Physikalisch-Technische Bundesanstalt
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Challenges in track structure nanodosimetry

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Outline:

- definition of quantities
- instrumentational / experimental aspects
- measurements

Instrumentational aspects

Goal: experimentally access the ionization cluster size distribution of ionizing particles (here: ions) in a DNA-segment

How : count all ionizations produced by a single ionizing particle in a volume element of the size of a DNA-segment for a large amout of ionizing particles

- no detection of single ionization events in solid or liquids
  → replace liquid water cylinder (DNA-segment) with low pressure gas volume
  density: 1 g/cm^3 → 1 µg/cm^3 ; **dimension:** nm → mm

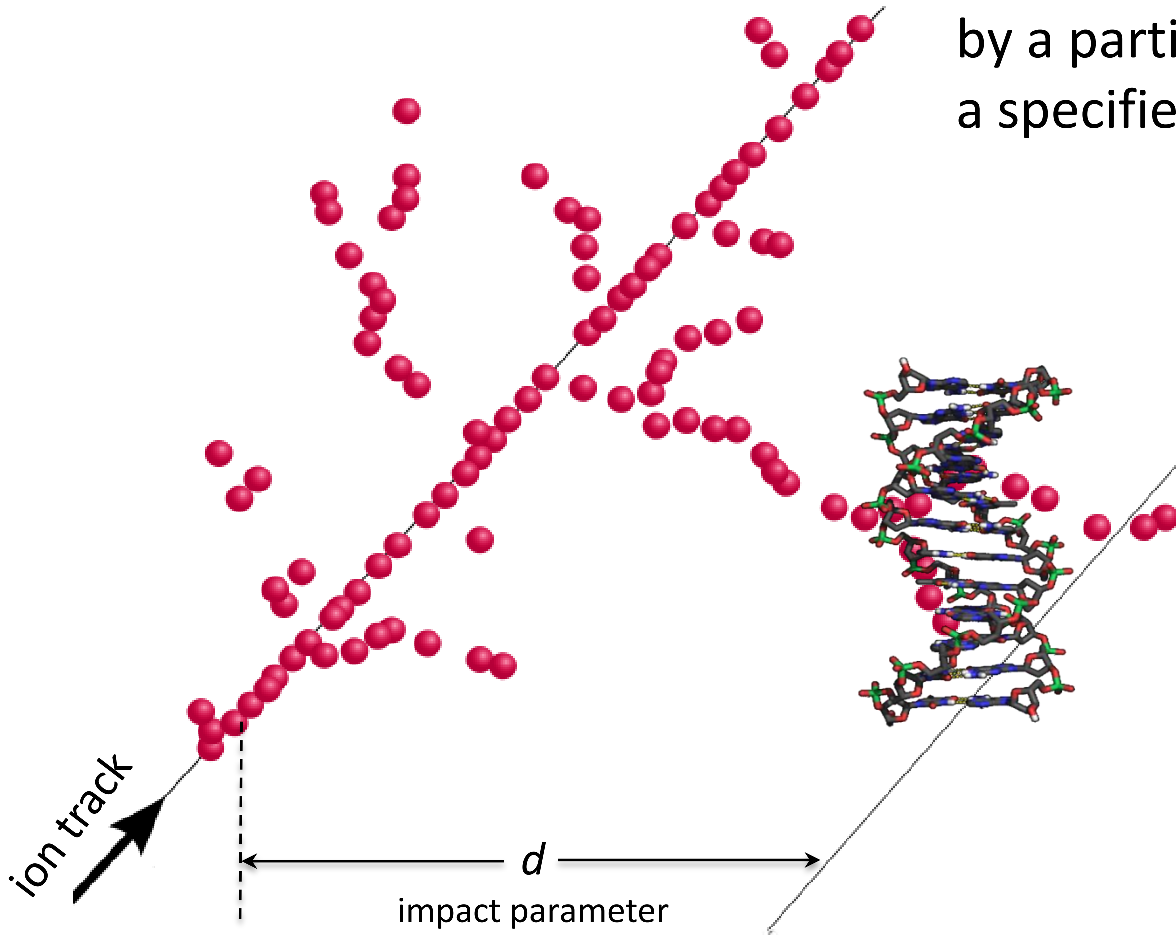
- drift the ionized gas molecules away from particle track, separate them in time and extract them from the interaction volume

