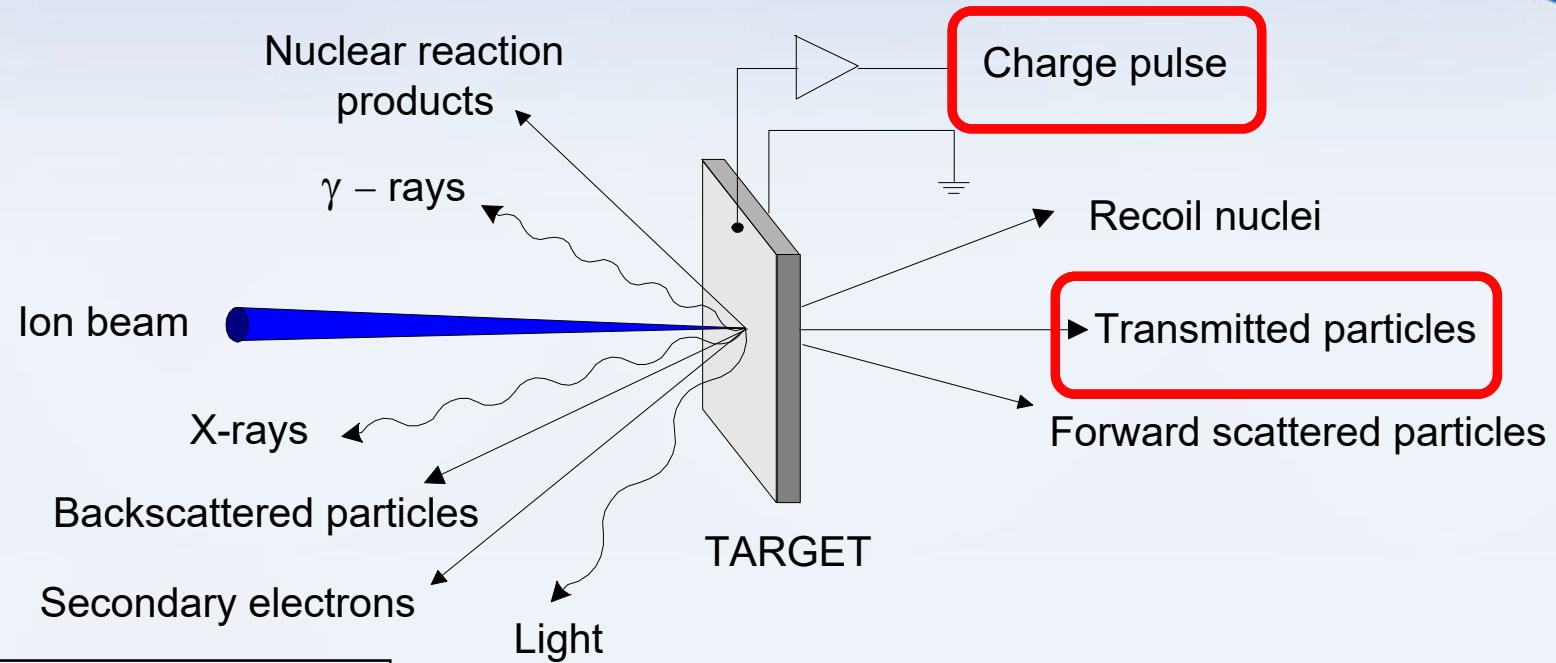


SPECIAL TOPICS IN ION BEAM ANALYSIS – PART 2 SINGLE ION TECHNIQUES: STIM & IBIC

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Experimental physics division
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Zagreb, Croatia

Ion Beam Analysis & NUCLEAR MICROPROBE



ANALYSIS (elements, isotopes)
with **MeV ION BEAMS** - (nA, pA)

- elements - x-rays (**PIXE**)
 - backscattering (**RBS**)
 - recoil (**ERDA**)
- isotopes - nuclear reactions
 - γ -rays (**PIGE**)
 - particles (**NRA**)



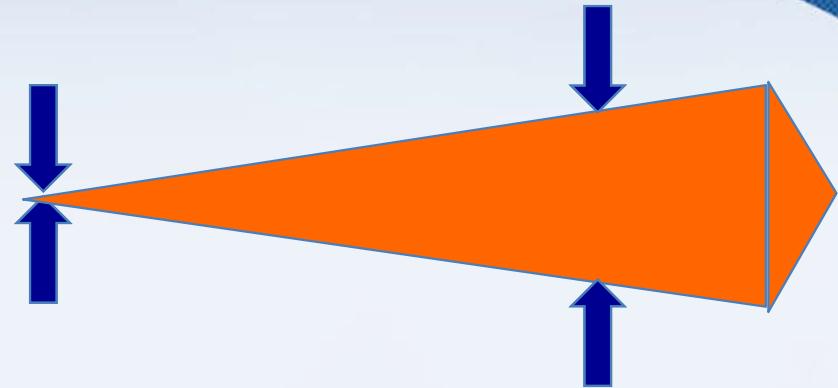
CHARACTERISATION (density, charge transport, crystal structure, morphology,...)
with **MeV SINGLE IONS** - (fA)

- density - transmitted ions (**STIM**)
- charge transport - charge pulse (**IBIC**)
- crystal structure - **channelling**
- morphology - secondary electrons (**SEI**)

Single ion implantation

Why single ions?

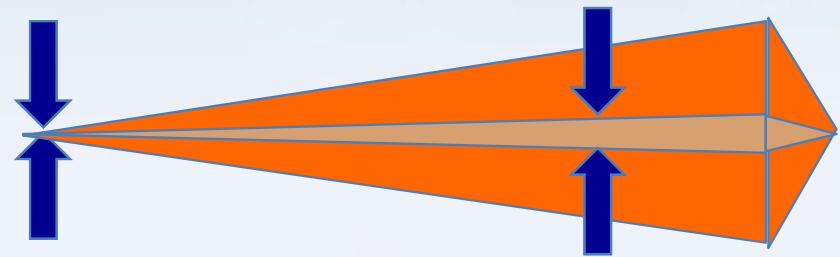
- Implantation of one particular atom at exactly known position in exactly known time seems to be extremely attractive!
- And it is easy (to perform experimentaly) !



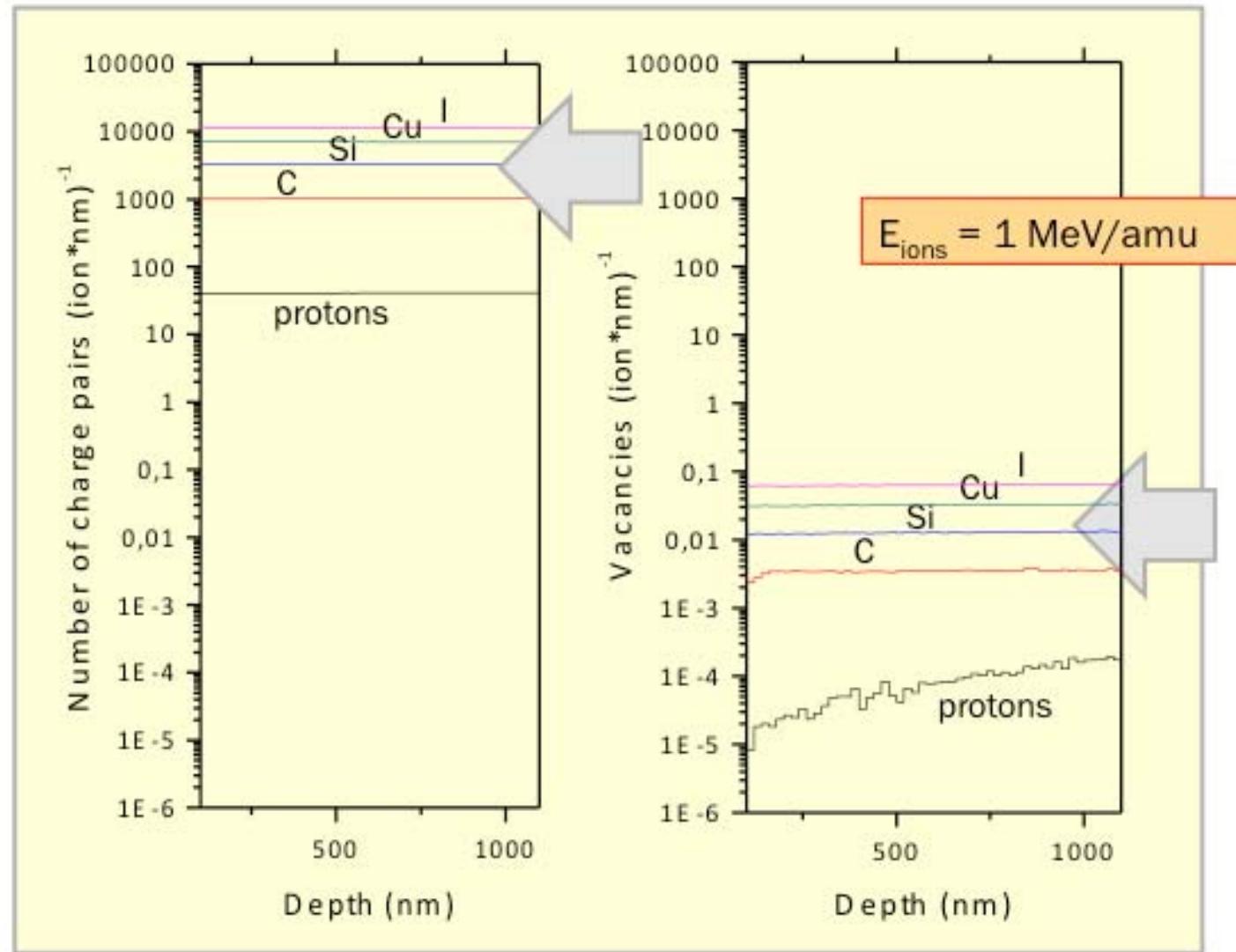
Single ion implantation

Why single ions?

- Implantation of one particular atom at exactly known position in exactly known time seems to be extremely attractive!
- And it is easy (to perform experimentaly) !



Single ions – ionisation & defects



Every ion:

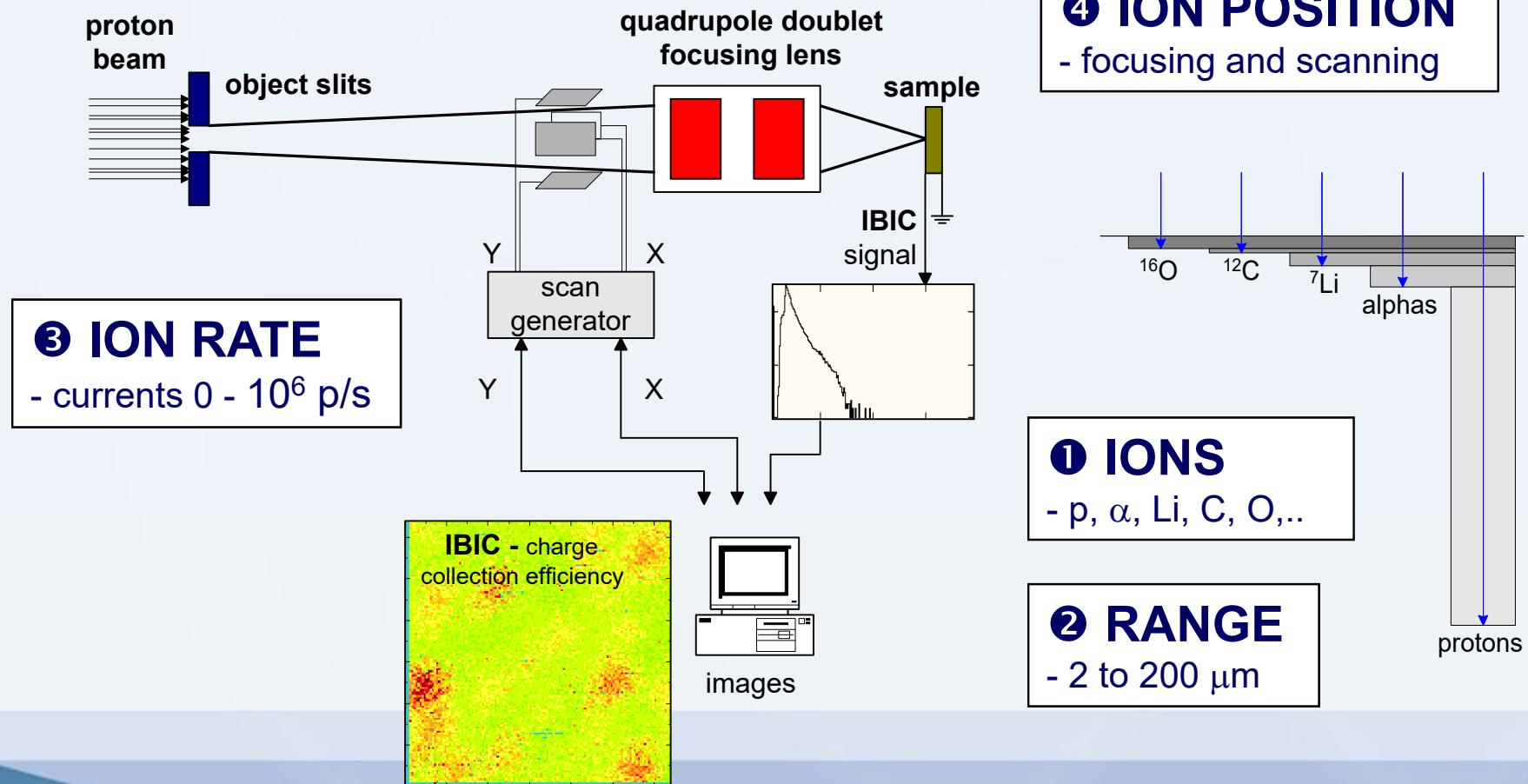
- Implants itself into the substrate
- Ionises many atoms on its way - creates large number of charge pairs

Heavy ions:

