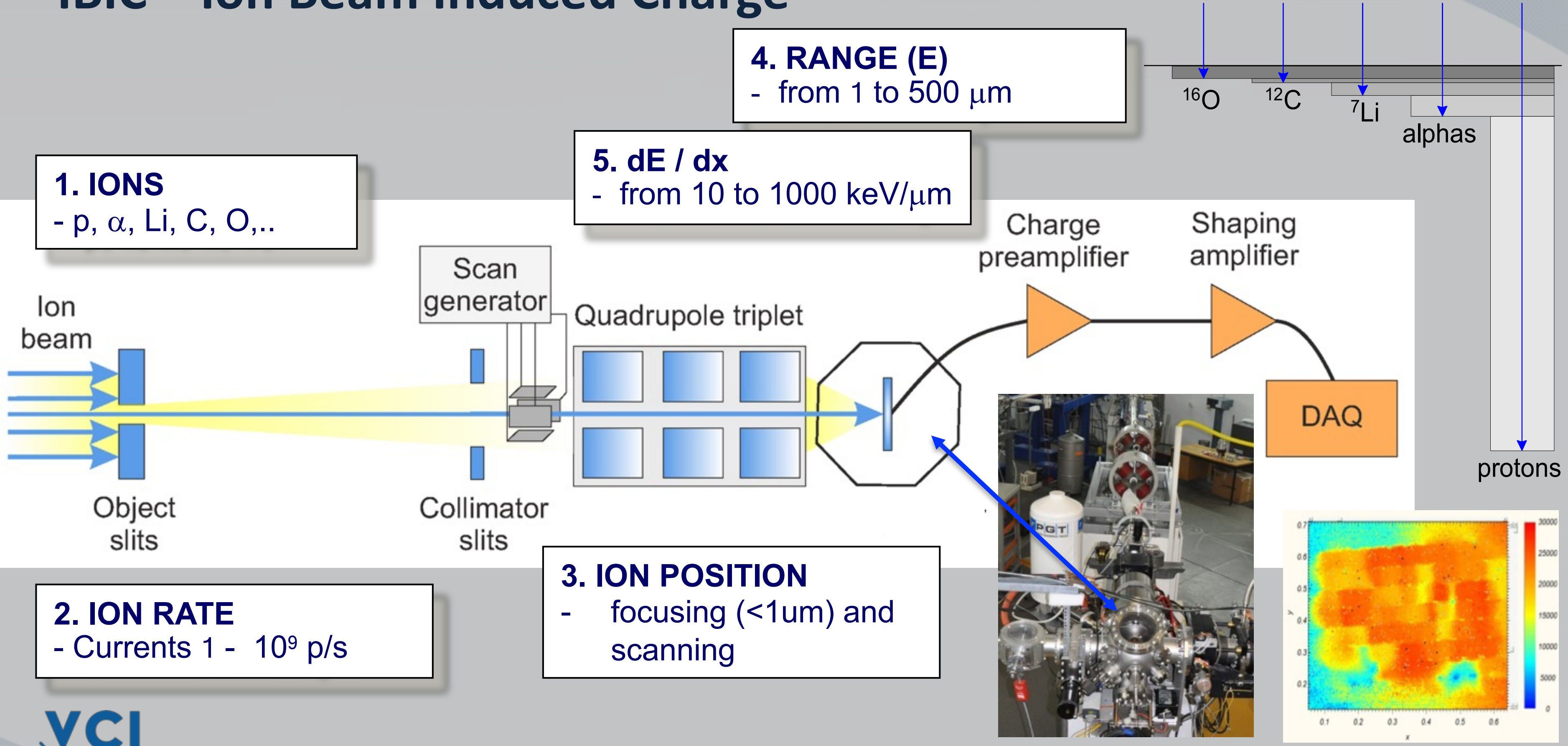
- Small electrostatic accelerators
- Straight trajectory
- Induce charges & damage
- Microprobe focussing to 1 µm





Ion microprobe – ideal radiation source for detector testing!

IBIC – Ion Beam Induced Charge



1. IONS
- p, α, Li, C, O,..

2. ION RATE
- Currents 1 - 10^9 p/s

3. ION POSITION
- focusing (<1um) and scanning

4. RANGE (E)
- from 1 to 500 μm

5. dE / dx
- from 10 to 1000 keV/μm

Outline:

Motivation

LGAD detectors

- Surface layers
- Interpad distance
- Gain suppression

Diamond detectors

- 3D diamond
- ΔE/E detector

IBIC @ high temperatures

- Spectroscopic quality at 450 C
- QTS determination of trap levels

Conclusions

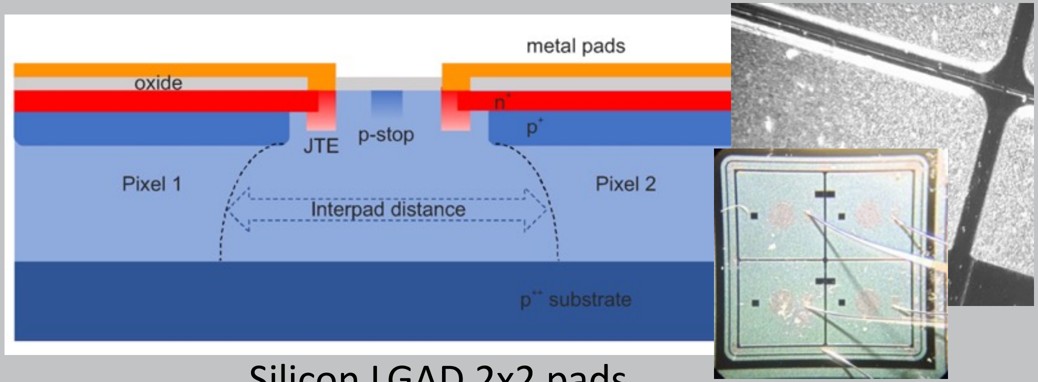
Transnational access

Motivation:

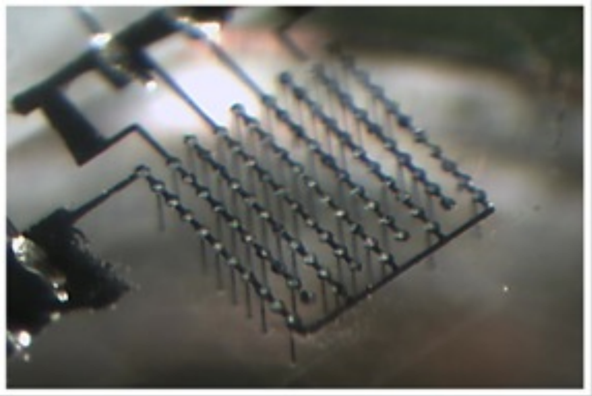
- Development of radiation hard pixelated detectors → new strategies (short collection distances and/or charge multiplication) → complex detector structures - e.g. for 4D tracking, with 3 dimensional distribution of charge transport - monolithic structures
- LGAD & diamond – excellent timing properties !

→ needs to characterise such structures on a microscopic scale & 3D

- **IBIC** is alternative to TCT and TPA-TCT, etc.
  - Transparent for contacts
  - Can induce damage