- establish a correlation between the collected target gas ions and the ionizing particle
  → trigger data acquisition by primary particle

- count all collected ionized gas molecules before next primary particle trigger
  → single primary event measurement

- repeat this over and over again …

Nanodosimetric quantities



ionization cluster size:

Number ν of ionizations produced by a particle (radiation quality $\boldsymbol{Q}$) in a specified piece of matter.

distribution:

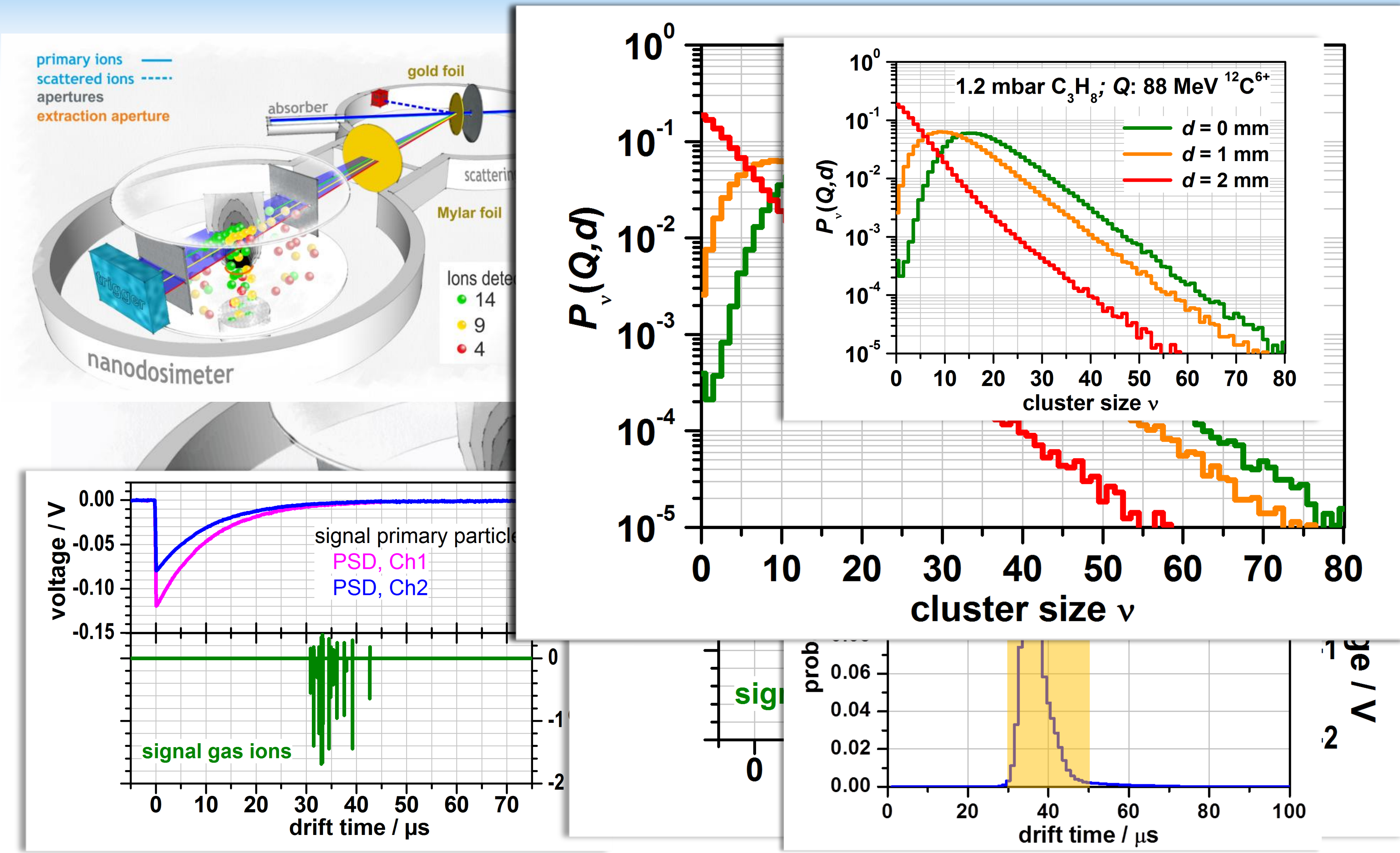
$P_\nu(Q)$ is the probability of producing an ionization cluster of size ν.