- Create many vacancies
- Some secondary electrons
- Some desorbed molecules

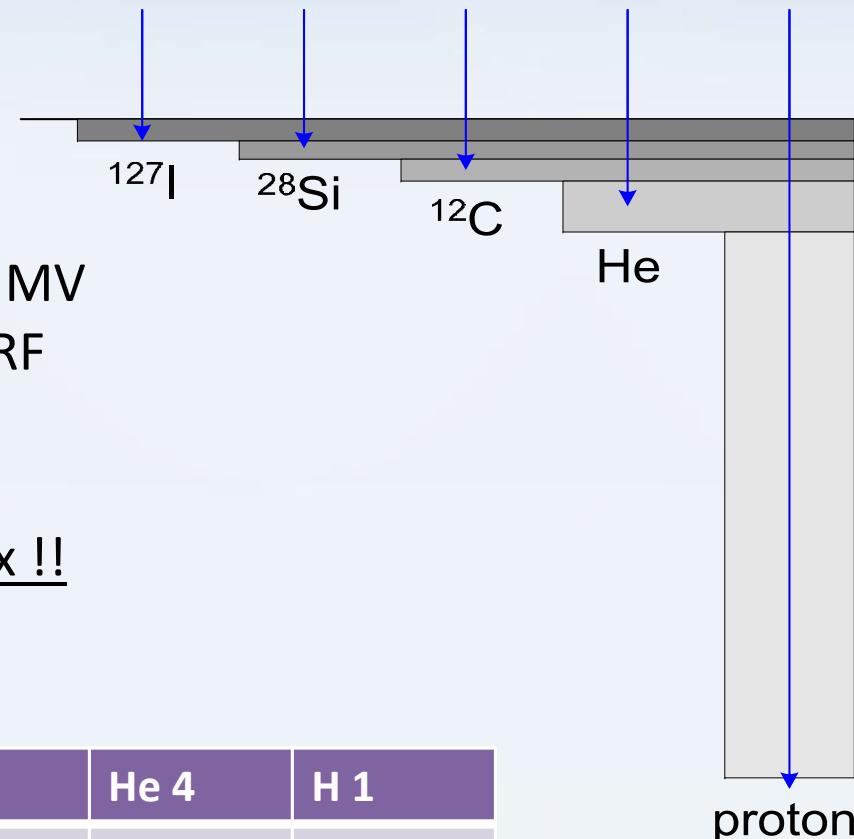
Accelerator & nuclear microprobe

Ideal radiation source



Accelerator & nuclear microprobe

Available ion beams



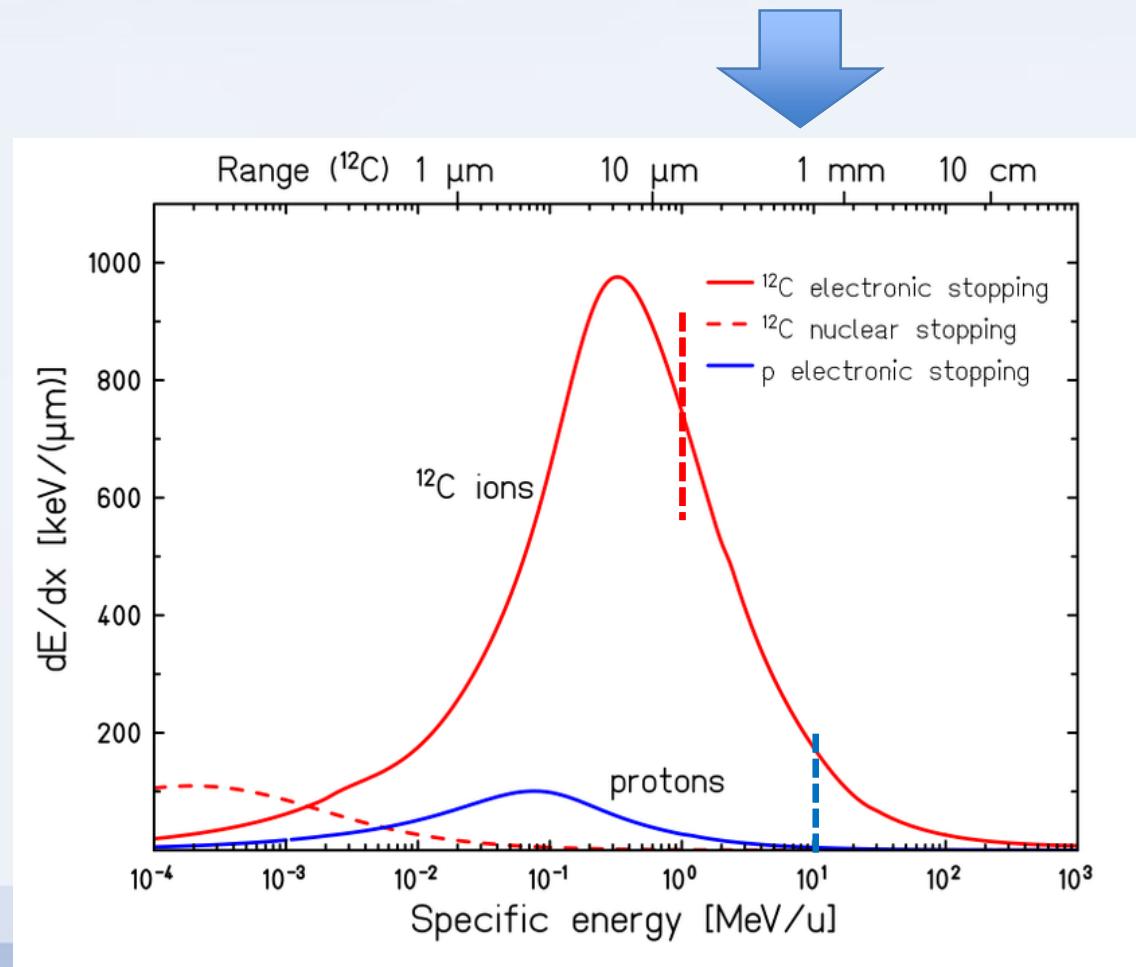
AT RBI - terminal voltages – 0.1 to 6 MV

Ion sources – sputtering, RF
albatross, duoplasmatron

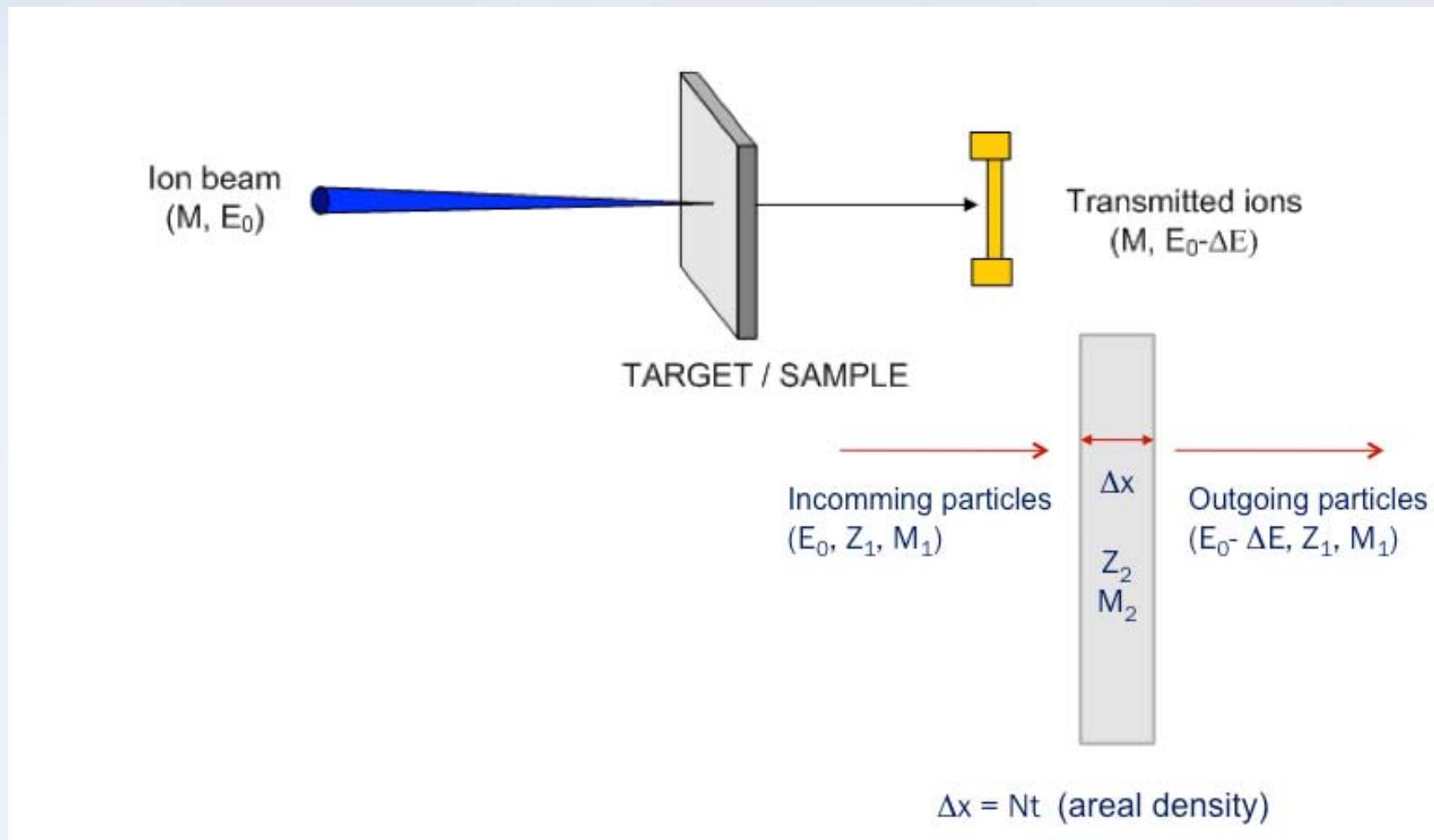
Good selection of ion ranges / dE/dx !!

Silicon	I 127-	Si 28	C 12	He 4	H 1
Range(μm) $E=1 \text{ MeV}$	0.37	1.13	1.6	3.5	16.3
Range (μm) $E=10 \text{ MeV}$	3.7	4.8	9.5	69.7	709

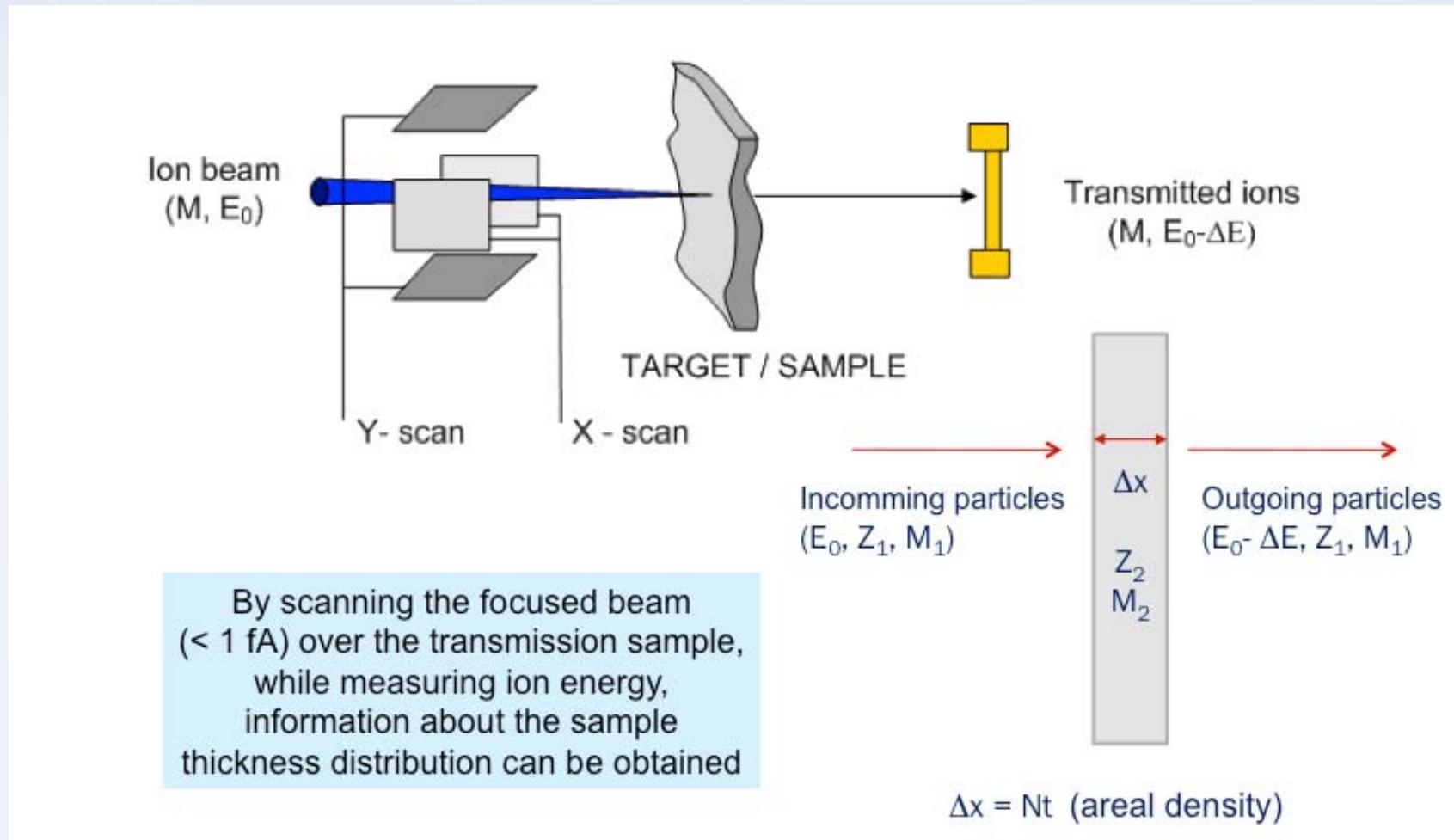
Single ion characterisation: STIM – Scanning Transmission Ion Microscopy: imaging of areal densities (dE/dx)



STIM – Scanning ion transmission microscopy

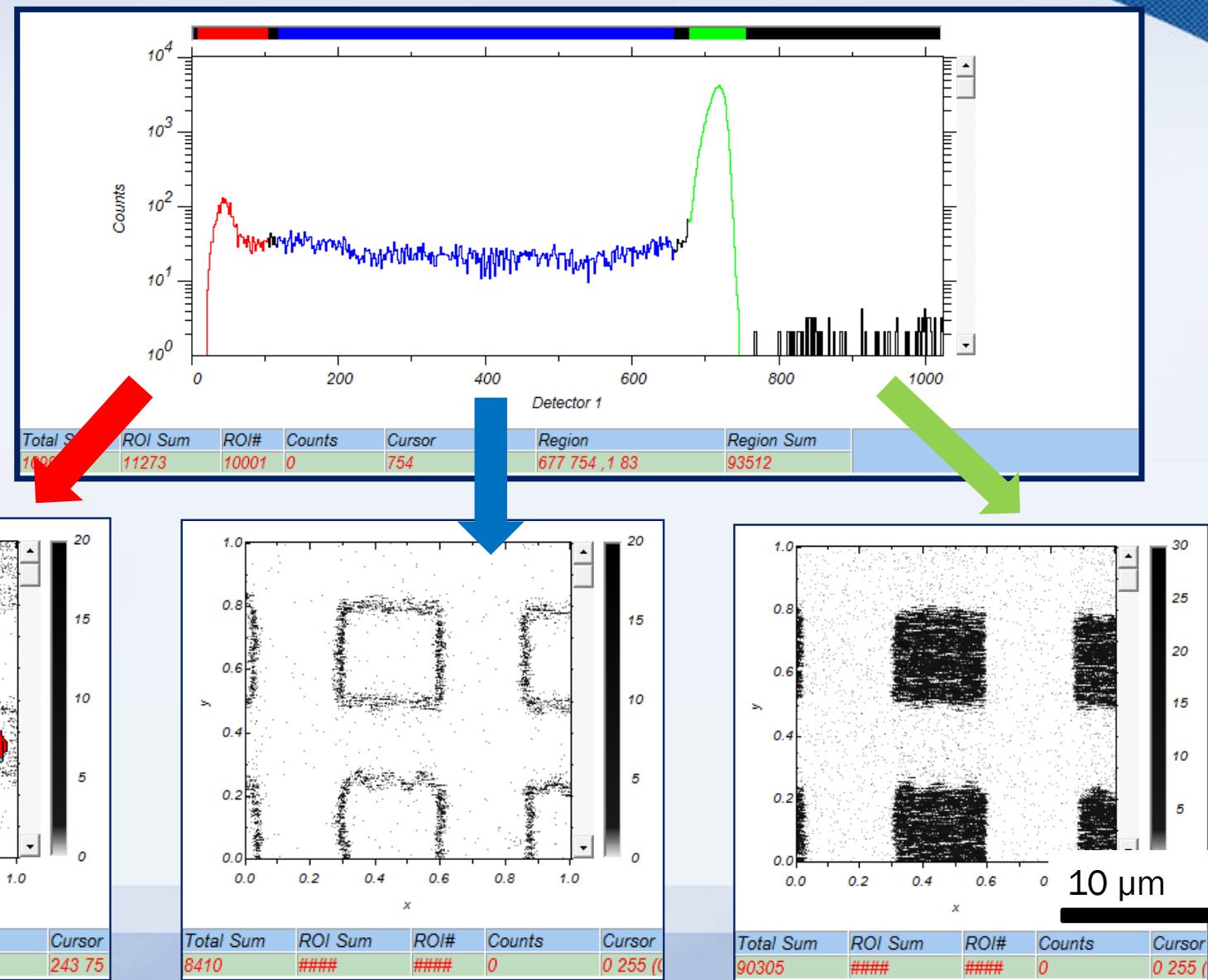


STIM – Scanning ion transmission microscopy

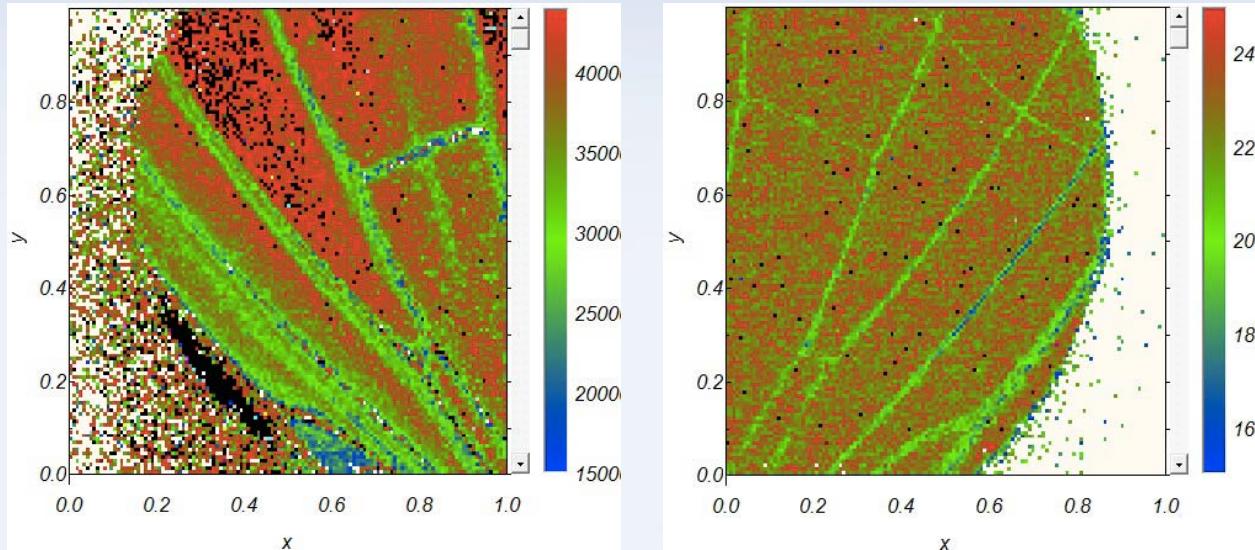


STM – Scanning ion transmission microscopy

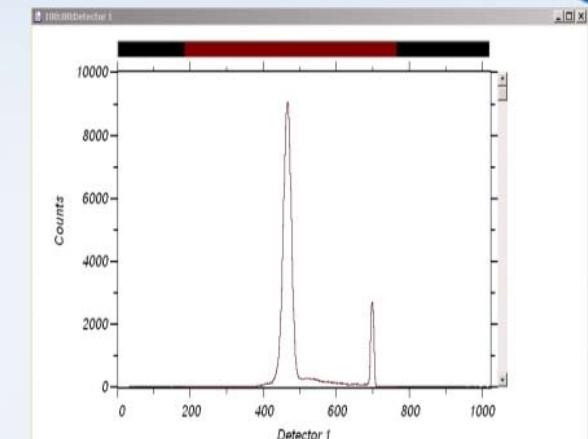
STIM image of copper grid using 8 MeV O³⁺ ions