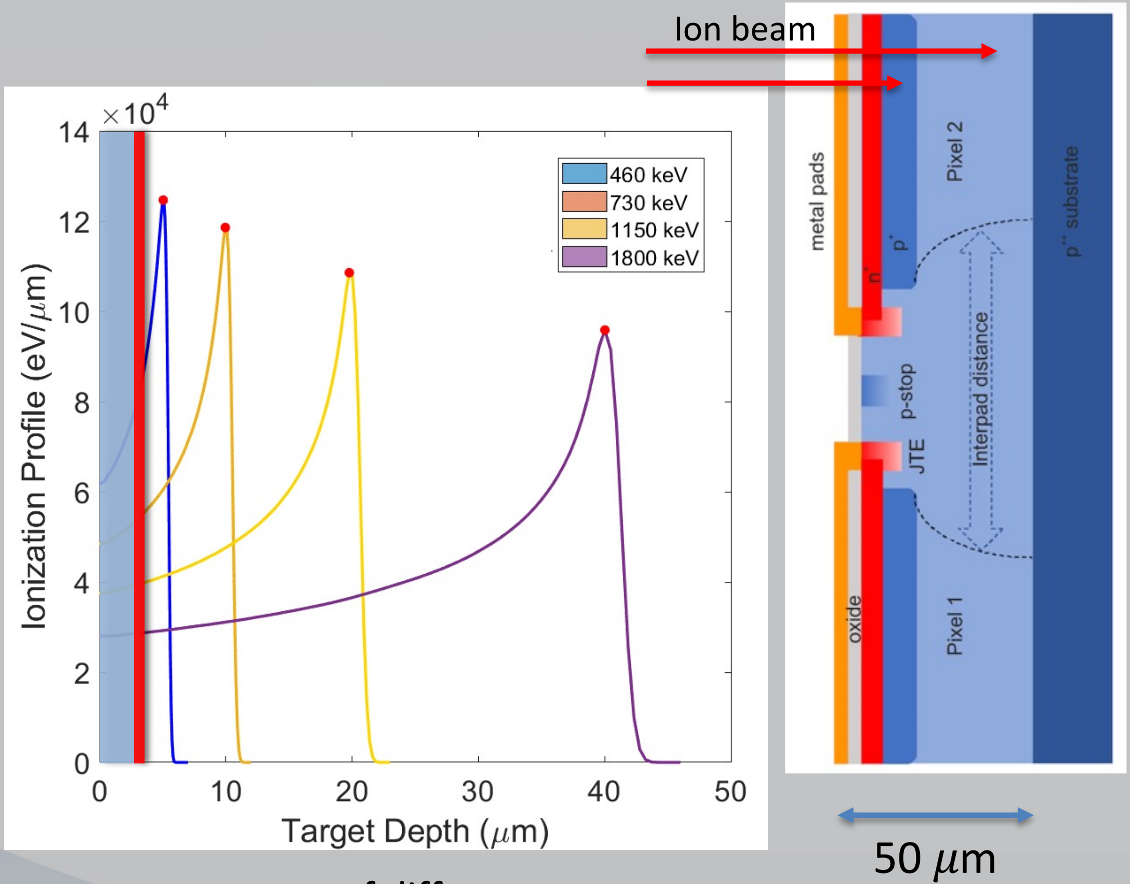


Silicon LGAD 2x2 pads



Diamond 3D detectors

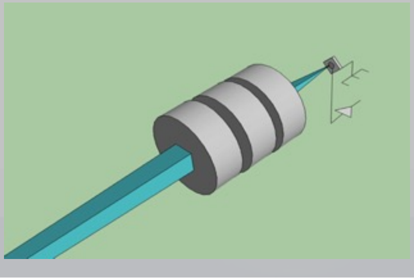
IBIC depth profiling – LGAD detectors



protons of different ranges

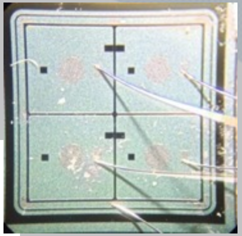
a) Different ion ranges → IBIC probes different detector depths
  - Low penetration – surface layers
  - Deep penetration – interpad distance

b) How to avoid time consuming refocussing (needed for different energies)
  - Same rigidity ions
  - Collimated beam
  - Quadrupole magnetic field recalculation



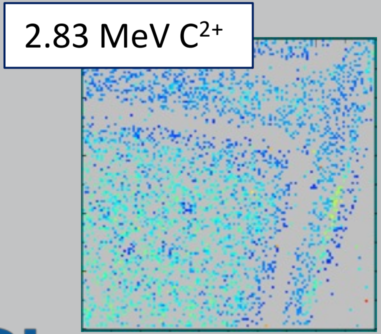
Surface layers' thicknesses (in LGAD)

The use of ions of the same magnetic rigidity



One of solutions for depth profiling is the use of ions of same magnetic rigidity!
e.g.: $ME/Q^2 = 1.41$ MeV

- 1.41 MeV protons
  - range 27.5 μm
- 1.81 MeV $^7Li^{3+}$
  - range 4.32 μm
- 2.83 MeV $^{12}C^{2+}$
  - range 3.15 μm



Lost charges in contacts and inactive surface layers !!

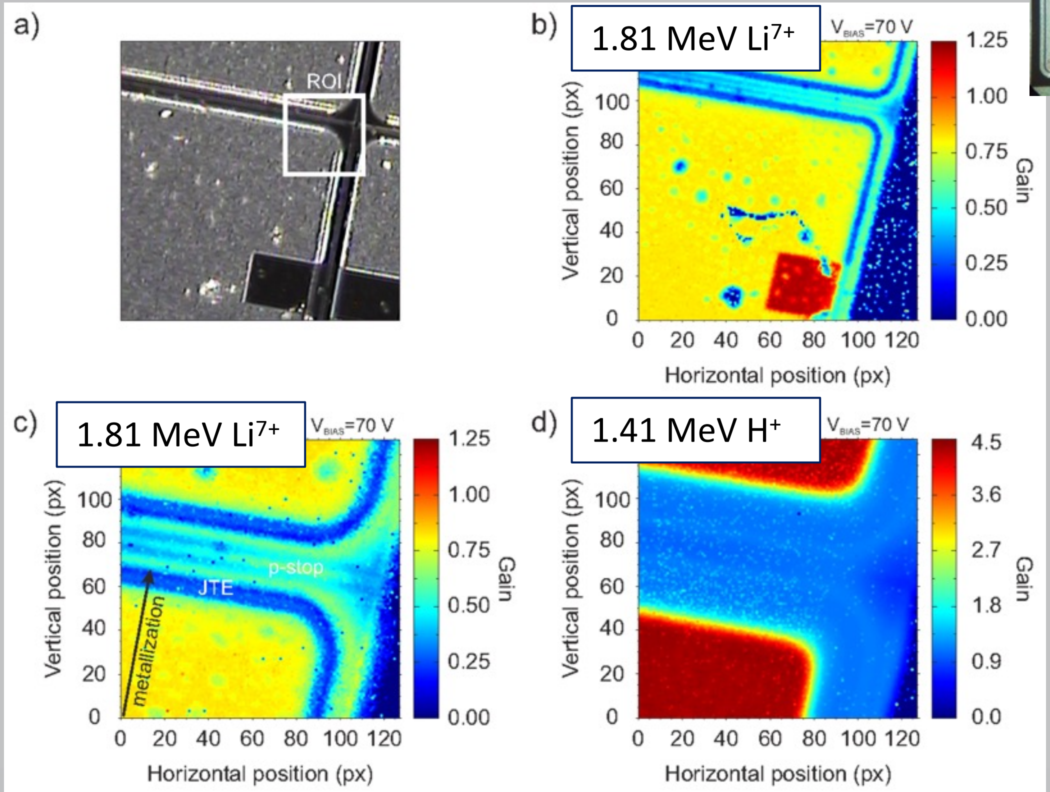
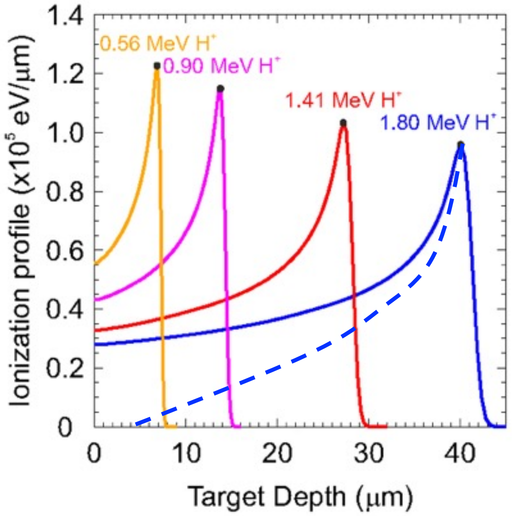


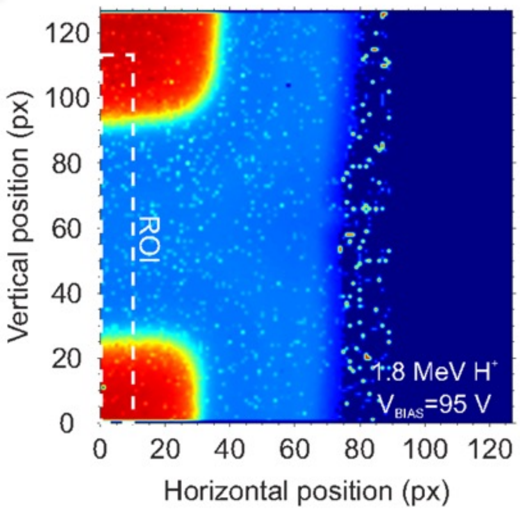
image of surface layers

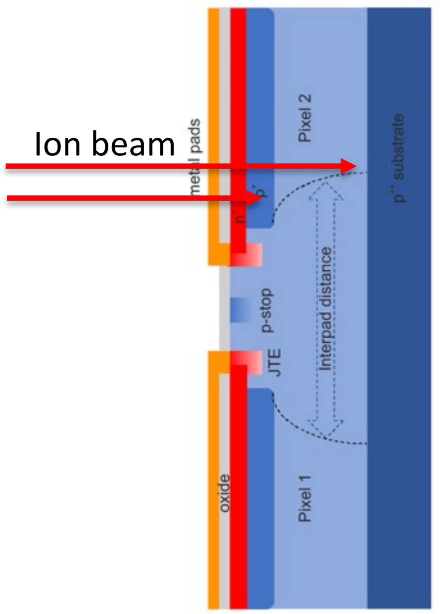
image of multiplication areas

Interpad distance vs. ion range

Refocusing done by recalculation of magnetic field (in focussing quadrupoles)