moments:

$$M_i(Q) = \sum_{\nu=0}^{\infty} \nu^i \cdot P_\nu(Q)$$

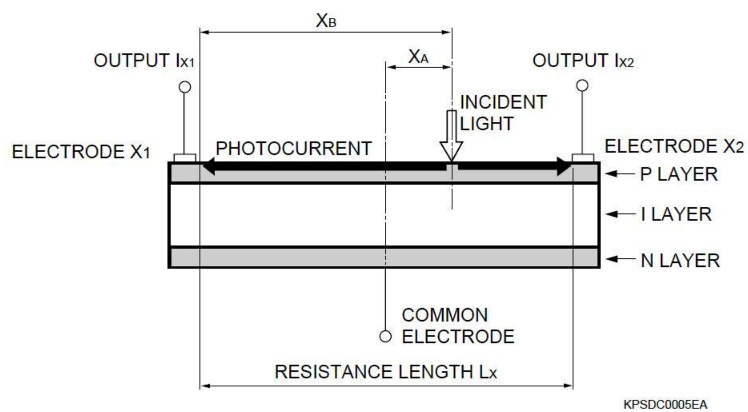
is the i-th moment of $P_\nu(Q)$

Experimental setup

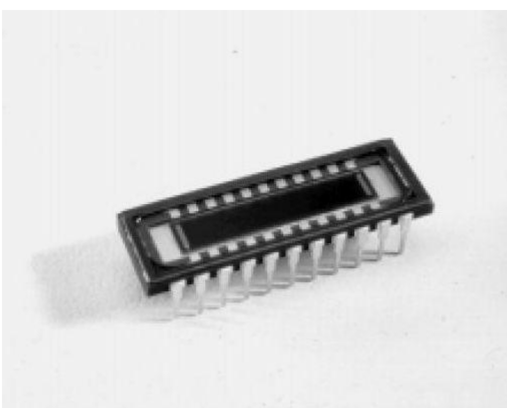


Position sensitive detection

Figure 1-1 PSD sectional view



Courtesy: Hamamatsu Photonics K.K.