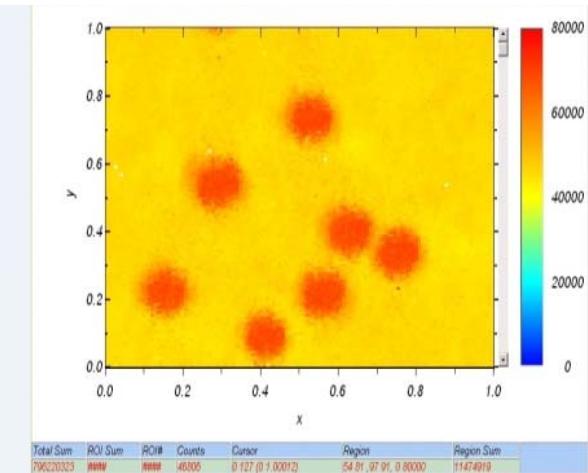
STIM – Scanning ion transmission microscopy



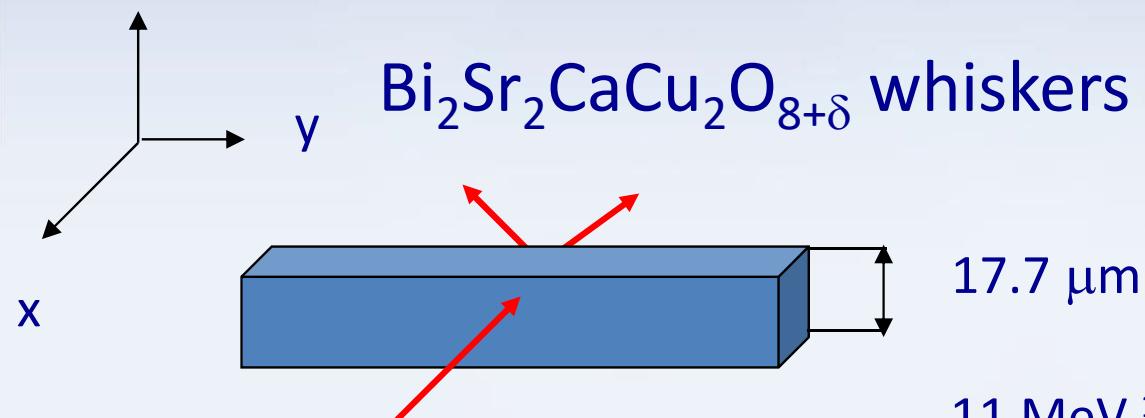
Density map for flies wing: 6 MeV O ions (left)
and 2 MeV protons (right)



Track shape characterisation

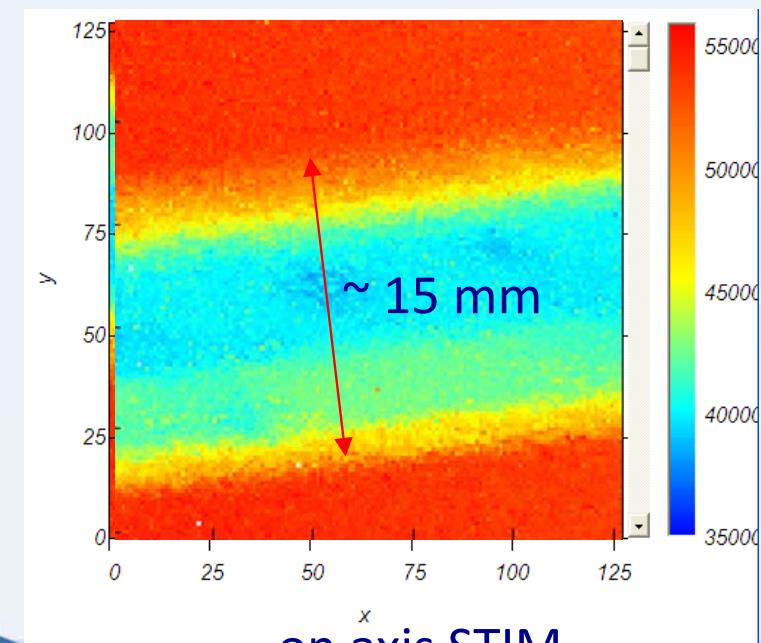


STIM – Scanning ion transmission microscopy

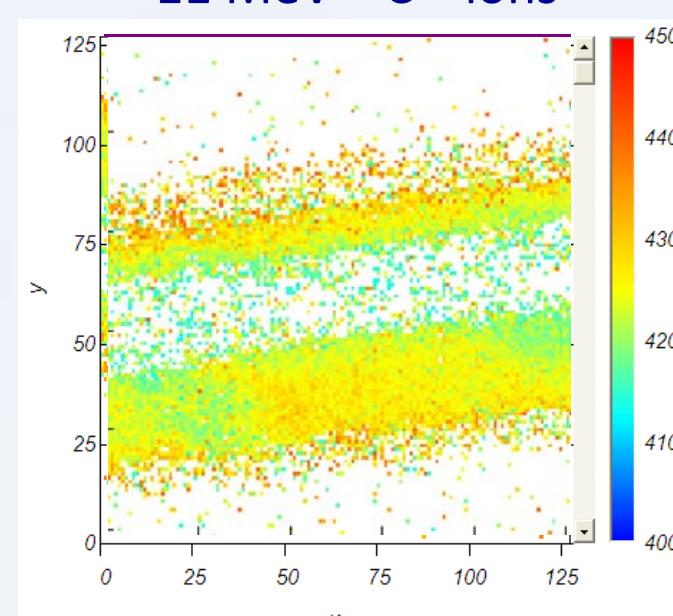


Combination of STIM with 3D analysis
using C ion induced coincidence
spectroscopy

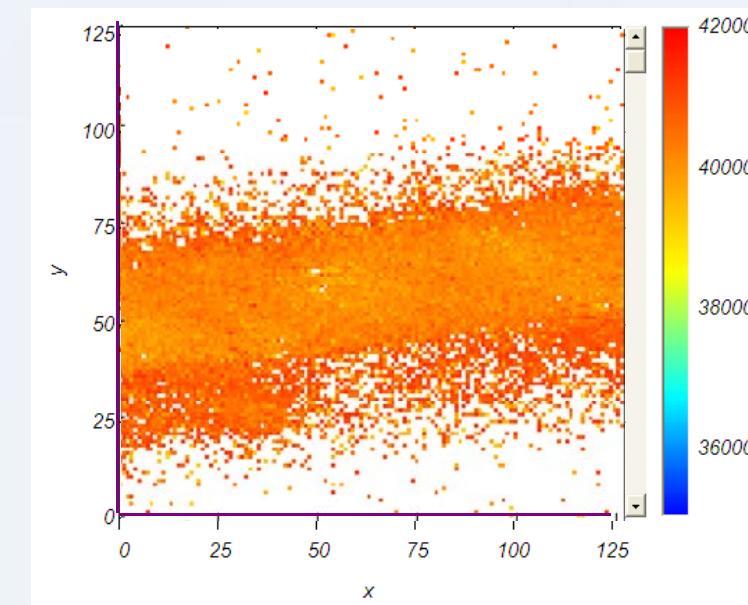
O distribution and concentration in z
direction - small sample dimensions



on axis STIM
 $28 \times 28 \mu\text{m}^2$



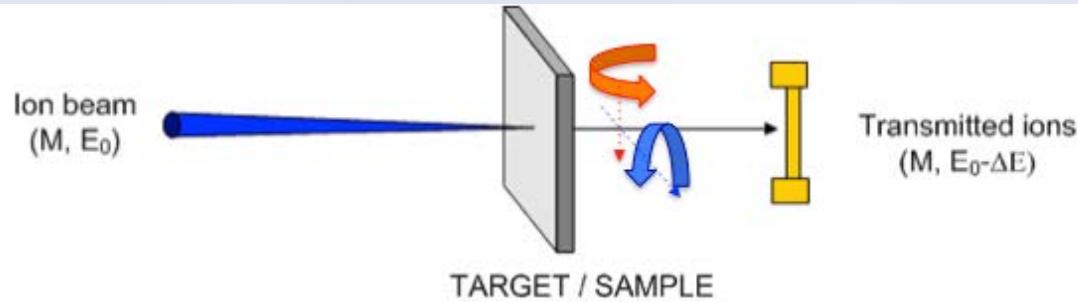
low energy loss
 $d \sim 1.45 \mu\text{m}$



high energy loss
 $d \sim 1.68 \mu\text{m}$

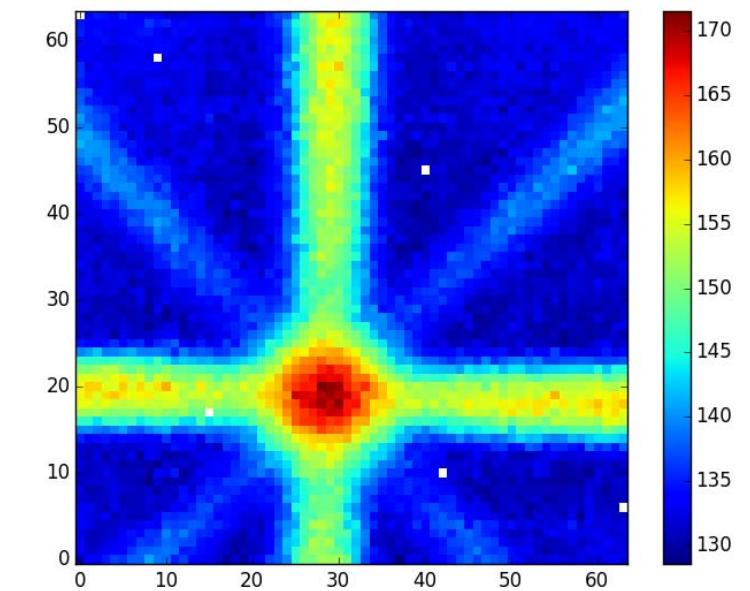
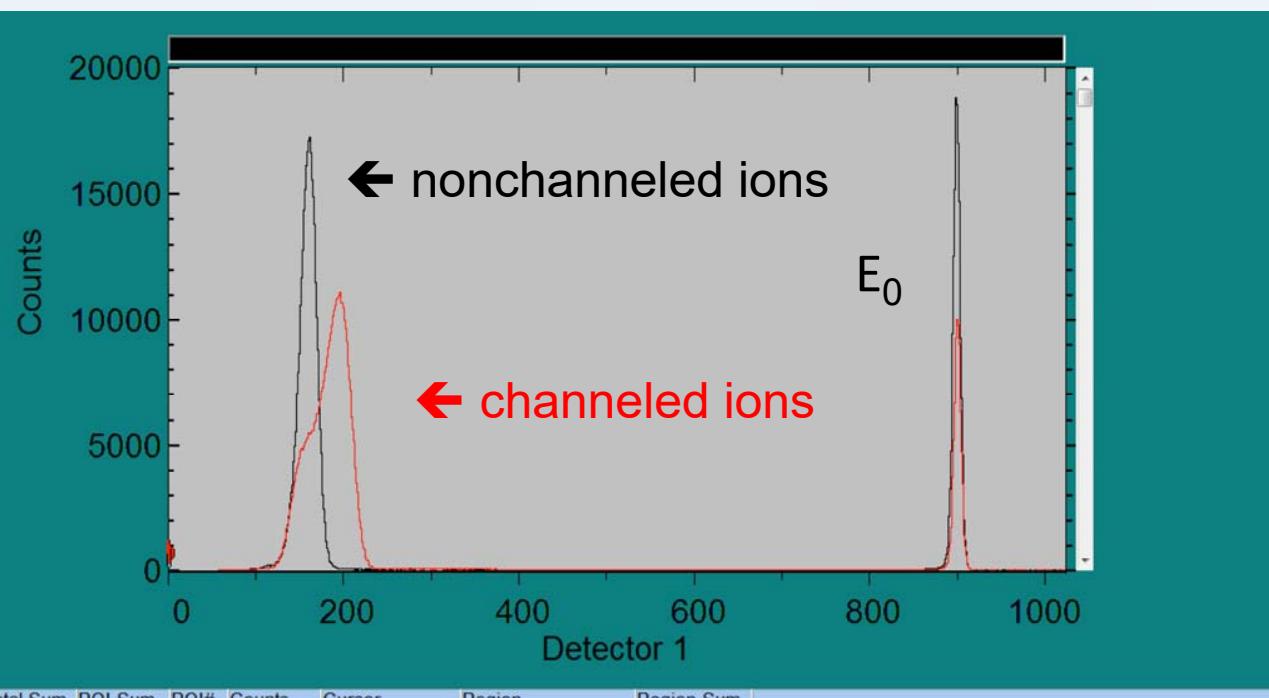
11 MeV $^{12}\text{C}^{3+}$ ions

Channeling STIM



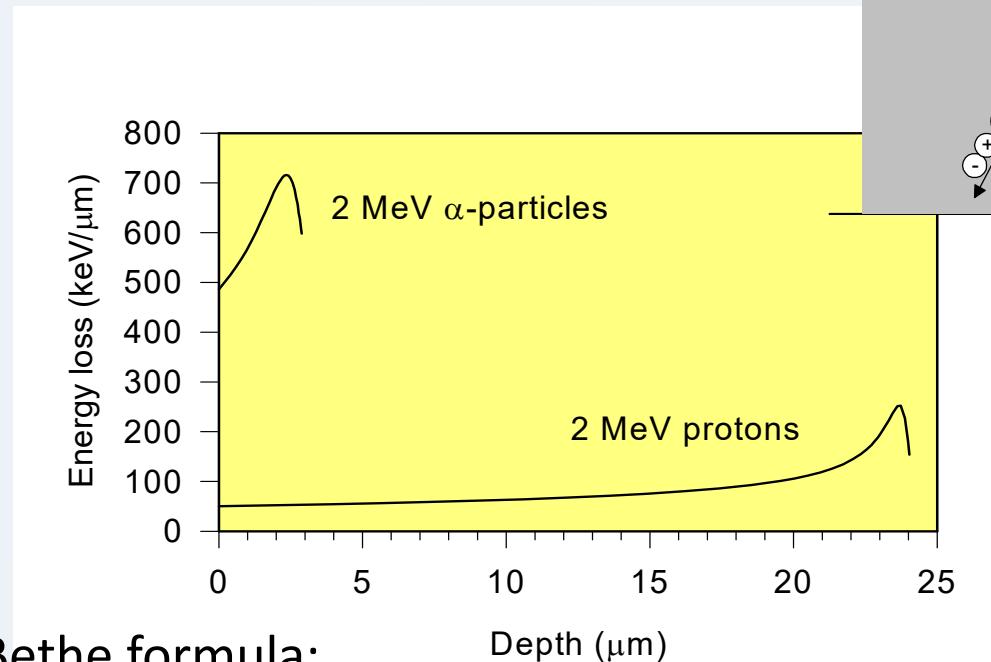
STIM (transmission) channeling

- currents $\approx 1 \text{ fA} \rightarrow$ radiation damage can be neglected
- but, only transmission samples