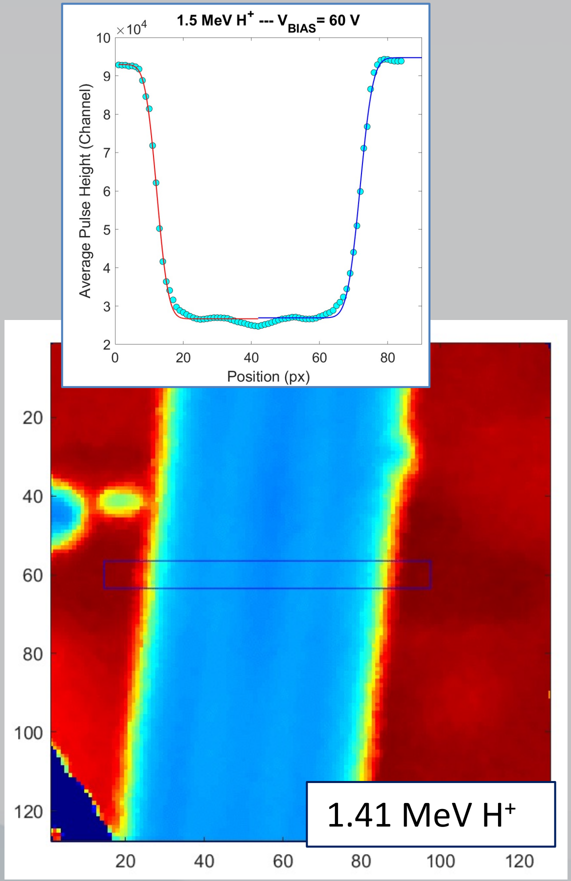
Ion	Energy (MeV)	Range in Si (μm)	Bragg peak max. (μm)
H	1.80	42.8	40
H	1.41	29.1	27
H	0.9	14.9	14
H	0.56	7.7	7

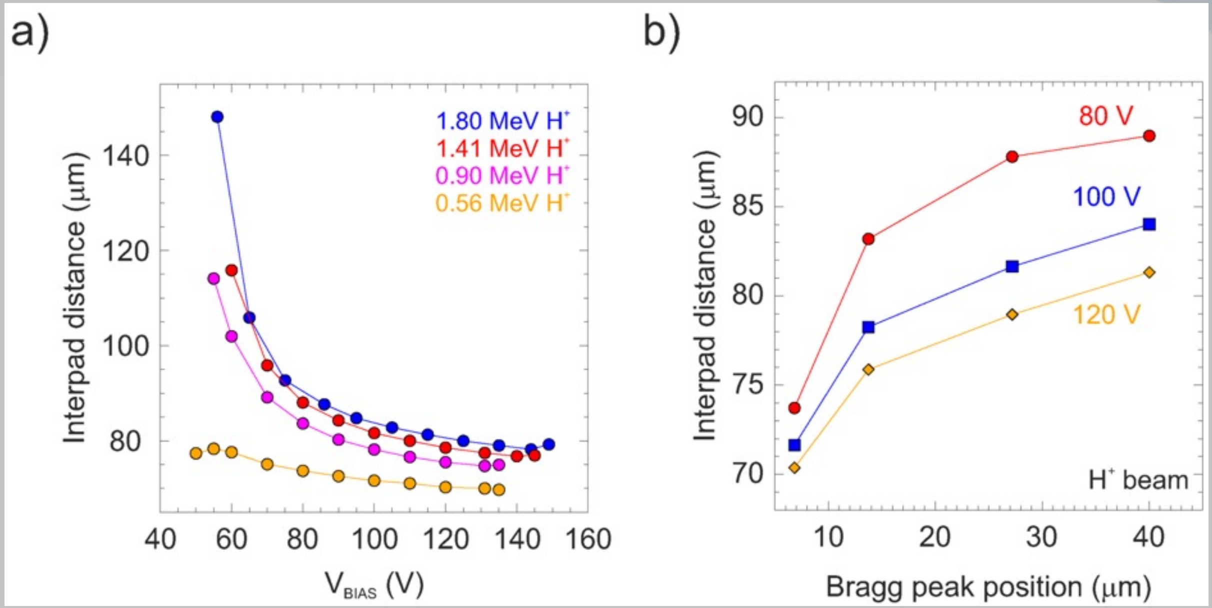
Which is the representative depth?

In LGAD – gain signal is created by electrons
→ charges created within the Bragg peak dominate !

Interpad distance vs. ion range

Results for different voltages and ranges

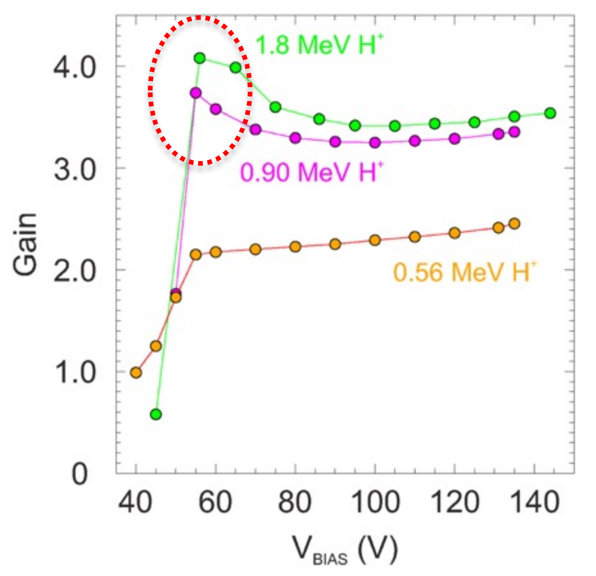


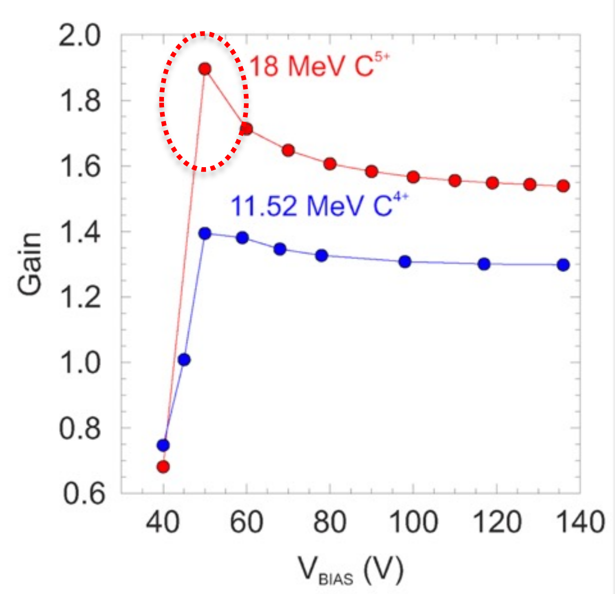


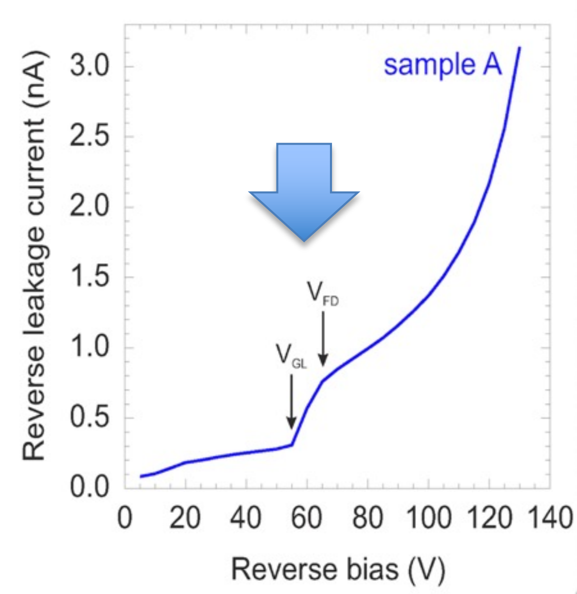
- For the nominal interpad distance of 70 μm (HPK W28 2x2 IP5-SE3), at high bias voltages the interpad distance is measured 80 μm, which decreases the fill factor by few percent
- Precision of ∽ 1 μm can be obtained

Gain-to-voltage dependences with depth

Signs of gain suppression !