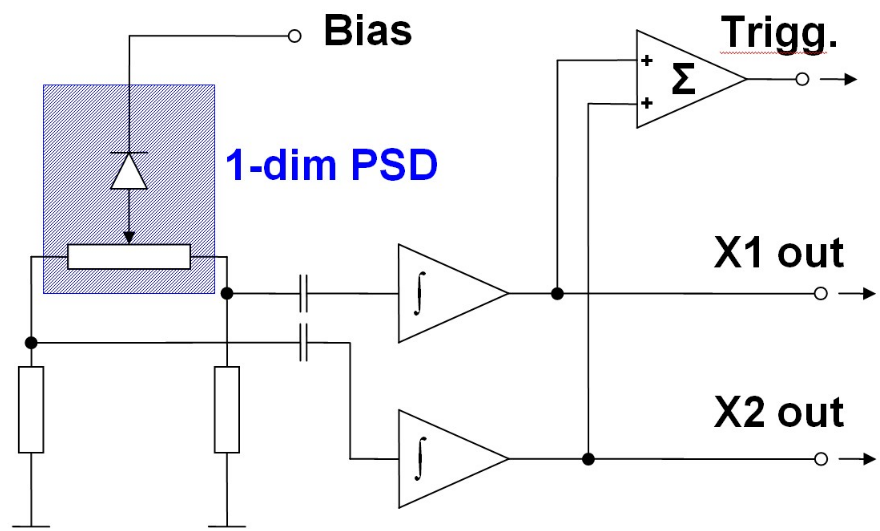


Courtesy: SiTek Electro Optics AB

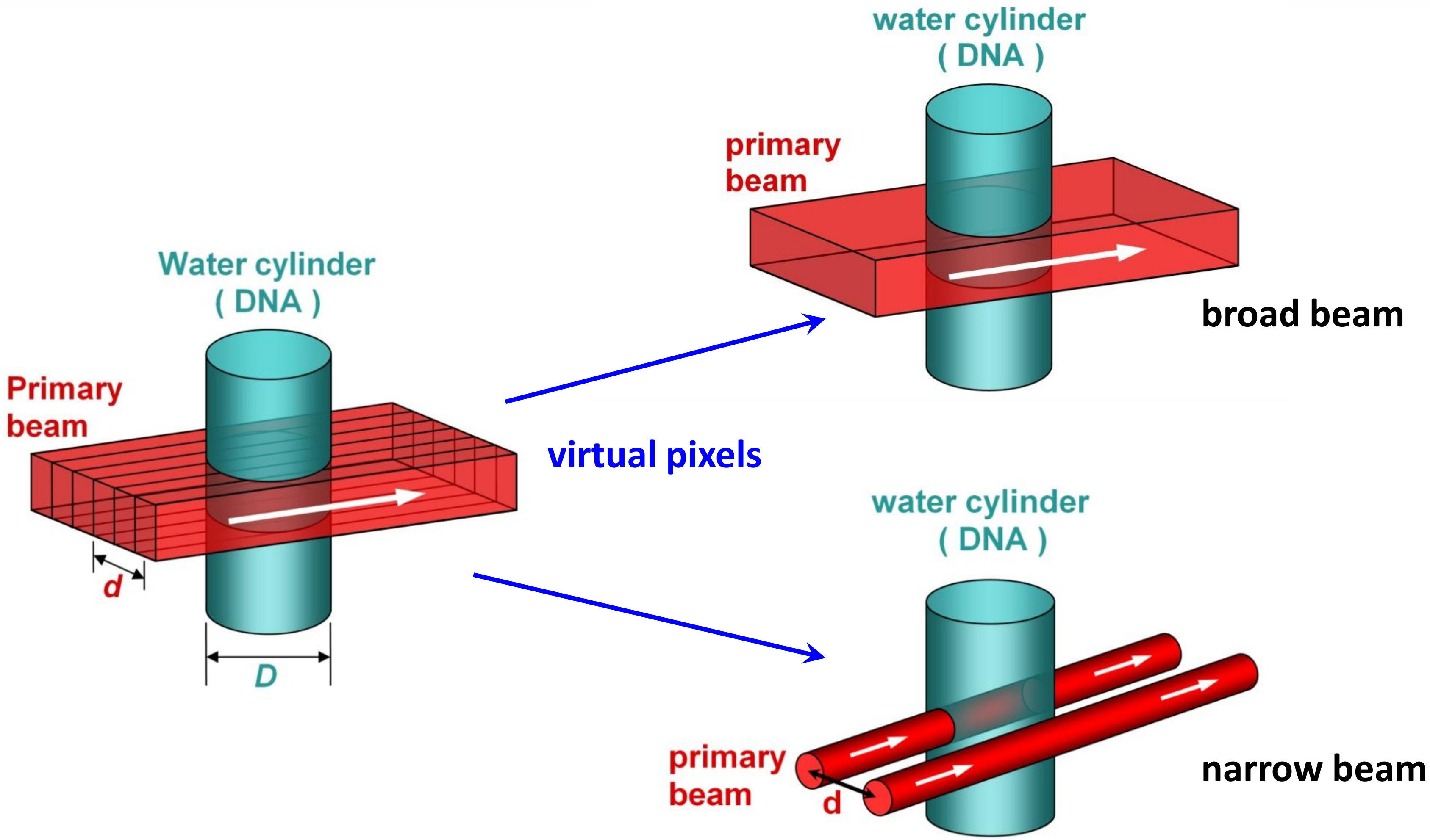
Output currents are inversly proportional to the distance: incident light – electrode $X_{1/2}$