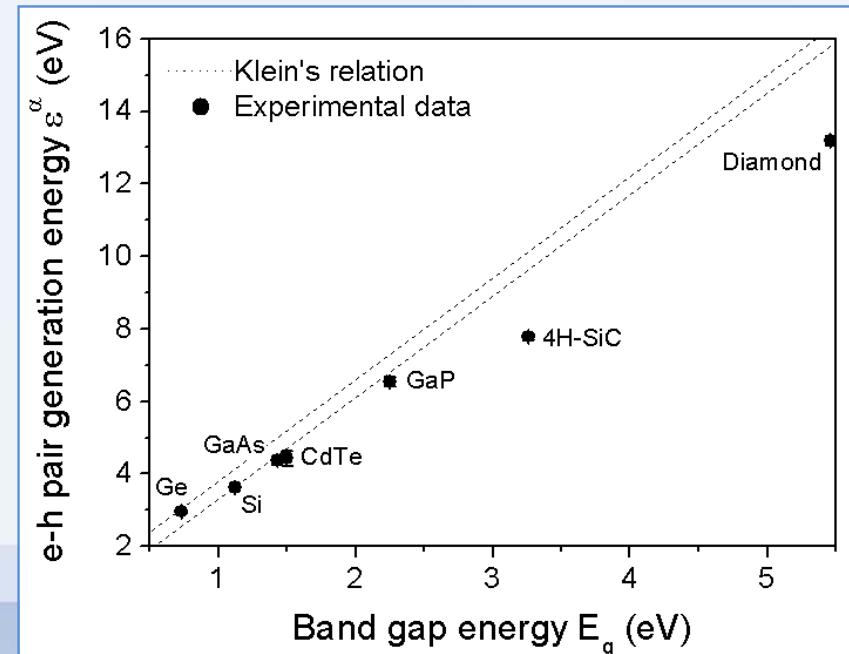
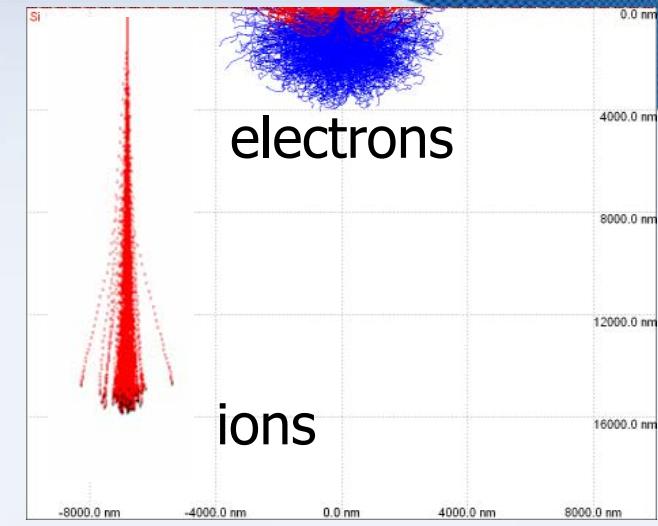
Ion beam induced charge - IBIC

- a) Ions lose their energy dE/dx
- b) Creation of charge pairs e/h



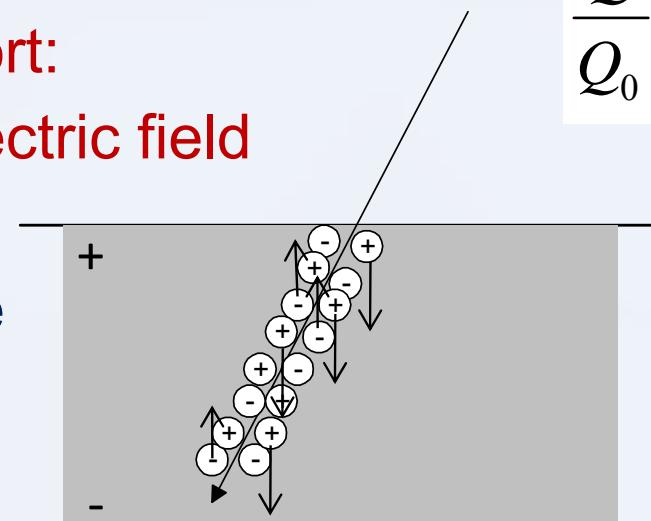
Bethe formula:

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{m_0 v^2} NZ \left[\ln \frac{2m_0 v^2}{I} - \ln \left(1 - \frac{v^2}{c^2} \right) - \frac{v^2}{c^2} \right]$$



Ion beam induced charge - IBIC

- a) Ions lose their energy dE/dx
- b) Creation of charge pairs e/h
- c) Charge transport:
 - 1. Drift - in electric field
 - 2. Diffusion
- d) Induced charge
- e) IBIC signal



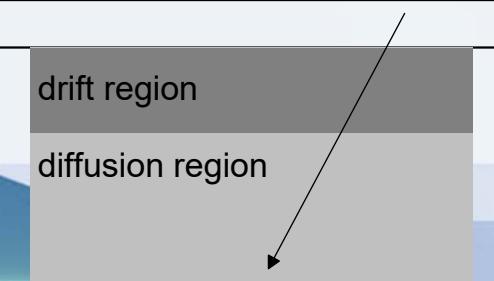
1. for $E \neq 0$ charge drift

$$\frac{Q}{Q_0} = \left[\frac{d_e}{L} \left(1 - e^{-x_e/d_e} \right) + \frac{d_h}{L} \left(1 - e^{-x_h/d_h} \right) \right]$$

- Charge carriers produced along the ion path drift in electric field
- Charge pulse height depends on the local value of electric field, mobility and lifetime of charge carriers.
- Collection length

$$d_i = (\mu\tau)_i E$$

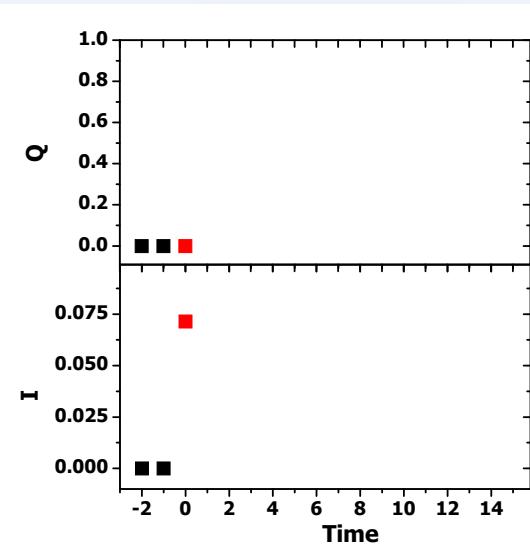
- for constant E , Induced charge signal corresponds to the value of $\mu\tau$



$$Y = \int_0^{x_d} \frac{dE}{dx} dx + \int_{x_d}^{r_i} \frac{dE}{dx} e^{-\left(\frac{x-x_d}{L(x)}\right)} dx$$

Ion beam induced charge - IBIC

- a) Ions lose their energy dE/dx
- b) Creation of charge pairs e/h
- c) Charge transport:
 1. Drift - in electric field
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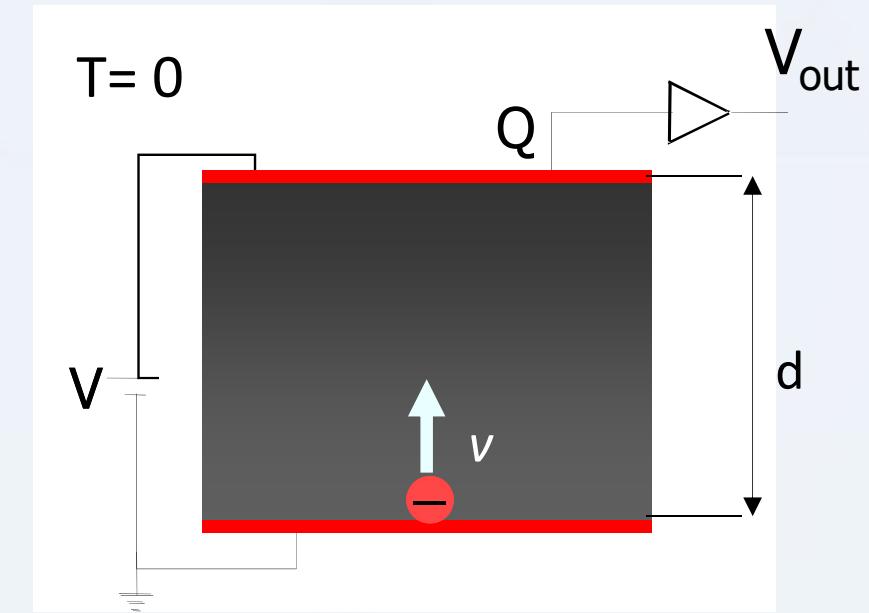


Induced current

$$I(t) = q \cdot \frac{V}{d}$$

Induced charge

$$Q(t) = \int_0^T I(t) dt$$



Ion beam induced charge - IBIC

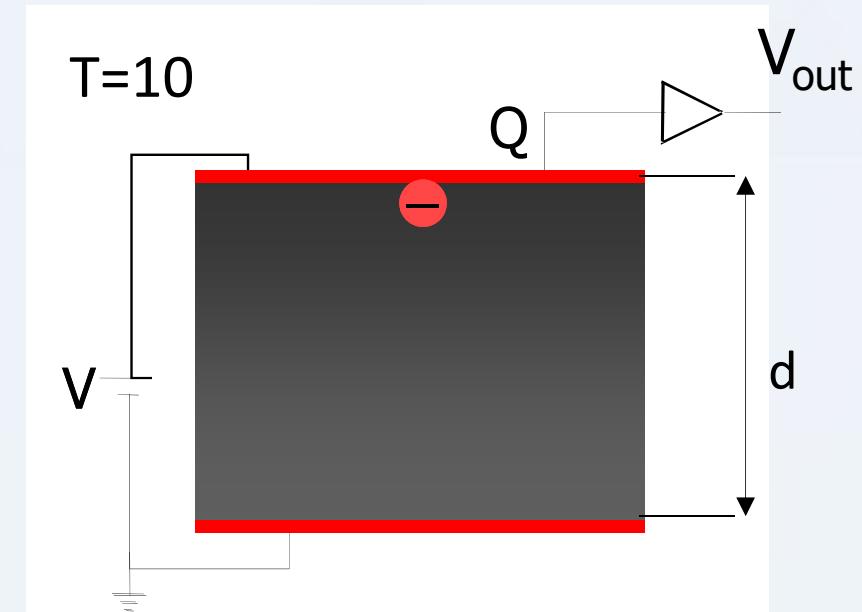
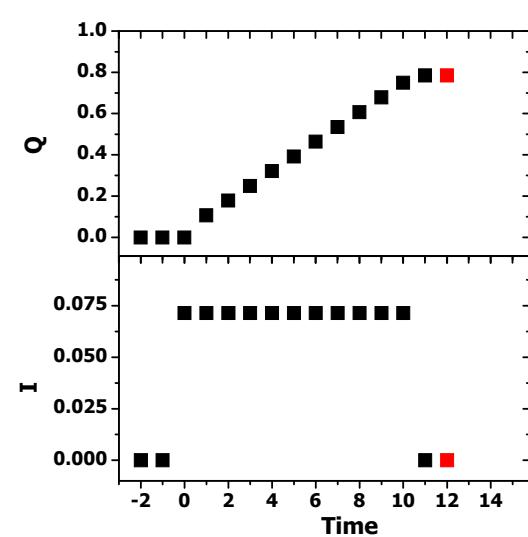
- a) Ions lose their energy dE/dx
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Induced current

$$I(t) = q \cdot \frac{V}{d}$$

Induced charge

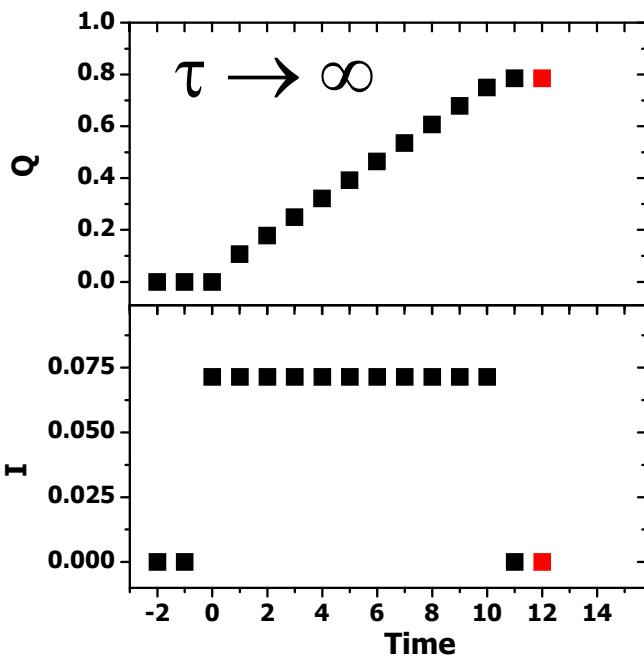
$$Q(t) = \int_0^T I(t) dt$$



Ion beam induced charge - IBIC

Velocity; $v = \mu E = d/T_R$

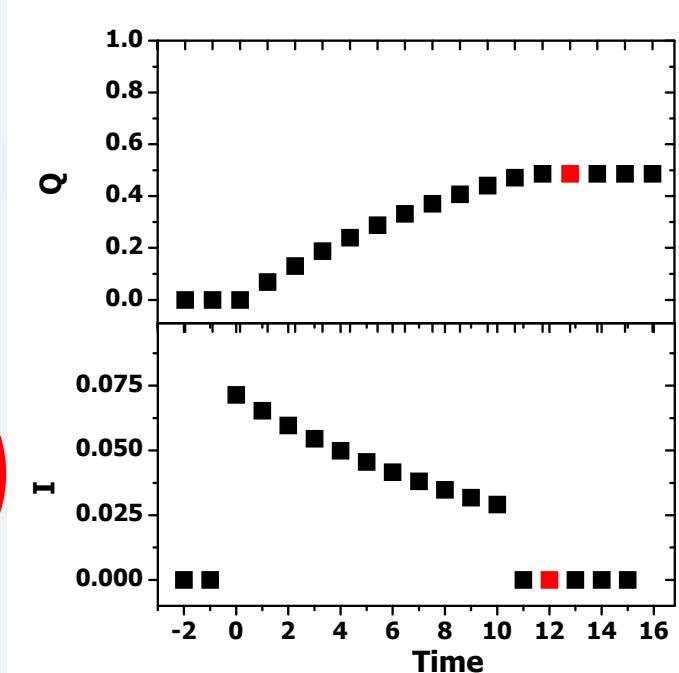
Mobility; $\mu = d^2 / (T_R * V_{Bias})$



$$Q(t) = \int_0^T I(t) dt$$

$$I(t) = q \cdot \frac{v}{d} \cdot \exp\left(-\frac{t}{\tau}\right)$$

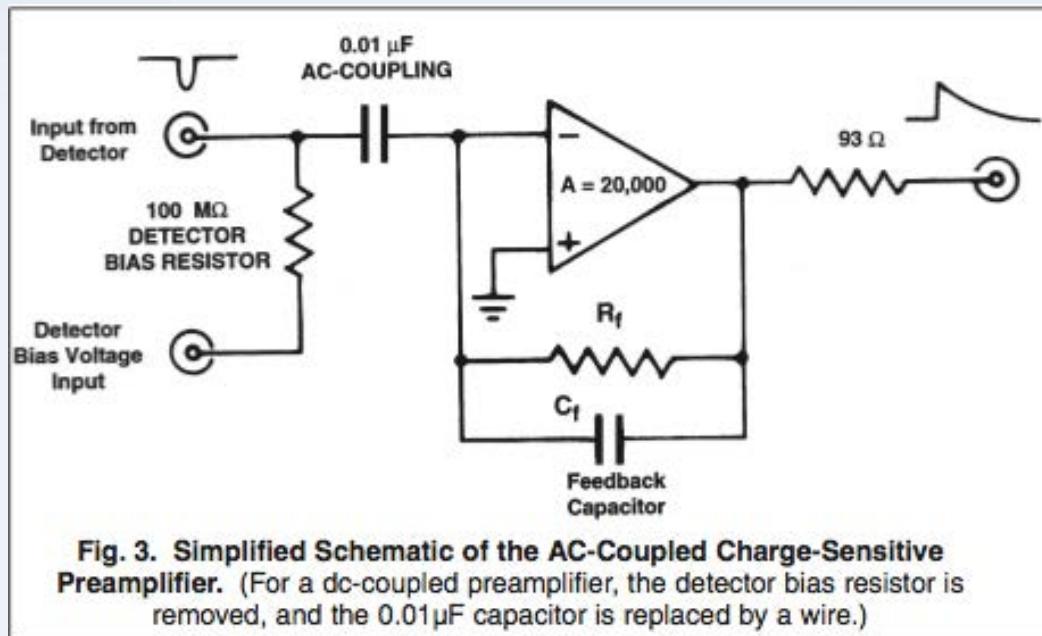
A red circle highlights the term $\frac{t}{\tau}$. A blue arrow points to the right below the equation.



In reality τ (charge carrier lifetime) can be short due to defects !