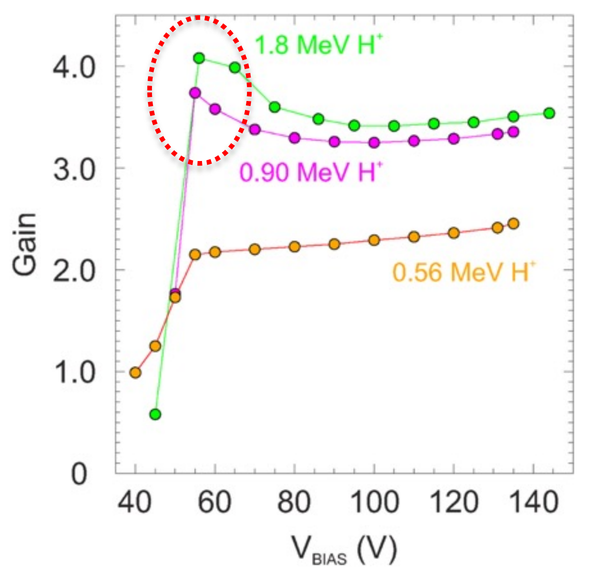


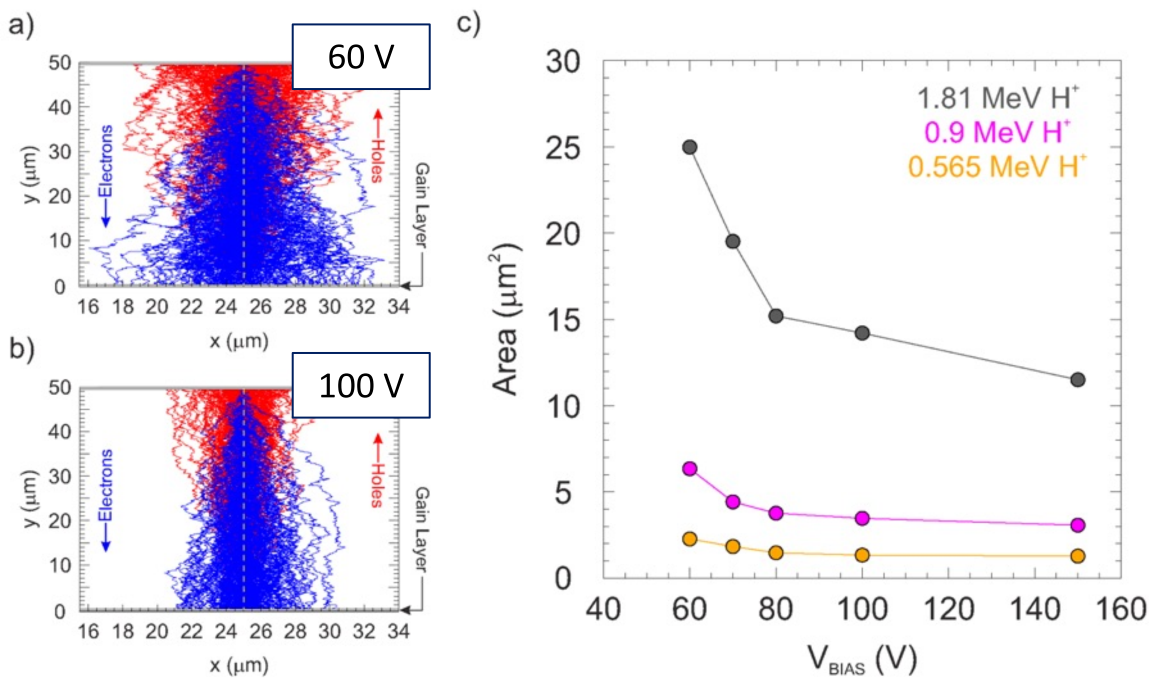


- In the conditions of low electric field & for deep probing ions – gain is higher ?

Gain-to-voltage dependences with depth

Signs of gain suppression !



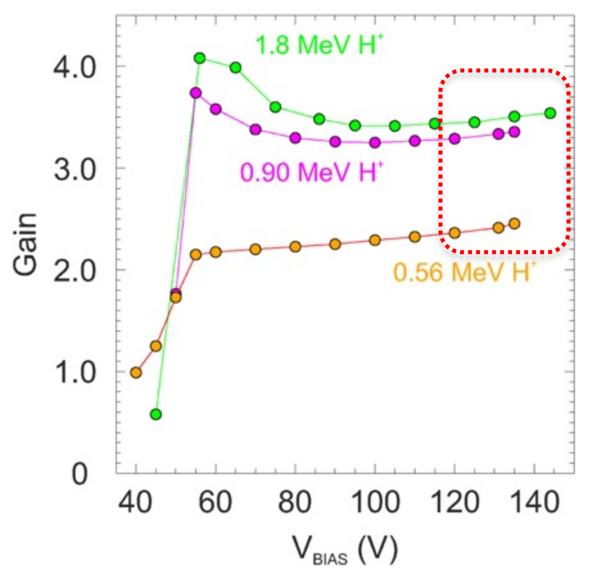


- In the conditions of low electric field & for deep probing ions – gain is higher ?
- Diffusion of charge carriers becomes important !!
- Charge cloud is extending
- Electric field screening is reduced
- Gain increases !

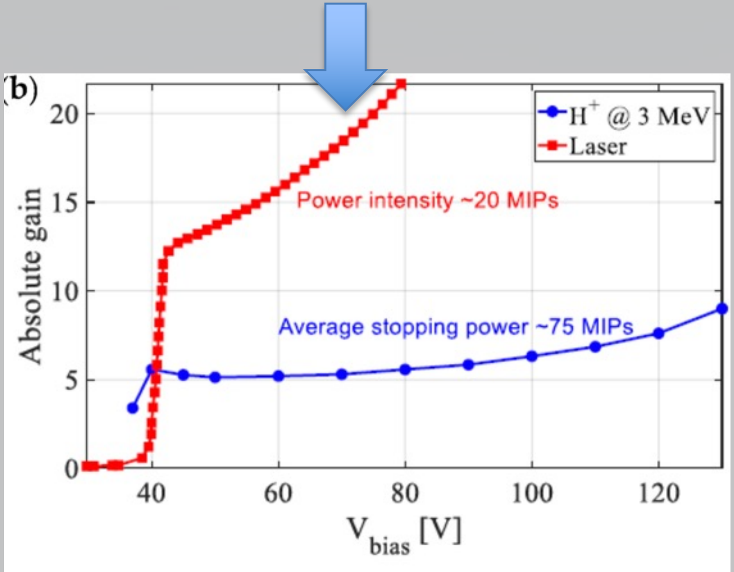
Kramberger, G. "KDetSim—a simple way to simulate detectors." (2016).

Gain-to-voltage dependences with depth

Signs of gain suppression !



At high voltages there is no characteristic increase of gain!

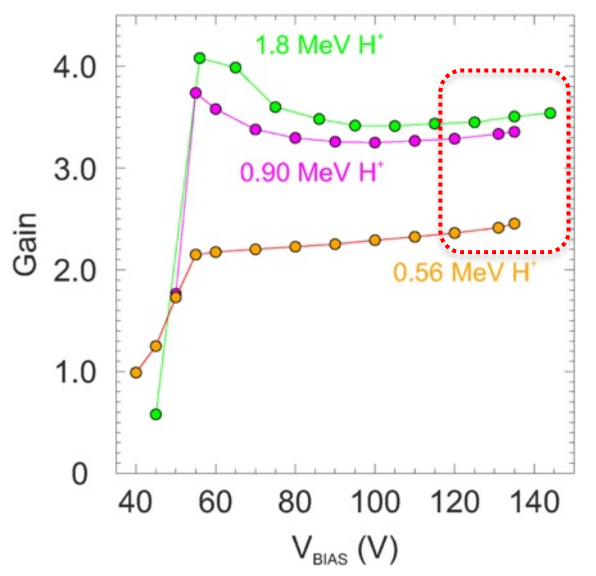


from Sevilla group: M.C.Jimenez-Ramos et al. *Sensors* **2022**, *22*(3)

- Protons (<2 MeV) have significantely higher energy deposition than MIPs (~ 100 times higher)

Gain-to-voltage dependences with depth

Changing the ionization density!