Position due to current distribution:
$X_A = 0{,}5\ L_X\ (\ I_{X1} - I_{X2}\ )\ /\ (\ I_{X1} + I_{X2}\ )$

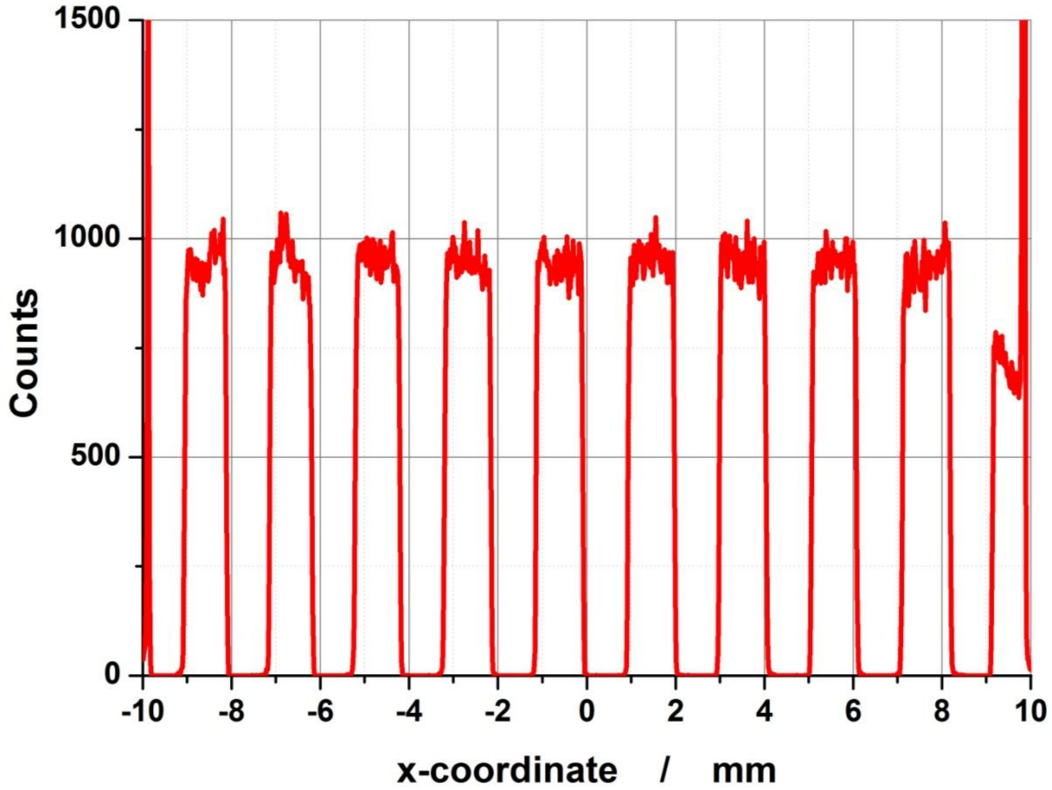
Circuit for charged particle detection



Irradiation geometry