Ion Beam Induced Charge

Pulse processing (visit ORTEC tutorial)



Current preamplifier

- For studying of pulse time structure
- TRIBIC)

Charge sensitive preamplification

- For high resolution PHA (pulse height analysis)
- Due to integration, time structure of the signal is forgotten
- Shaping time constant

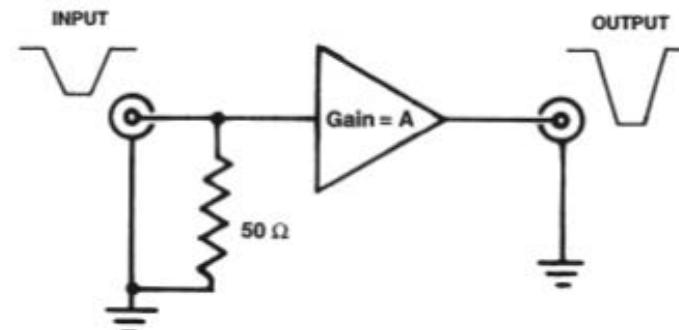
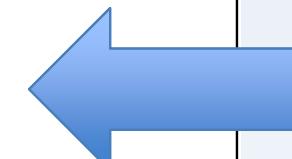
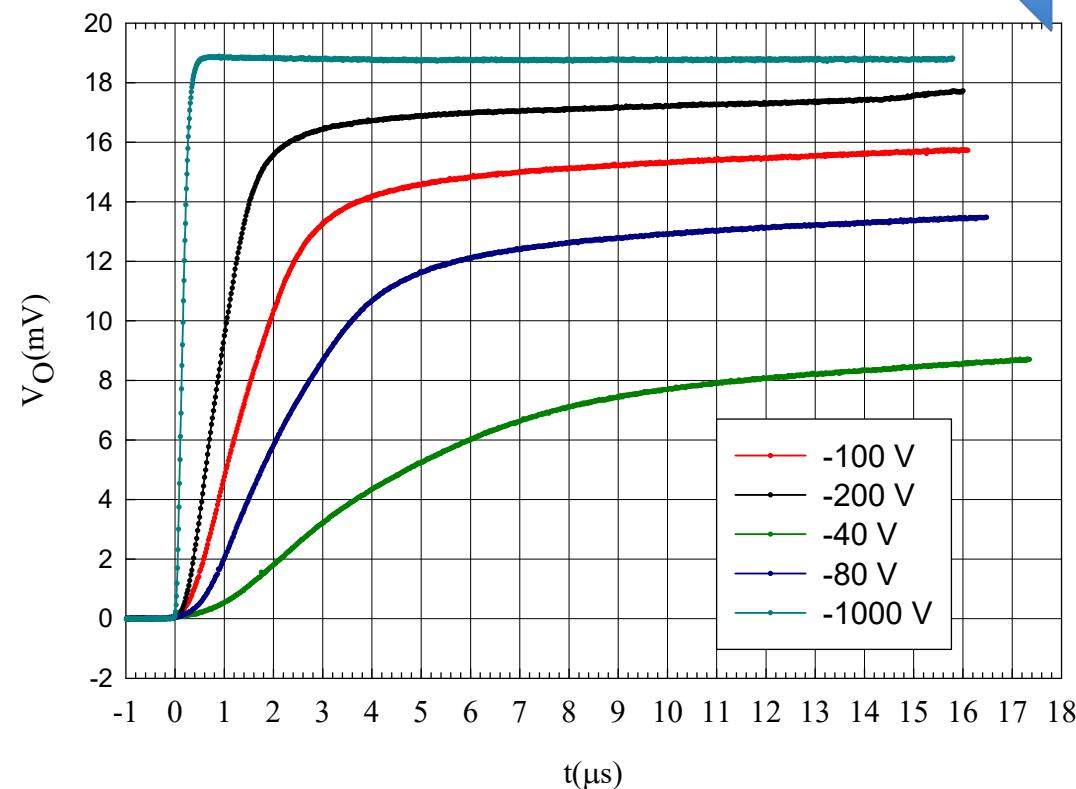


Fig. 1. A Simplified Schematic of the Current-Sensitive Preamplifier.

Ion Beam Induced Charge

Pulse processing (time resolved IBIC)

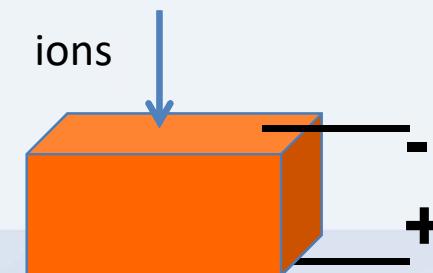
CdZnTe



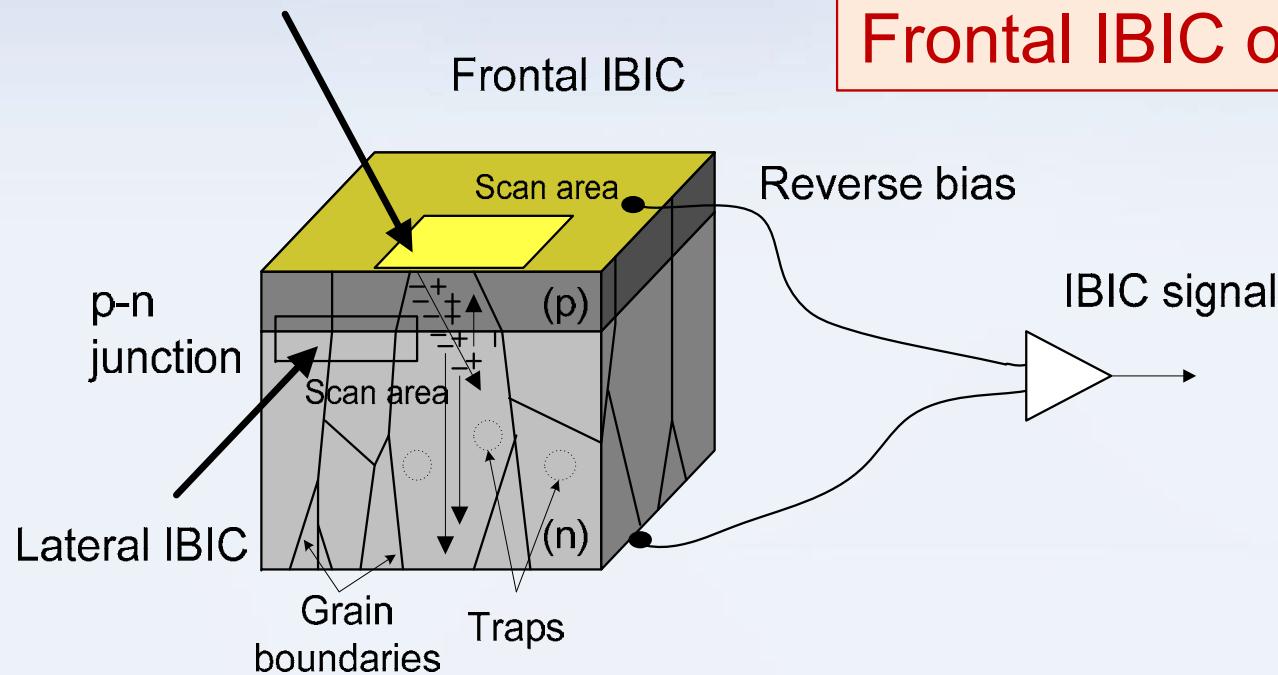
Output from the charge
sensitive preamplifier at
digital oscilloscope

$$\mu = \frac{d^2}{t_r V}$$

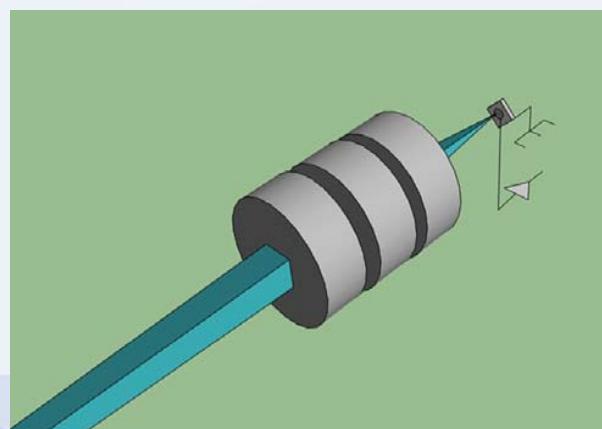
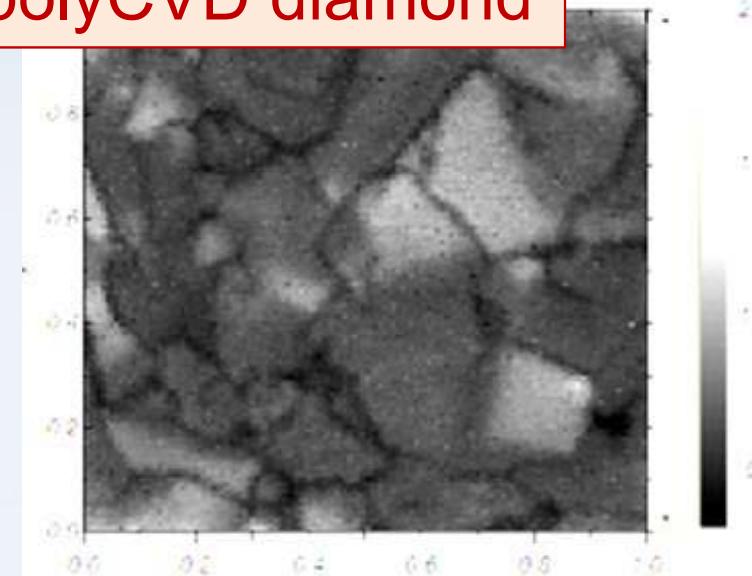
Electron mobility:
 $\mu_e = 781 \text{ cm}^2/\text{Vs}$



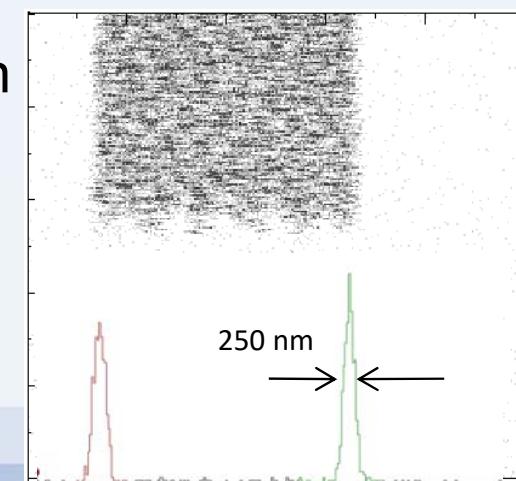
Ion beam induced charge - IBIC



Frontal IBIC on polyCVD diamond

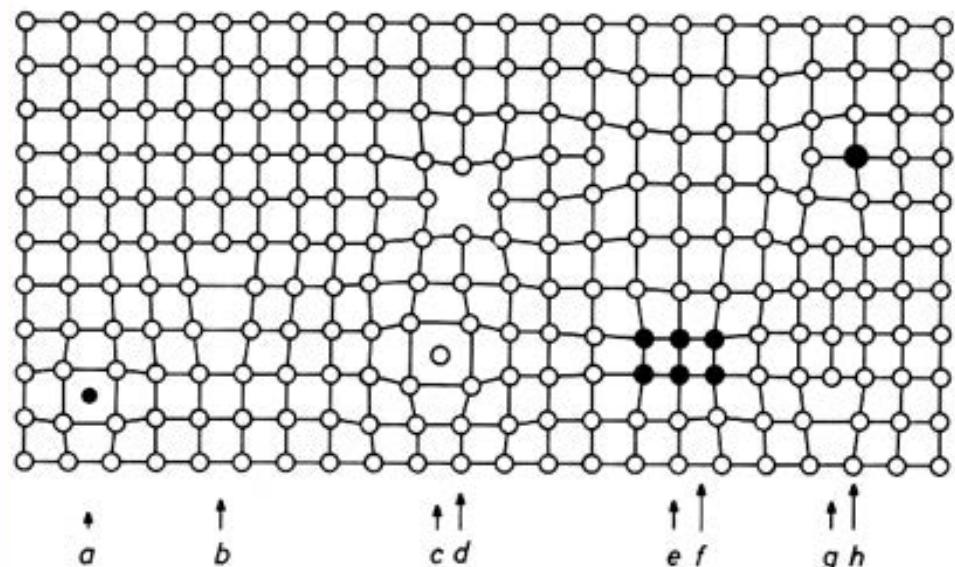


IBIC spatial resolution
→ down to $0.25 \mu\text{m}$

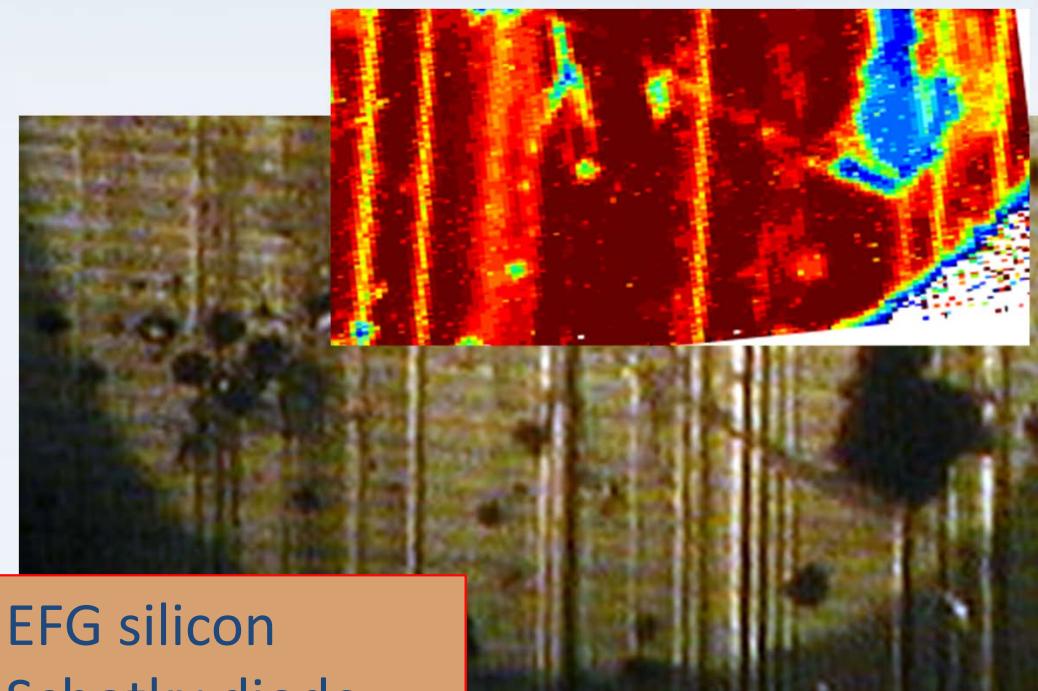


Ion beam induced charge

Frontal IBIC



a) Interstitial impurity atom, b) Edge dislocation, c) Self interstitial atom, d) Vacancy, e) Precipitate of impurity atoms, f) Vacancy type dislocation loop, g) Interstitial type dislocation loop, h) Substitutional impurity atom

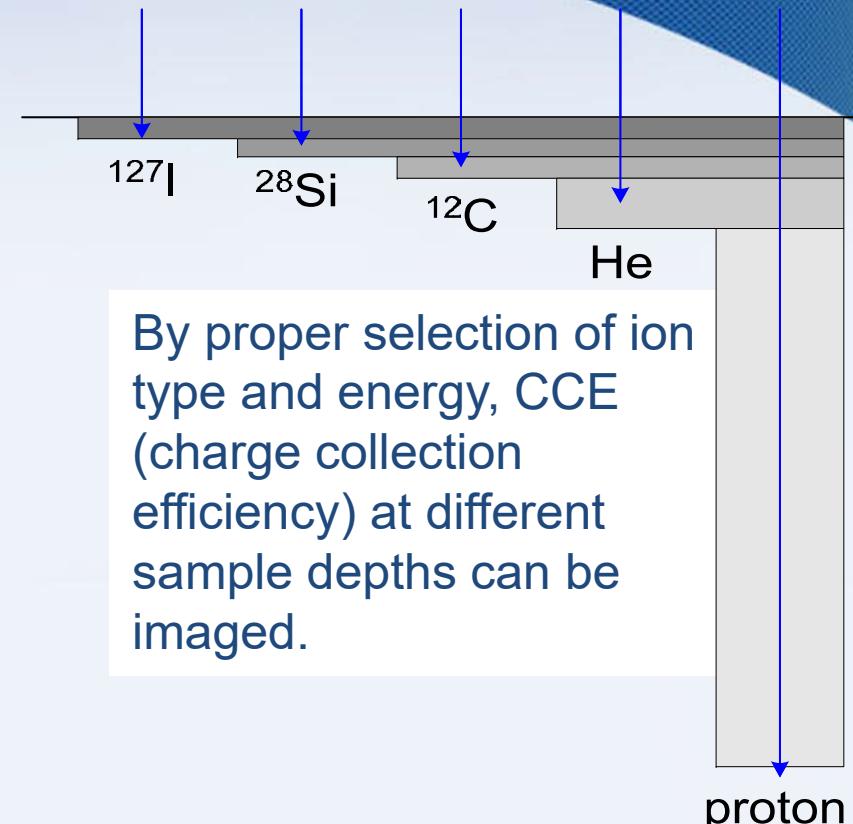
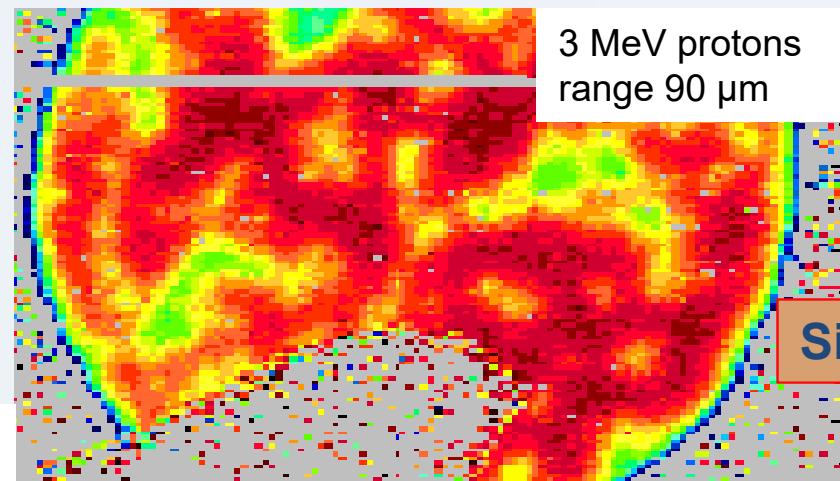
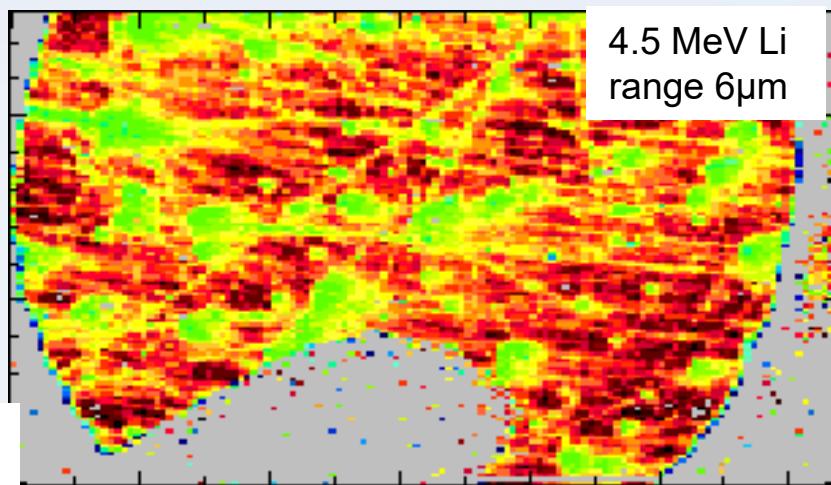


EFG silicon
Schotky diode

Frontal IBIC images can identify
distribution of electrically active defects !