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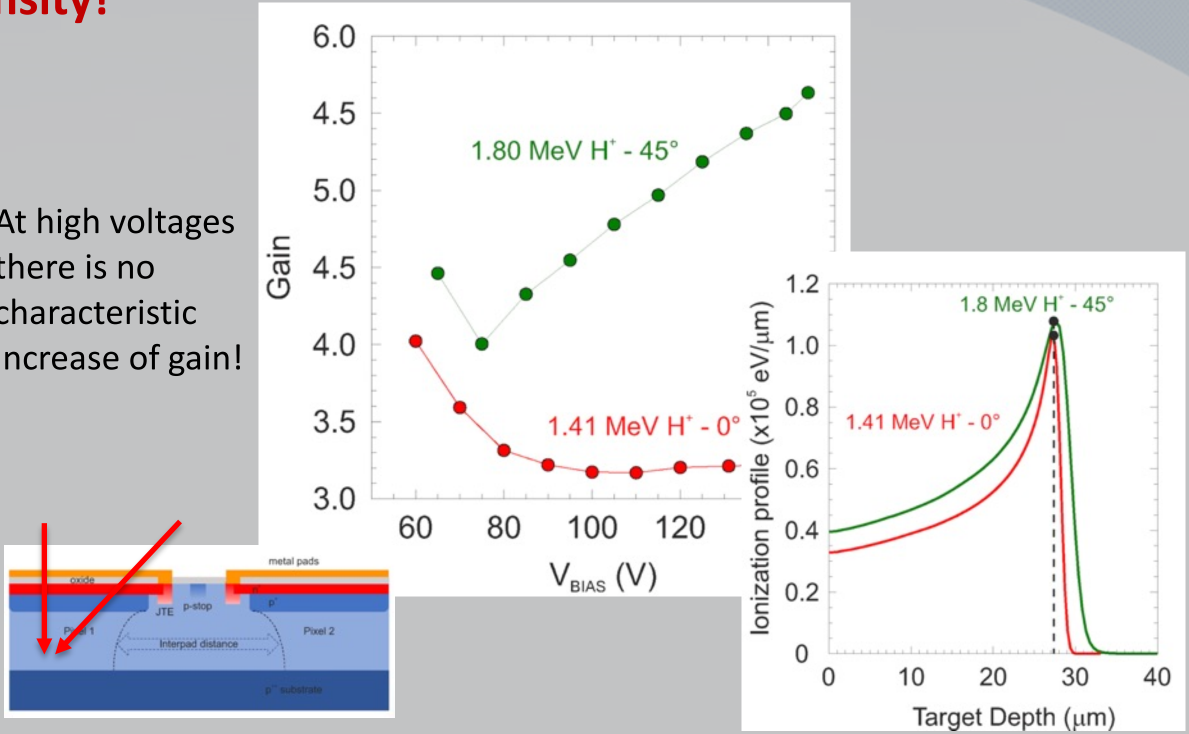
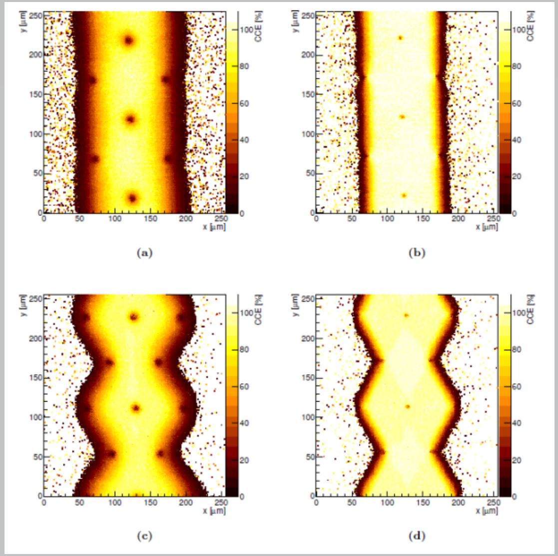


- Protons have significantely higher energy deposition than MIPs (~
- Can be increased by protons if IBIC probing is done under an angle
- At 45 degree angle - charge carrier cloud is distributed to more tha
- Electric field screening is reduced → gain suppression is decreased

More about the gain suppression experiment – presentation by Gordana Medin at VCI2022: no. 210: *Studies of LGAD performance limitations, Single Event Burnout and gain suppression, with fs-laser and ion beams*

Other examples of IBIC depth profiling:

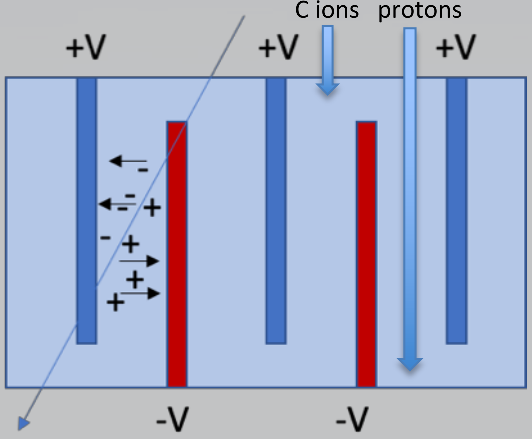
3D diamond detectors



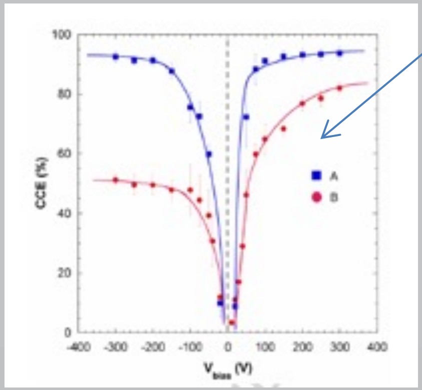
CCE maps for different biases and geometries

AIDA-2020-RBI-2015-4 and AIDA-2020-RBI-2017-5

3D diamond, Alexander Oh, University of Manchester, UK



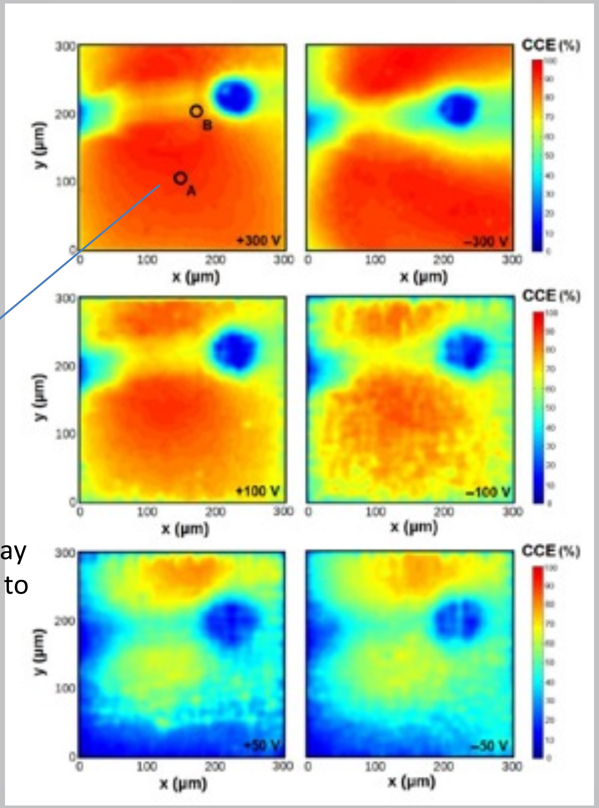
Increasing radiation hardness by shortening collection distance



Average CCE measured far away (A) and close (B) to the pillar

AIDA-2020-RBI-2017-2

buried graphite pillars in CVD diamond, G. Conte, INFN, Italy



IBIC map in case of front-side irradiation at different bias voltages.

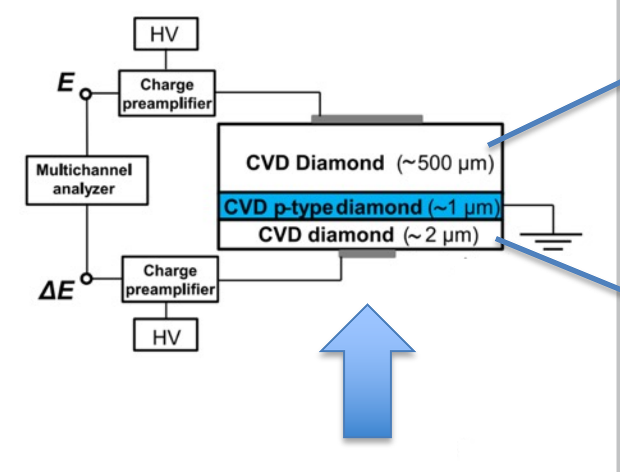
Other examples of IBIC depth profiling:

ΔE/E monolithic diamond detector (C. Verona et al.)