Characterisation PSD

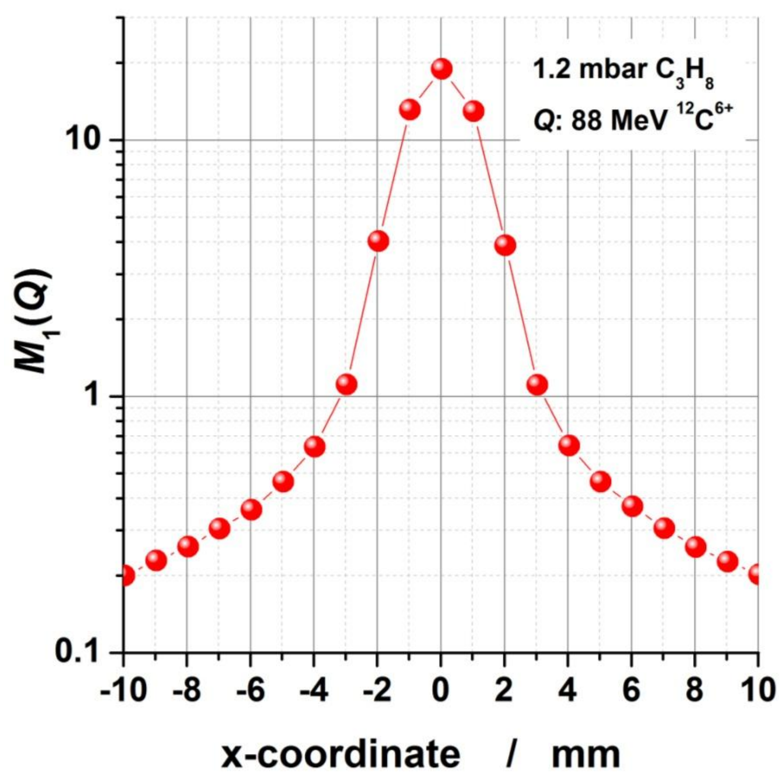


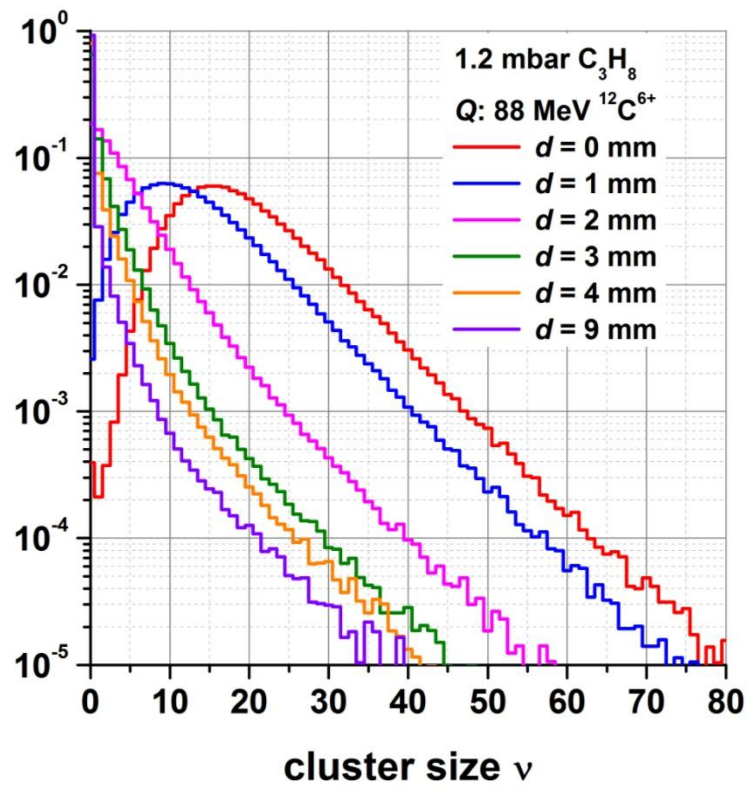
measurement with grid:
width strip: 1 mm
width slit: 1 mm
43 MeV $^{12}C^{6+}$-ions
„virtual pixel size“: 20μm