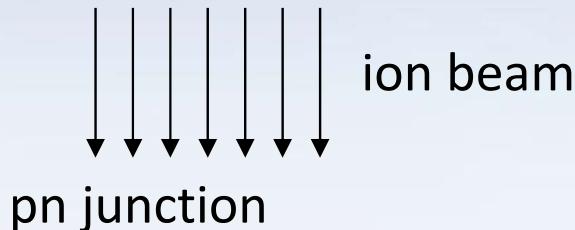
Ion beam induced charge

Frontal IBIC

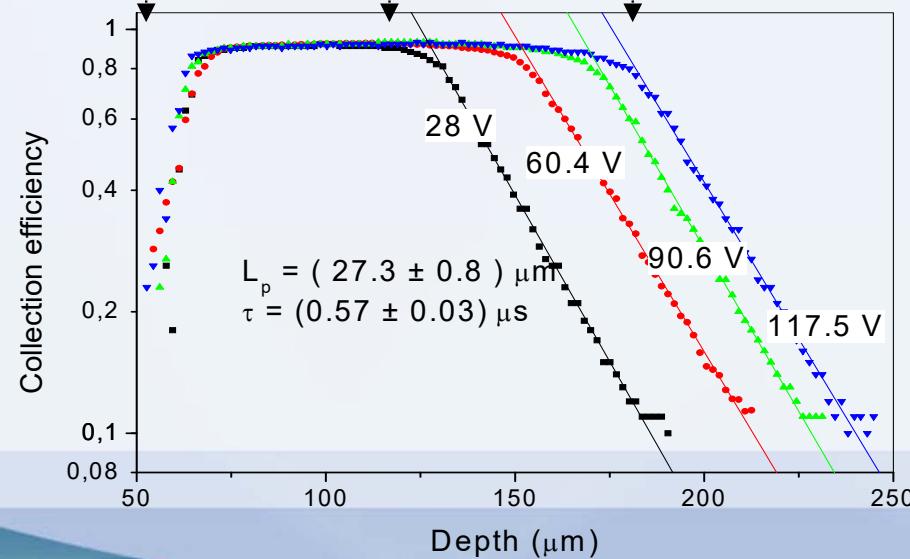
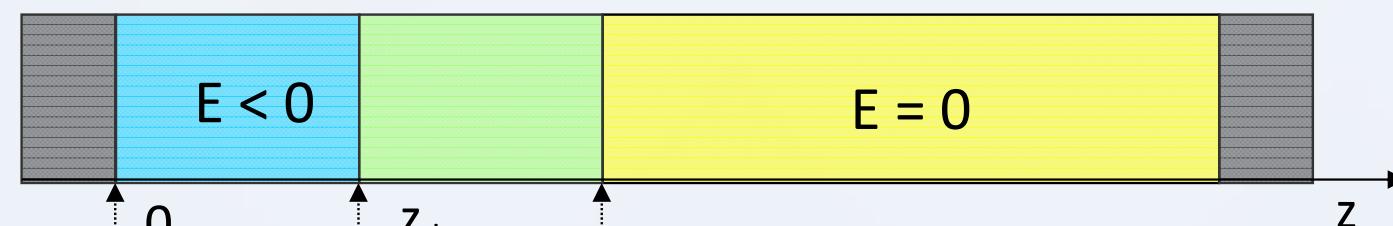


Ion beam induced charge - IBIC

contact and/or
heavily doped
region



Lateral IBIC on Si power diode

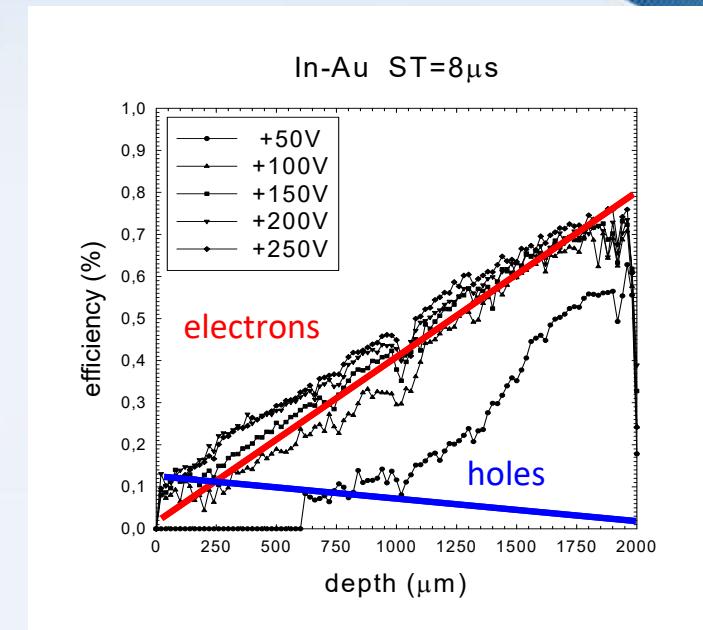
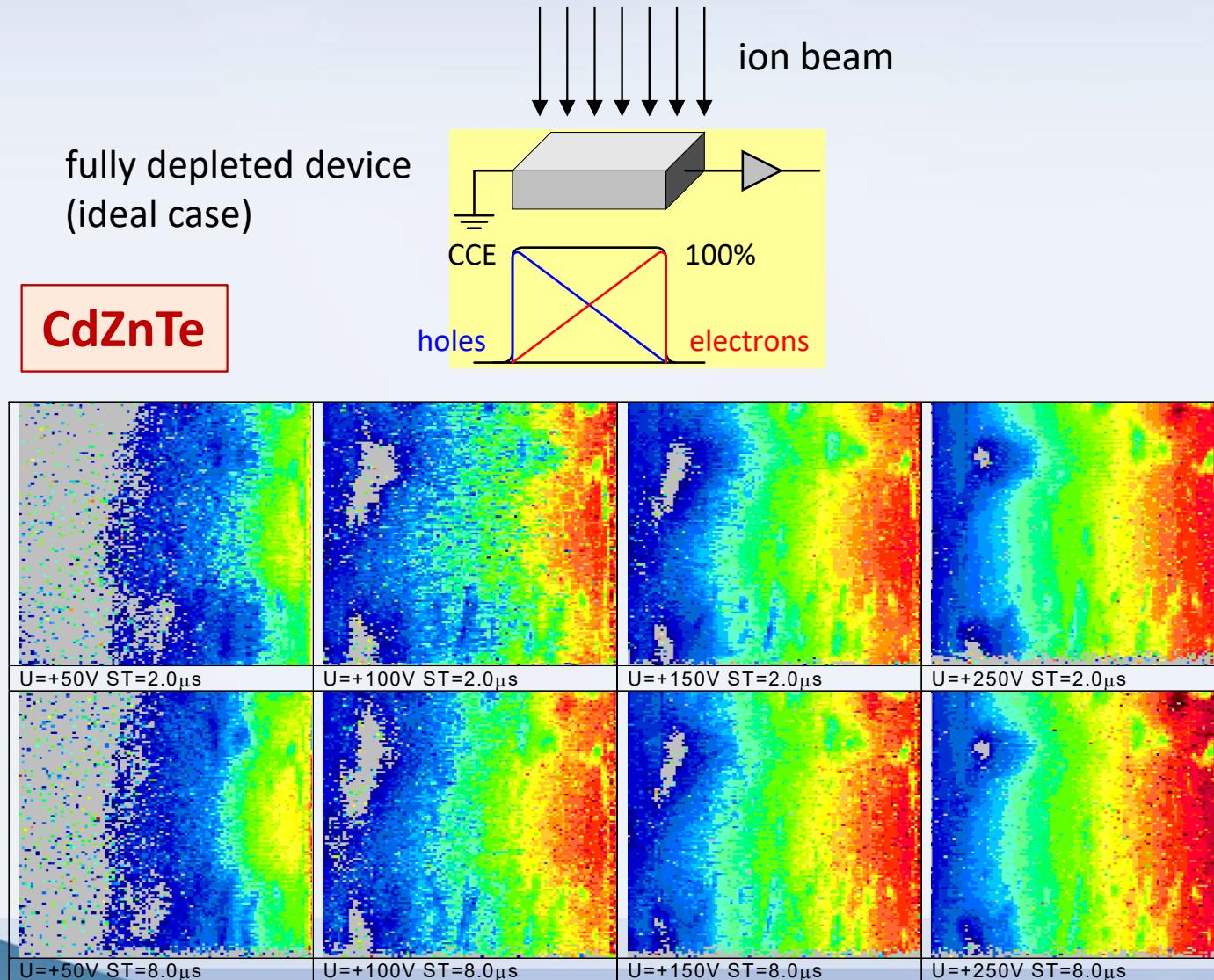


$$\eta(z < z_d) = 1$$

$$\eta(z > z_d) = \exp(-(z-z_d)/L_{p,n})$$

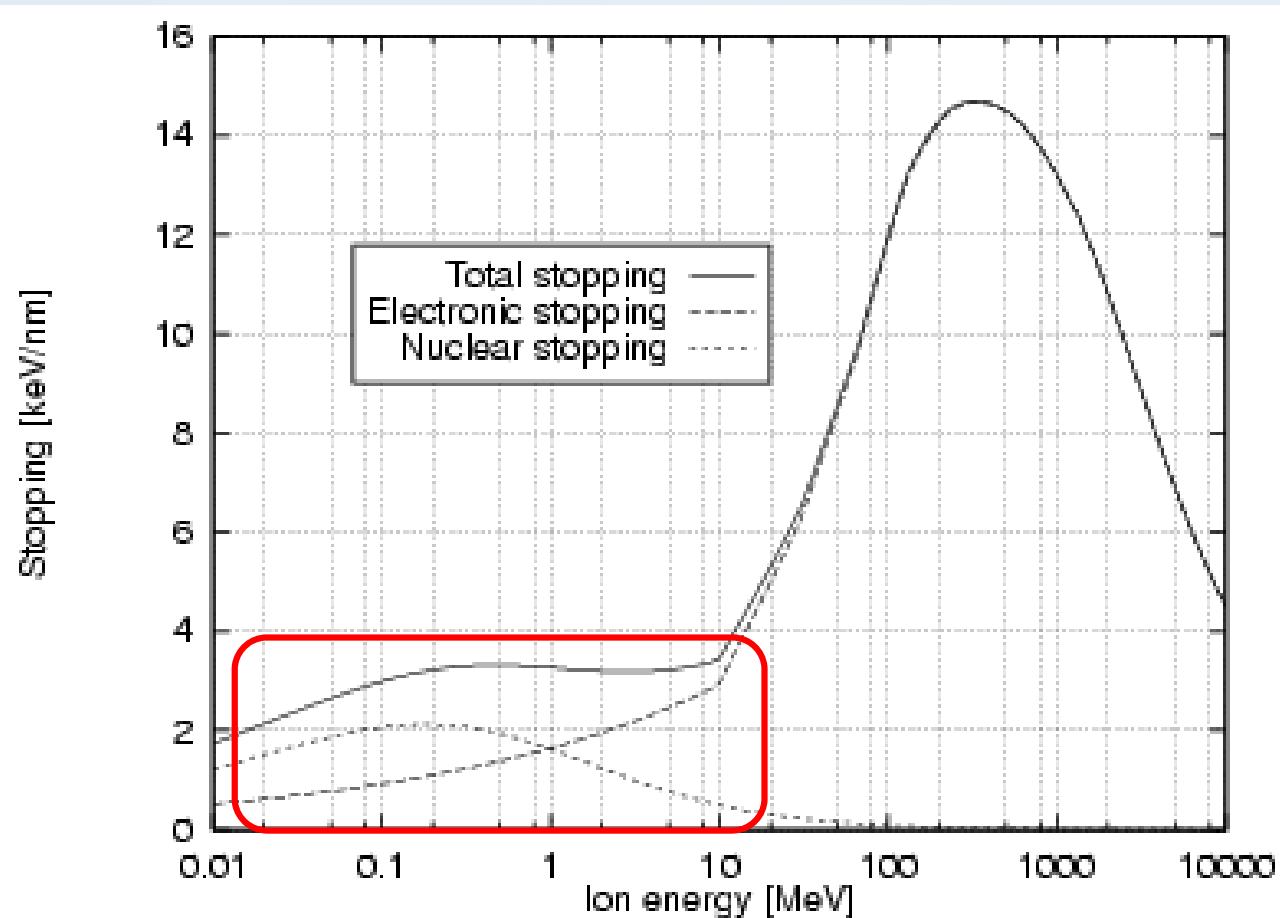
hole or electron
diffusion length

Ion beam induced charge - IBIC



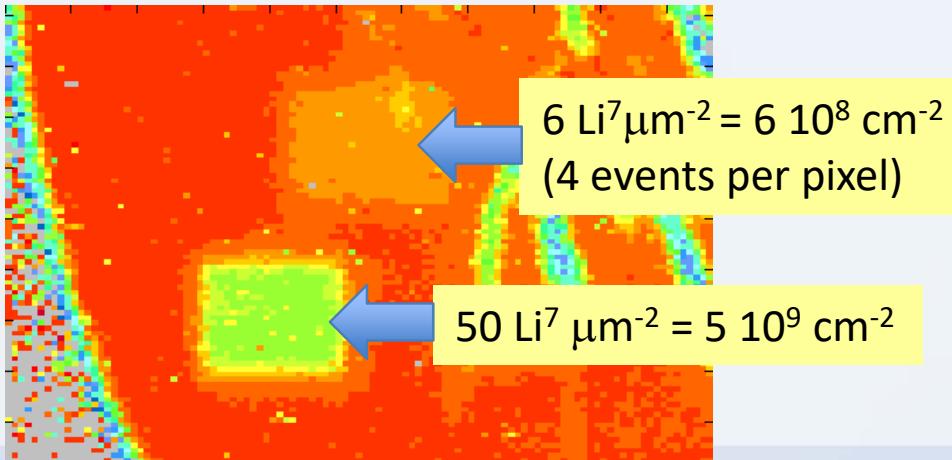
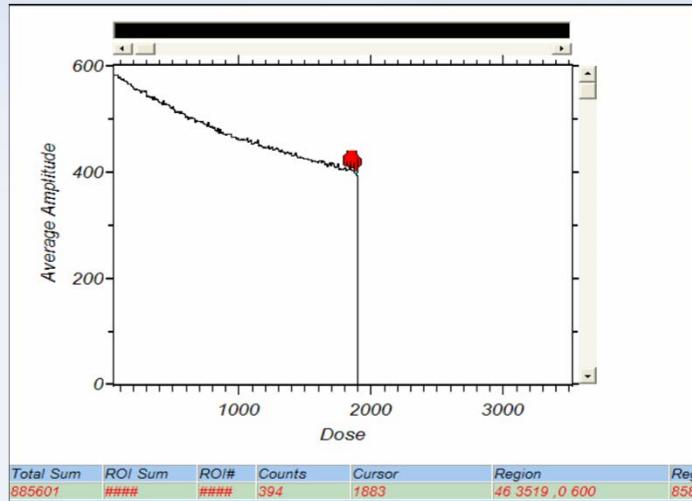
Ion beam induced damage