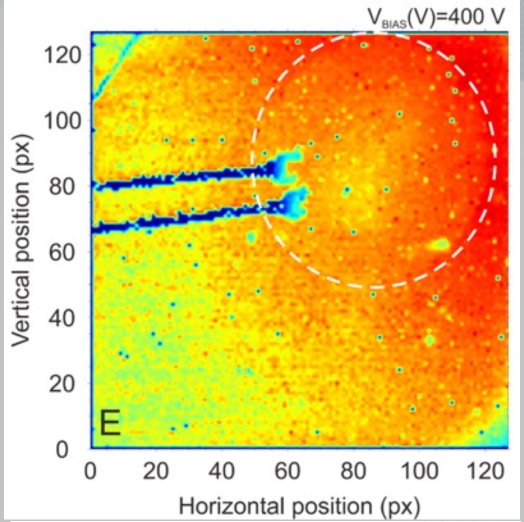
Characterisation of *ΔE – E* telescope by 4 different C ions of same rigidity:

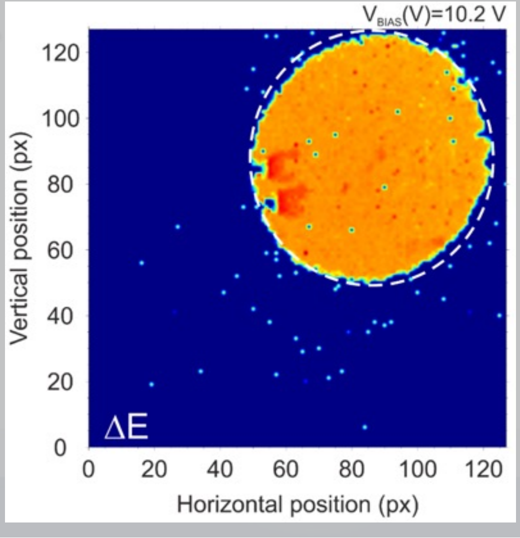
- 6.0 MeV C^{3+}
- 10.7 MeV C^{4+}
- 16.7 MeV C^{5+}
- 24.0 MeV C^{6+}

Possible applications in microdosimetry for hadron therapy !



C ion microbeam

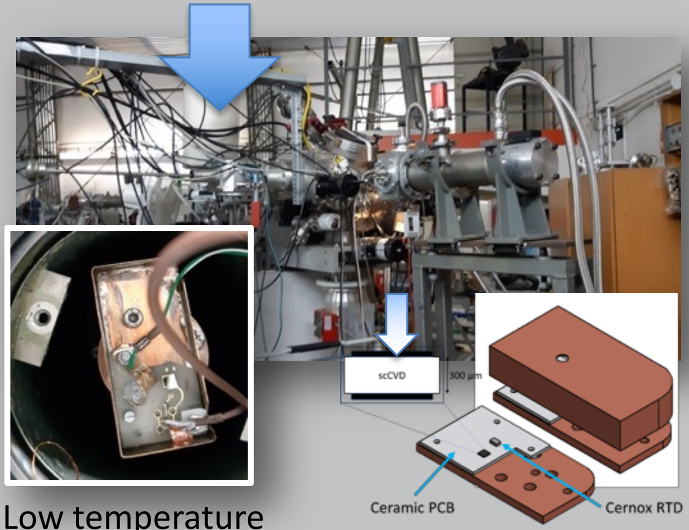




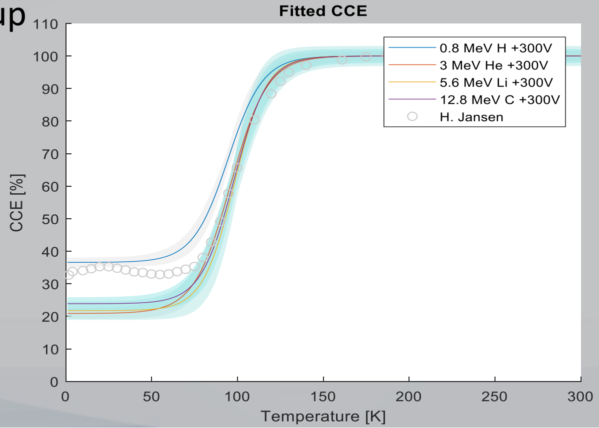
S.Cesaroni, M.Marinelli, E.Milani, G.Prestopino, C.Verona, G.Verona-Rinati, *ΔE – E single crystal diamond based telescope,* Nucl. Instr. and Meth. A947 (2019) 162744

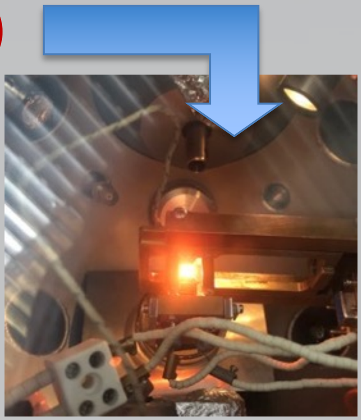
IBIC at different temperatures (diamond):

low (47 K to RT) and high (RT to 450 C)

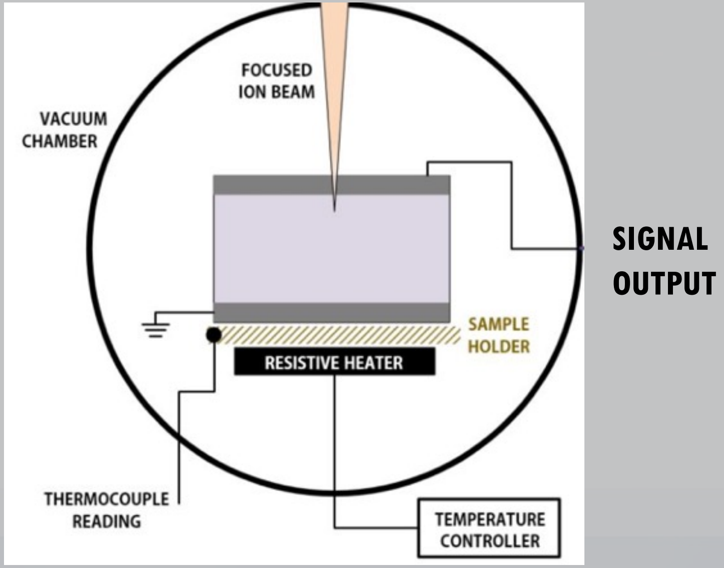


Low temperature cryo-cooler setup



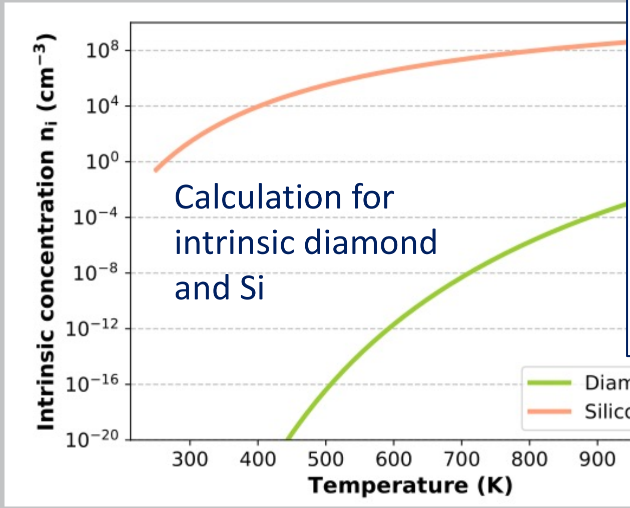


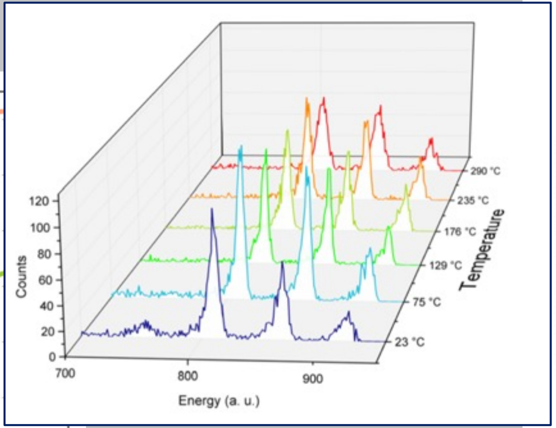
Detector exposed to heating, viewed with IR camera