dE/dx – nuclear stopping

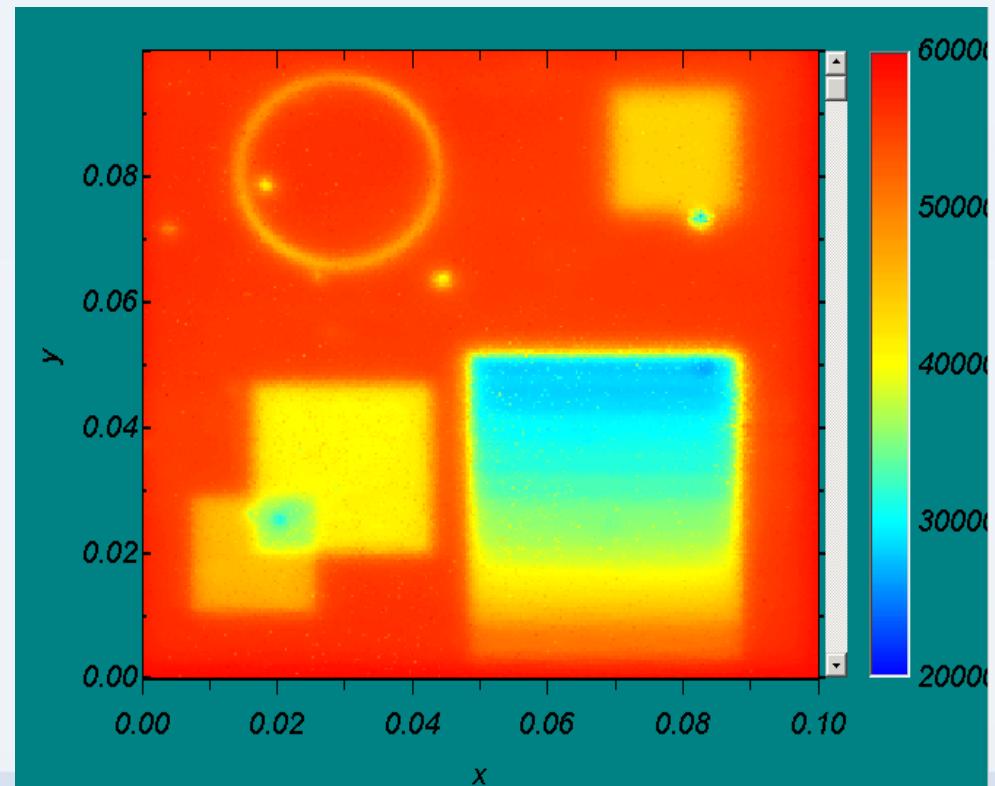


dE/dx of Xe ions in silicon

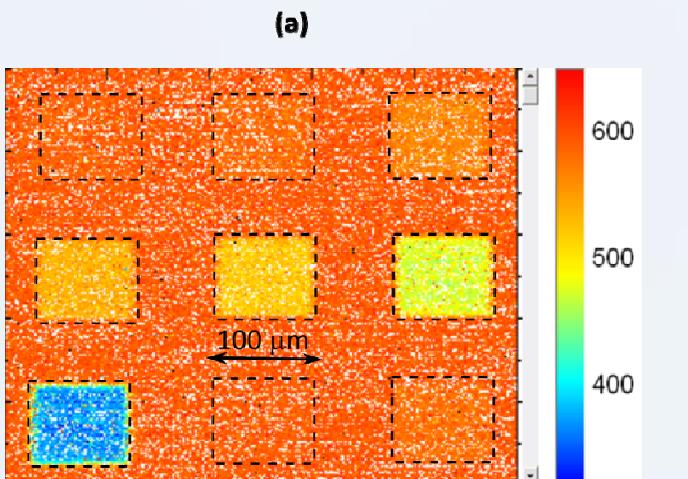
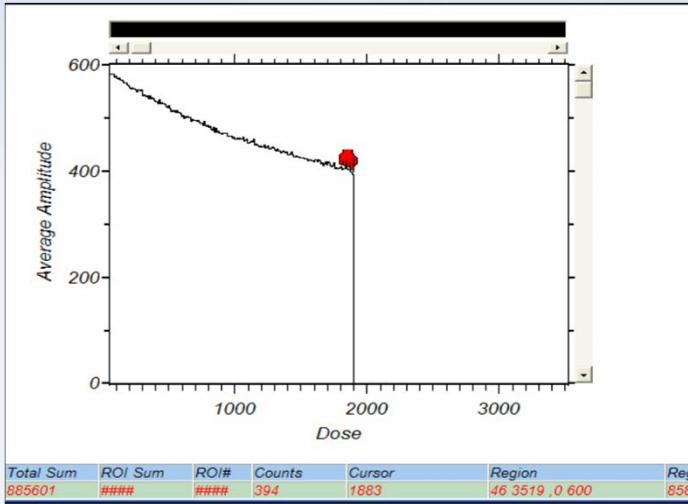
Ion microprobe irradiation & IBIC probing



- For 100% ion impact detection efficiency, IBIC can be used to monitor irradiation fluence
- Irradiation of arbitrary shapes
- On-line monitoring of CCE degradation



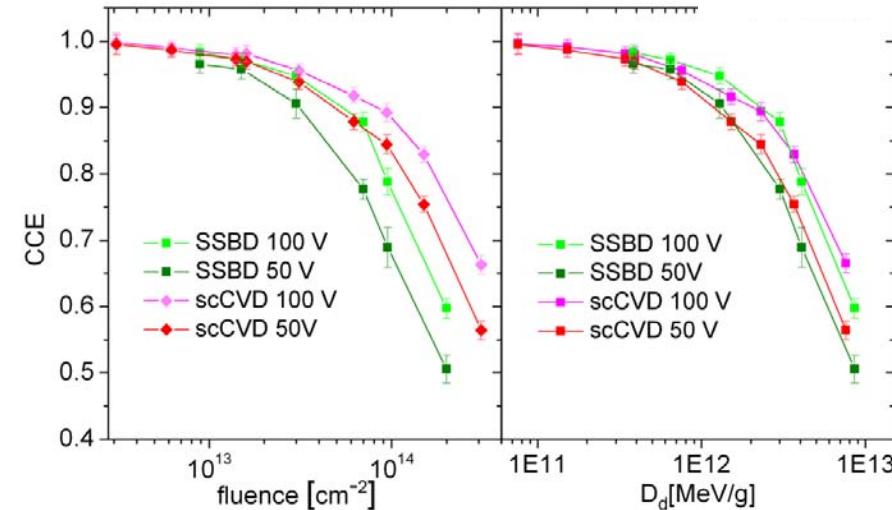
Ion microprobe irradiation & IBIC probing



- By excessive irradiation of small detector regions (e.g. $50 \times 50 \mu\text{m}^2$) induced defects (charge carrier traps) degrade charge collection efficiency (CCE)
- Irradiation fluence and CCE are continuously monitored on-line
- Damaging/probing concept can be used for radiation hardness tests (e.g Si vs. diamond)

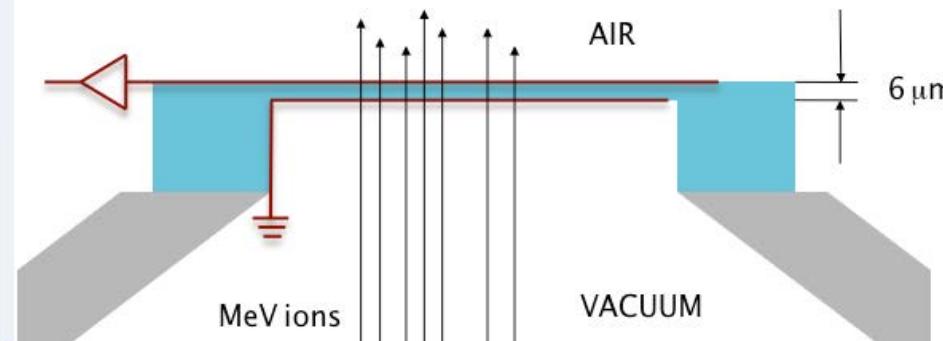
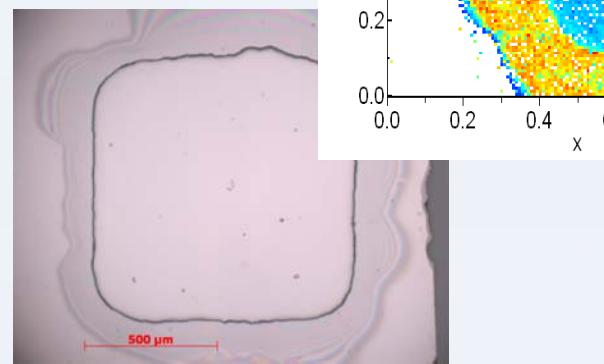
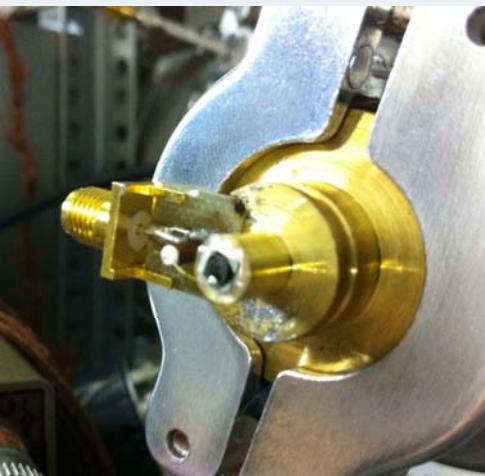


V. Grilj et al (RBI, JAEA)
Nucl. Instr. Meth. B306 (2013) 191

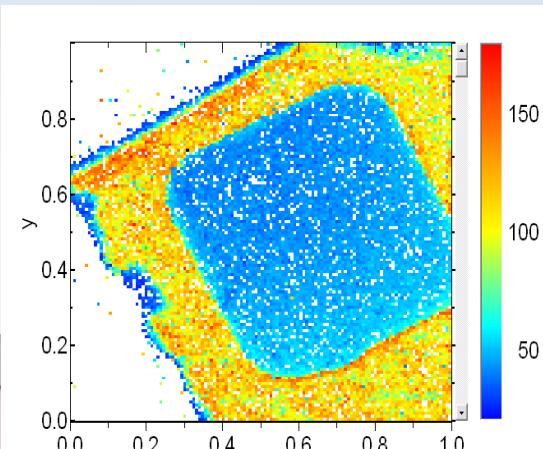


Ion beam induced charge - IBIC

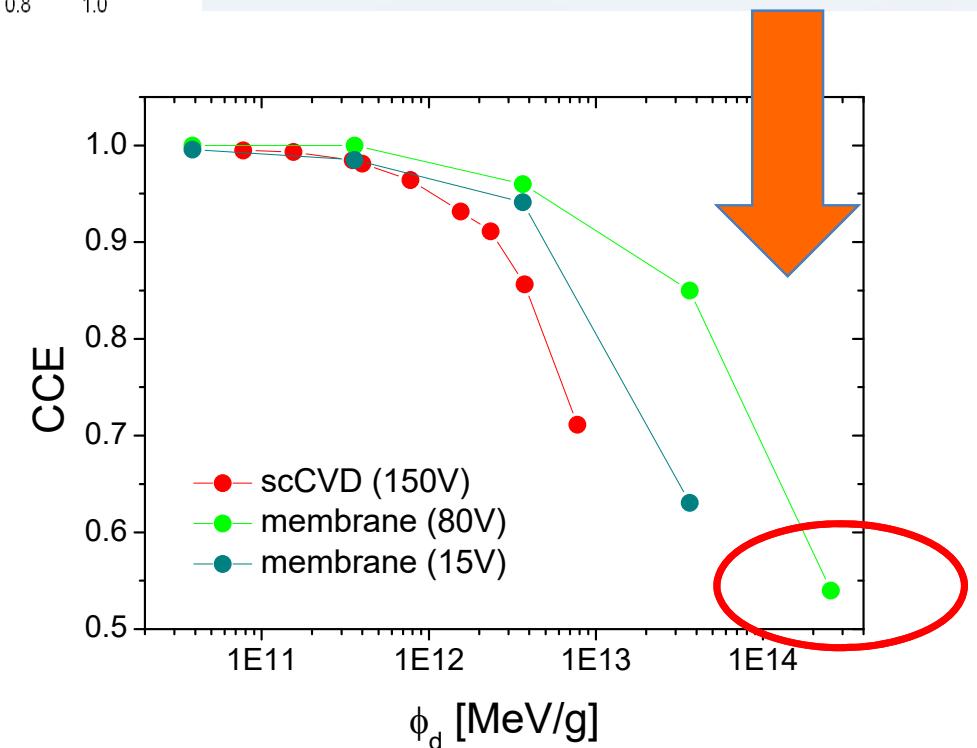
scCVD diamond membrane detector



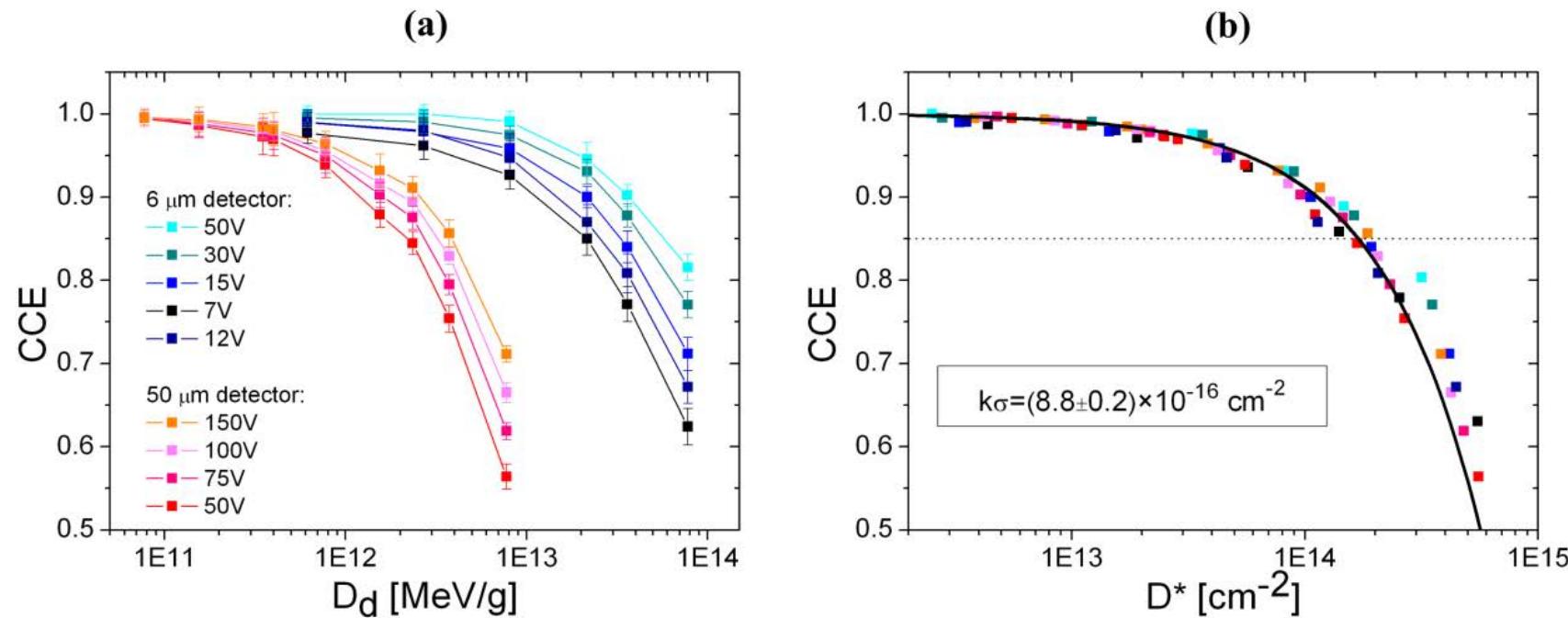
CVD diamond membrane provides a trigger for each single ion transmitted to the air



Extreme radiation hardness – equivalent of 10^{16} cm^{-2} of 1 MeV neutrons !!