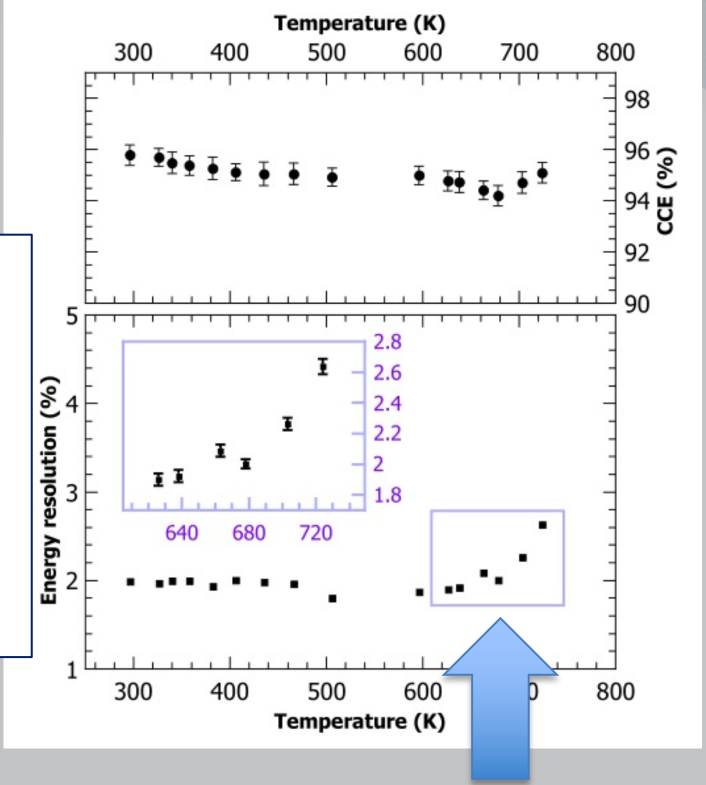


Diamond spectroscopic quality at high temperatures

- Very wide band-gap → diamond has an extremely low number of electrons in conduction band → even at elevated temperatures
- True HT operational limit will be determined by crystal quality (defects)







Pristine diamond: near 100% CCE for temperatures up to 725 K (limit), 40 keV energy resolution (for 2 MeV protons)

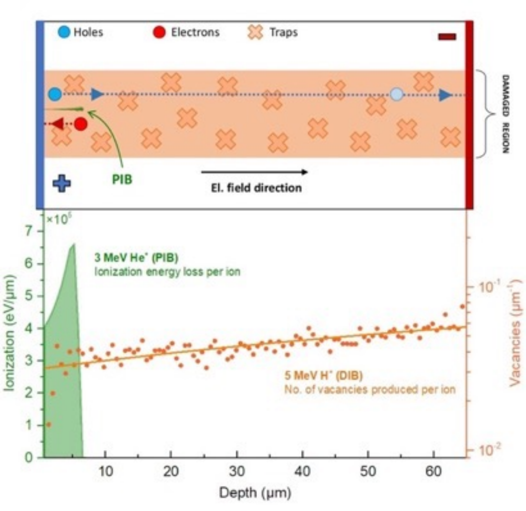
Highest reported temperature for diamond-based detector!

A. Crnjac et al., *Electronic Properties of a scDiamond at High Temperature and High Radiation*, Materials 2020, 13, 2473

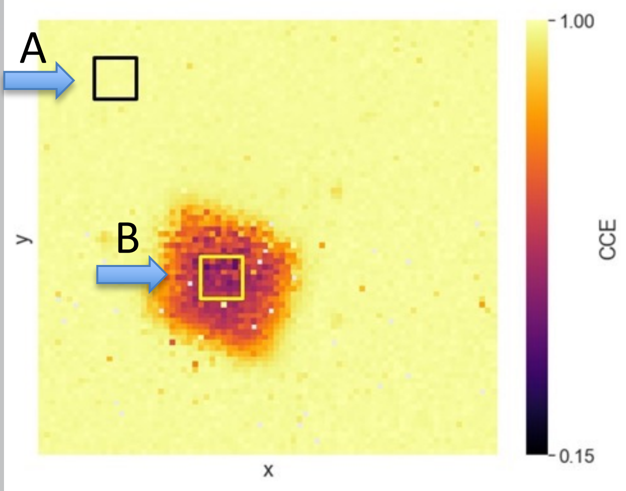
Identification of nature of defects

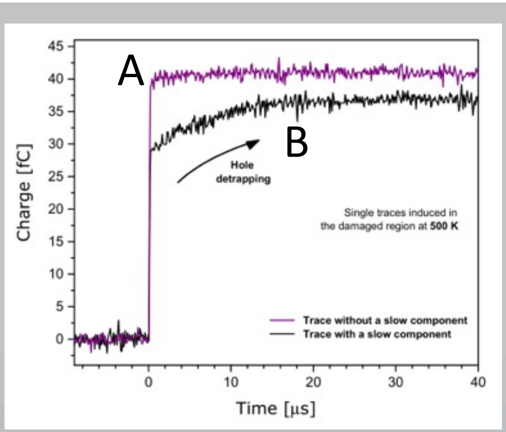
by time resolved IBIC vs. temperature (Q-DLTS)

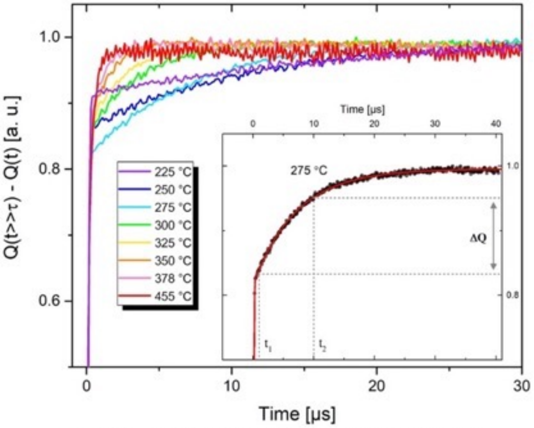
1. Irradiation of $100\times100\ \mu m^2$ regions with 5 MeV protons to create radiation damage

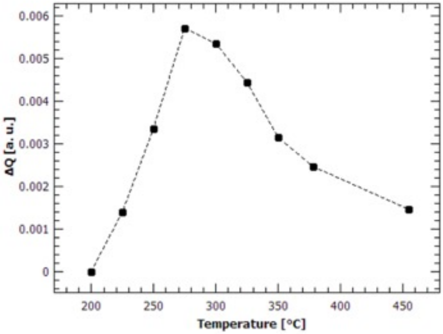


2. IBIC probing of regions A and B with 3 MeV He ions (PIB) at different temperatures (up to 450 C)





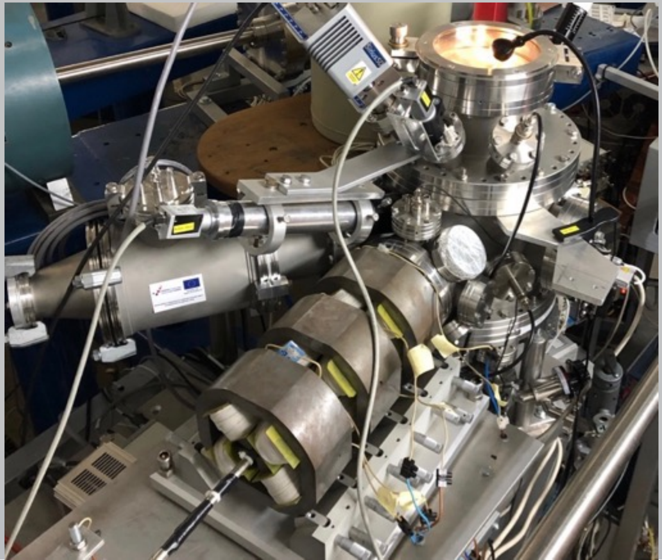




- Difference of the charge pulse amplitude measured in two time windows with the same t_2/t_1 ratio.
- ΔQ(T) plot (QTS spectrum) shows maximum charge difference at 550 K.
- Hole trap activation energy = 0.53 eV!

Conclusions

- IBIC probing of charge transport in (x,y) and (z) shown to be feasible
- (x,y) resolution 1 µm, (z) resolution is reducing by depth
- Maximum probing depth in Si – 300 µm
- Different ions – different ionization densities
- Simplified procedures of energy change in microprobe setup tested
- Can be performed in air (only protons and with reduced spatial resolution (10 µm))
- Upgrades at RBI:
  - Increasing capabilities at different positions
  - Piezo stage for positioning
  - New dual beam microprobe



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2015-2019 – AIDA2020

- **AIDA-2020-RBI-2015-1**, Systematic study of radiation damage in scCVD diamond material irradiated with relativistic Au beams, Jerzy Pietraszko, GSI Darmstadt, HADES, **Germany (26-30.10.2015.)**
- **AIDA-2020-RBI-2015-3**, Investigation of channeling depth profiles of high energy carbon and silicon ions implanted in diamond and SiC crystals for detector characterization, Michael Kokkoris, National Technical University of Athens, **Greece (23-27.11.2015.)**
- **AIDA-2020-RBI-2015-2**, Diamond Membranes for Radioisotope Batteries BATDiαm, Michal Pomorski, CEA, LIST, **France (15-19.2.2016.)**
- **AIDA-2020-RBI-2015-4**, 3D diamond, Alexander Oh, University of Manchester, **UK (11-15.4.2016.)**
- **AIDA-2020-RBI-2016-1**, IBIC characterization of single crystal diamond based Shottky diodes for microdosimetry application, Claudio Verona, 'Tor Vergata' University, **Italy (24-28.10.2016).**
- **AIDA-2020-RBI-2016-2**, Microbeam tests of silicon telescope for clynical dosimetry, G. Magrin, Austron, **Austria (18-20.1. and 9-10.2.2017.)**
- **AIDA-2020-RBI-2016-3,** Investigation of channeling depth profiles of high energy carbon and silicon ions implanted in SiC /Si crystals for detector characterization, University of Athens, **Greece (30.1.-3.2. 2017.)**
- **AIDA-2020-RBI-2017-1:** Diamond Membrane Microdosimeter, M. Pomorski, CEA, **France (2-5.5.2017.)**
- **AIDA-2020-RBI-2017-4:** Characterization of a large area CVDdiamond TimeofFlight detector with interdigitated electrodes for energyloss measurements of lowenergy ions in laserinduced plasmas , W. Cayzac, CMLA, ENS Paris, Saclay, **France (6-10.11.2017)**
- **AIDA-2020-RBI-2017-5:** Polycrystalline 3D Diamond IBIC and TRIBIC characterisation, A. Oh, Univ Manchester, **UK (27.11.-2.12.2017).**
- **AIDA-2020-RBI-2017-3:** Study of channeling depth profiles of high energy silicon ions implanted in diamond and silicon crystals at various fluences for detector characterization, S. Petrovic, Vinča, **Serbia (12-16.2.2018).**
- **AIDA-2020-RBI-2017-2:** Analysis of micrometer and millimeter-long graphite pillars buried in sc-CVD diamond , G. Conte, Roma Tre University, Rome, **Italy** (**12-14.9.2017. and 20-21.3.2018**)
- **AIDA-2020-RBI-2018-1:** Single event upsets in CMS pixel ROC, Wolfram Erdmann, PSI **Switzerland (2.7.-6.7.2018).**
- **AIDA-2020-RBI-2019-1:** IBIC of monolytic pixel detectors, Rogelio Pinto, University of Sevilla, **Spain (19.8.-23.8.2019).**

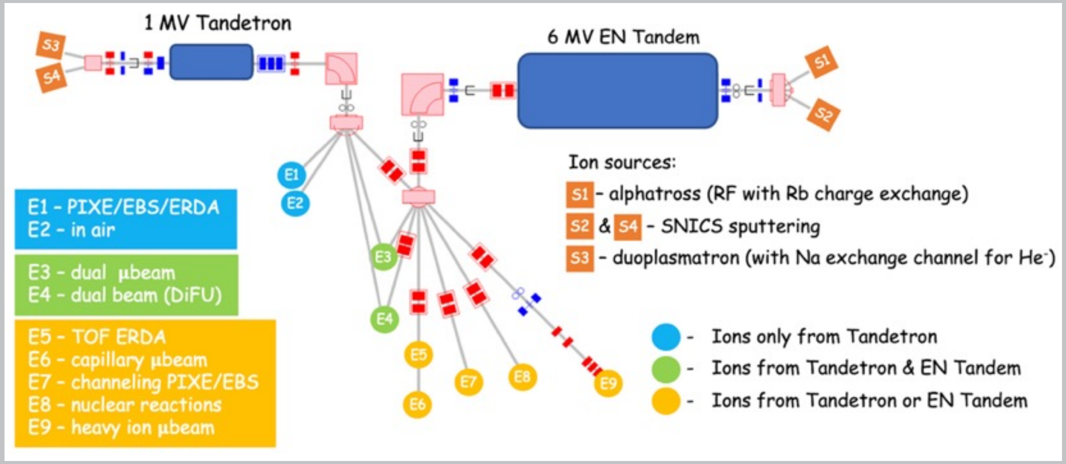
Providing Transnational Access

2020-2024 – RADIATE

IonBeamCenters.eu

RADIATE

RBI offers 1600 beam time hours through RADIATE project
1/3 proposals involve IBIC, SEE studies and detectors



RADIATE Transnational Access:

- User selection panel reviews proposals
- Response time is max. 2 months
- After proposal submission, RBI allocates beam time
- Accepted proposals scheduled within 3 months
- During the Covid-19 travel bans, remote operation is possible
- Project funds travel, accommodation and daily allowance

Providing Transnational Access

From the end 2022 until 2026 – EuroLabs

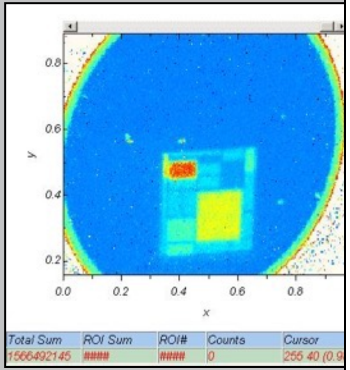
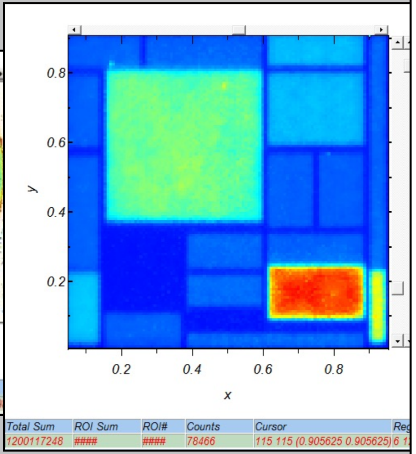
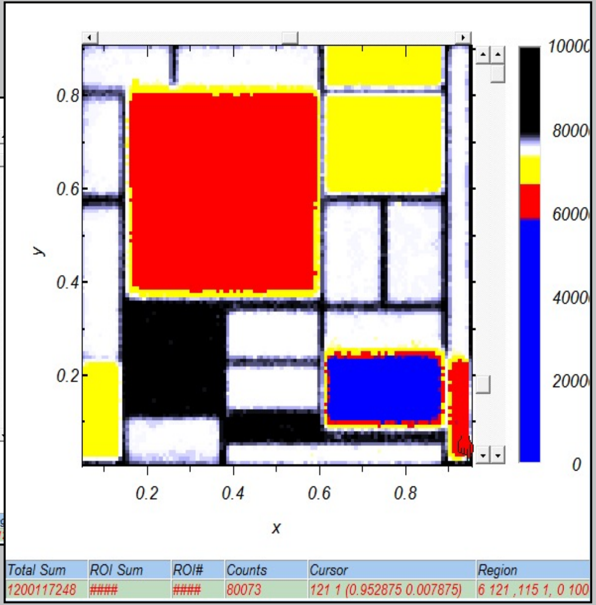
EURO LABS
EUROPEAN LABORATORIES
FOR ACCELERATOR
BASED SCIENCES

EUROpean Laboratories for Accelerator Based Science
EC funded Project 2022-2026

RBI is partner providing IBIC for detector testing

Thank you for attention !!

Introducing the radiation damage into the pin diode

Total Sum	ROI Sum	ROI#	Counts	Cursor
1566492145	#####	#####	0	255 40 (0.9

Total Sum	ROI Sum	ROI#	Counts	Cursor	Reg
1200117248	#####	#####	78466	115 115 (0.905625 0.905625)	6 1

Total Sum	ROI Sum	ROI#	Counts	Cursor	Region
1200117248	#####	#####	80073	121 1 (0.952875 0.007875)	6 121 ,115 1, 0 100