Ion beam induced charge - IBIC

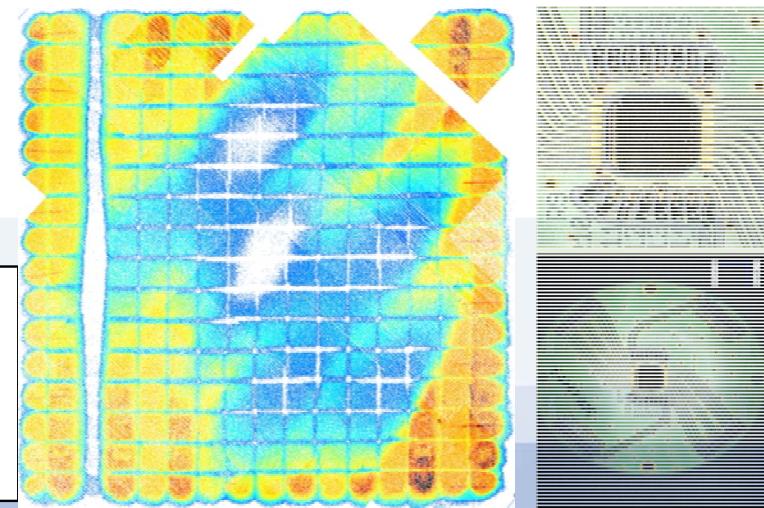


$$\text{CCE} = 1 - D^* k\sigma$$

$k\sigma$ je svojstvo materijala
 D^* efektivna doza

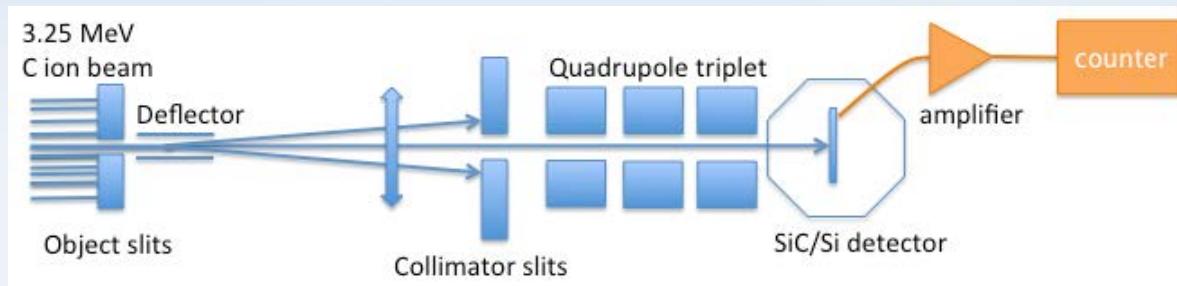
Zaključak da je otpornost na zračenje silicija i dijamanta vrlo slična !

Diamond: V. Grilj et al, Nucl. Instr. Meth. B372 (2016) 161
 Silicij: Ž. Pastuović et al, Appl. Phys. Lett. 98 (2011) 092101

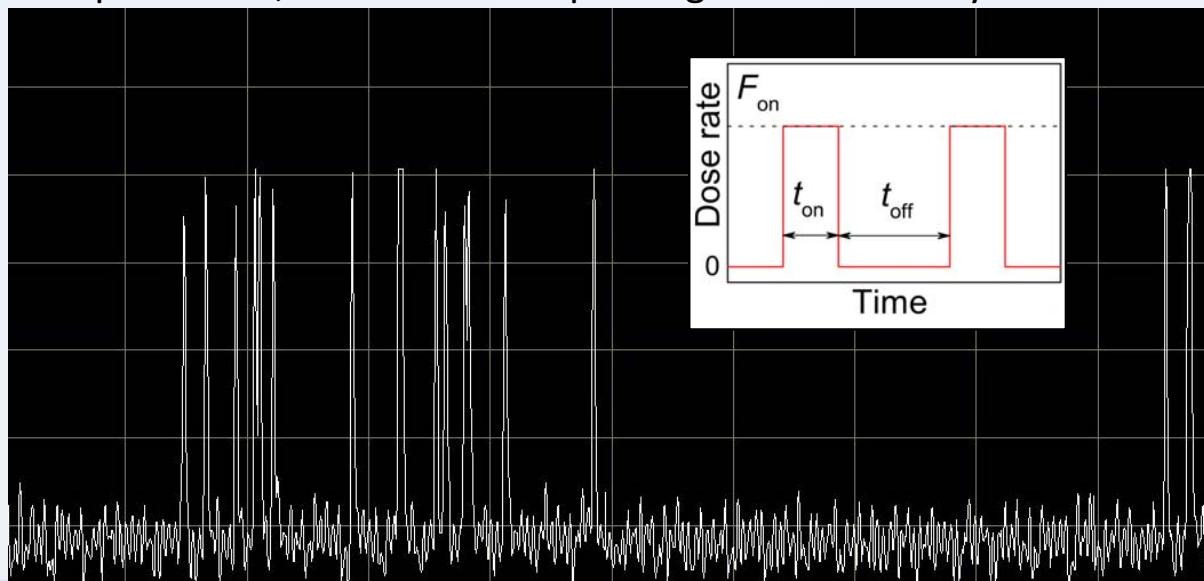


Probing the defect creation process (Si and SiC)

Pulsed beam



System is typically used for MeV SIMS & single ion implantation, irradiation and probing is controlled by SPECTOR



Samples:

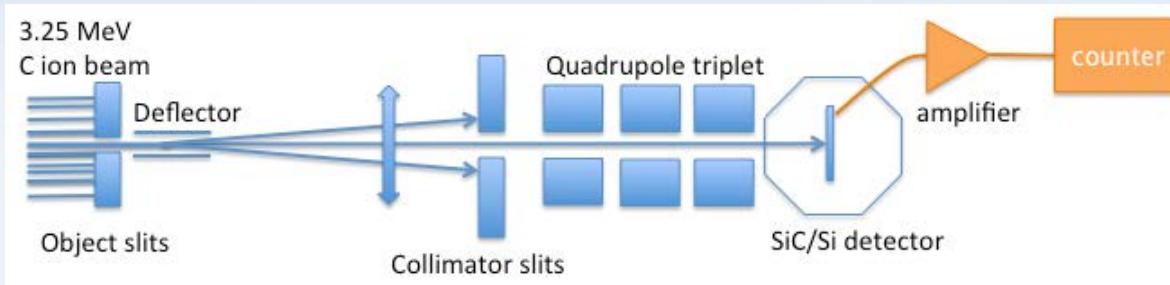
- Si PIN diode Hammamatsu S1223
- 4H-SiC Schottky diode

Irradiation and IBIC probing:

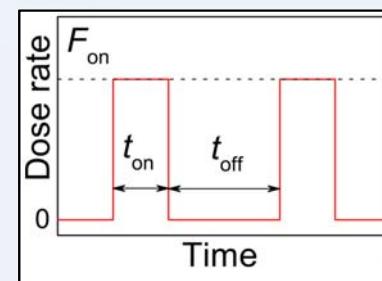
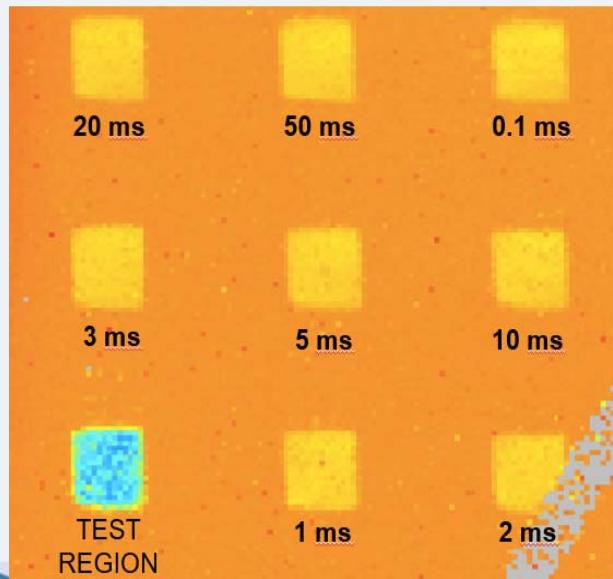
- 3.25 MeV C ions (both irradiation and IBIC probing)
- Ion range 3.5 μm in Si (as for 1 MeV He ions)
- $t_{\text{on}} = 1 \text{ ms}; t_{\text{off}} = 0.1 \text{ to } 50 \text{ ms}$
- fluence:
346 μm^{-2} (Si)
33 μm^{-2} (SiC)
- 400 pulses

Probing the defect creation process (Si and SiC)

Pulsed beam



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Samples:

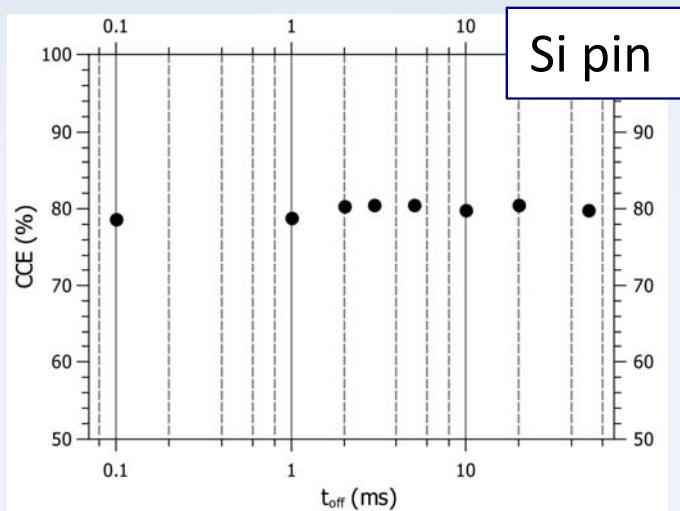
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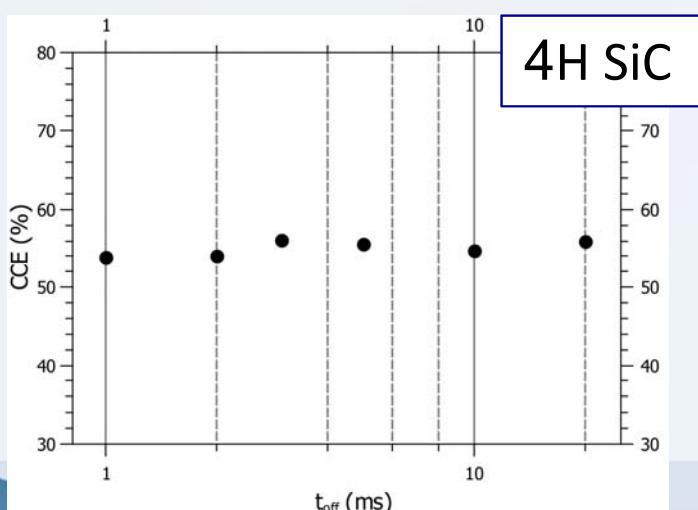
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- 400 pulses

Probing the defect creation process (Si and SiC)

Pulsed beam



No statistically significant changes have been observed for different $t_{\text{on}}/t_{\text{off}}$ cycles (millisecond range)



Average distance between ions within a single pulse was
 $> 1 \mu\text{m}$ too large for 'dynamic annealing' of defects

Irradiation and IBIC probing:

- 3.25 MeV C ions (both irradiation and IBIC probing)
- Ion range 3.5 μm in Si (as for 1 MeV He ions)
- $t_{\text{on}} = 1 \text{ ms}; t_{\text{off}} = 0.1 \text{ to } 50 \text{ ms}$
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 346 μm^{-2} (Si)
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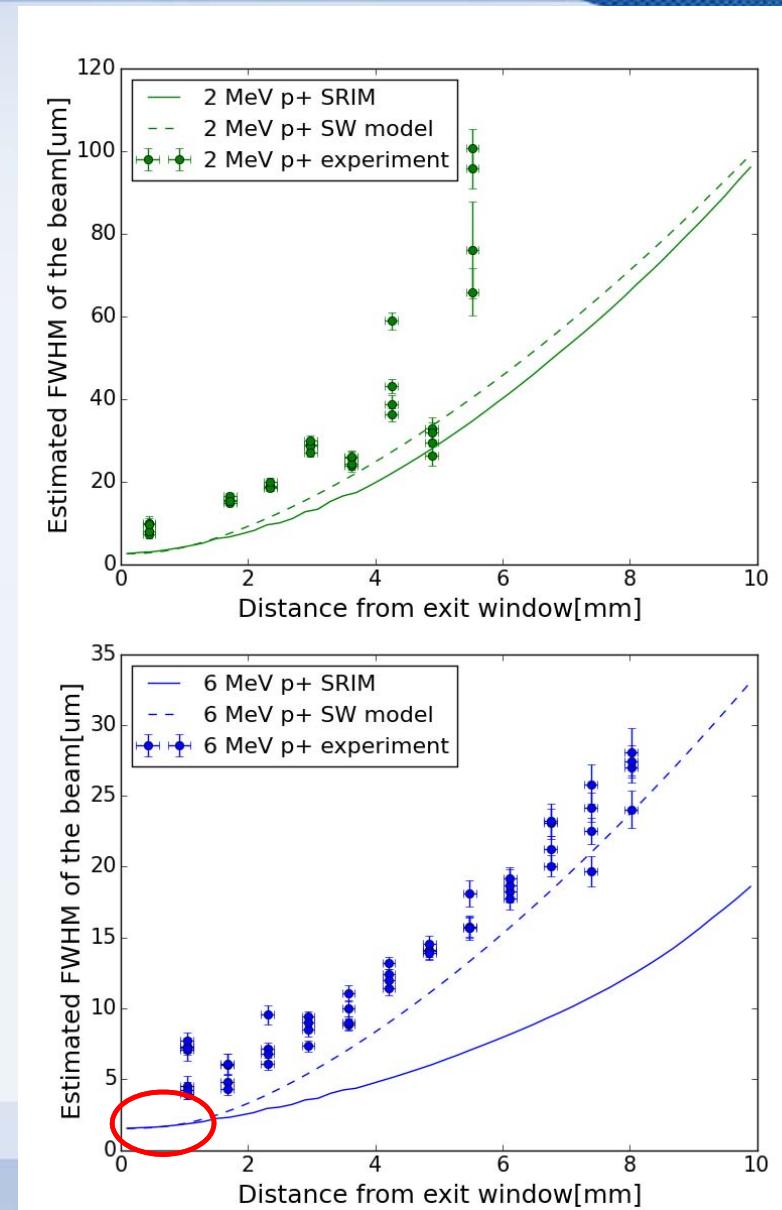
In air IBIC experiment

- Large detector structures (e.g. high energy physics detectors) can not be tested in small vacuum chamber
- Alternative – in air microbeam !
- But - beam spot degradation

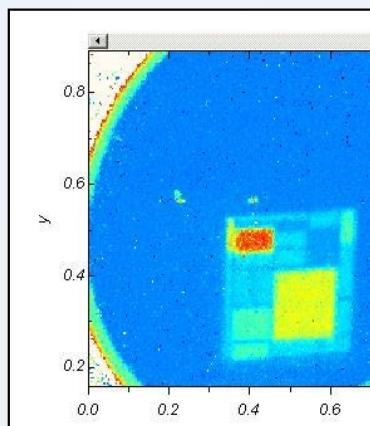
Energy / air path	100 nm Si ₃ N ₄	6 μm diamond
3 MeV / 0.5 mm	1.02	9.0
3 MeV / 2.0 mm	4.39	30.6
6 MeV / 0.5 mm	0.50	4.3
6 MeV / 2.0 mm	2.06	14.8
9 MeV / 0.5mm	0.34	2.9
9 MeV / 2.0 mm	1.40	9.9

Degradation of beam spot (in micrometers) for SiN and diamond exit foil

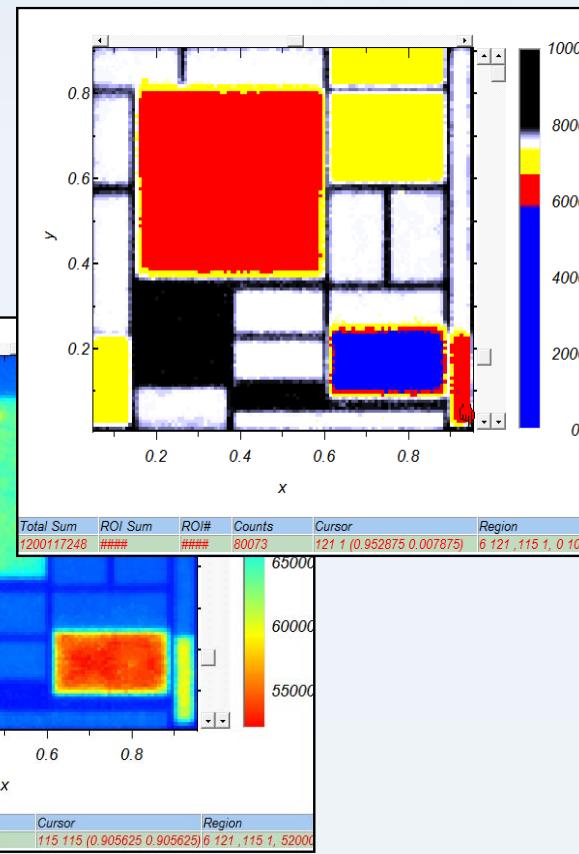
- SOLUTION:
 - SiN exit foil
 - up to 2 mm working distance
 - Proton energy > 6 MeV !!



Si pin diode



Total Sum	ROI Sum	ROI#	Counts	Cursor	Region
1566492145	#####	#####	0	255 40 (0.980475 0.15688)	[]



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

Total Sum	ROI Sum	ROI#	Counts	Cursor	Region
1200117248	####	####	78466	115 115 (0.905625 0.905625)	6 121 , 115 1 , 52000