result:
resolution (mean): 62 μm
range: -9.4 mm – 8.7 mm

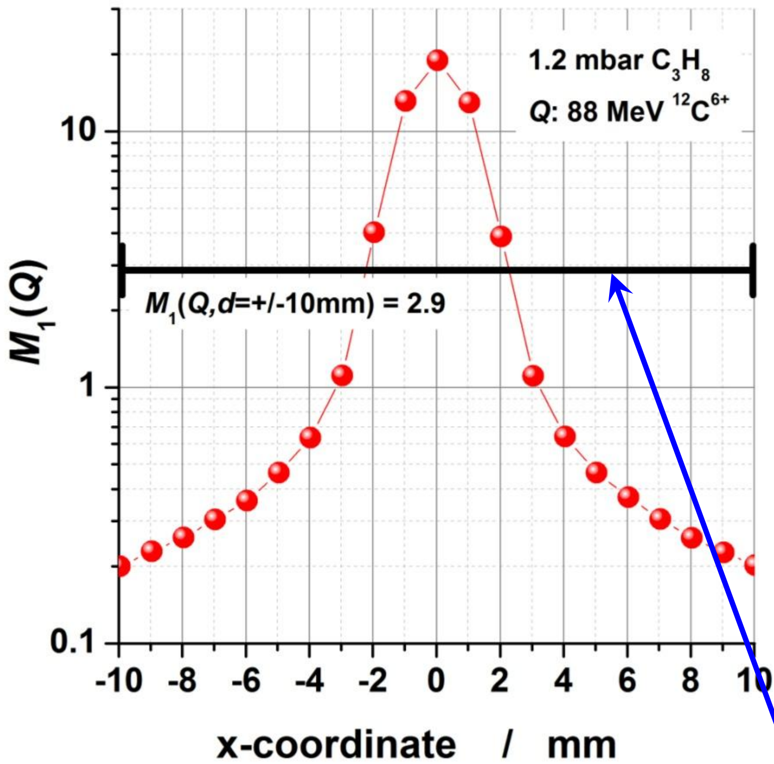
nonlinearity: 0.077 (±10 mm)
0.043 (±7 mm)

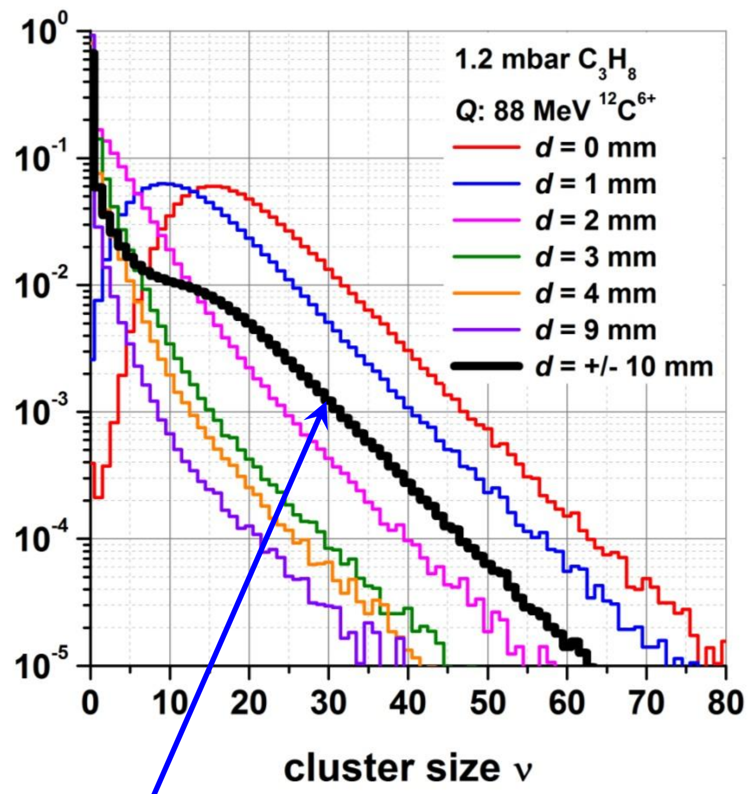
Ionization clusters; narrow beam





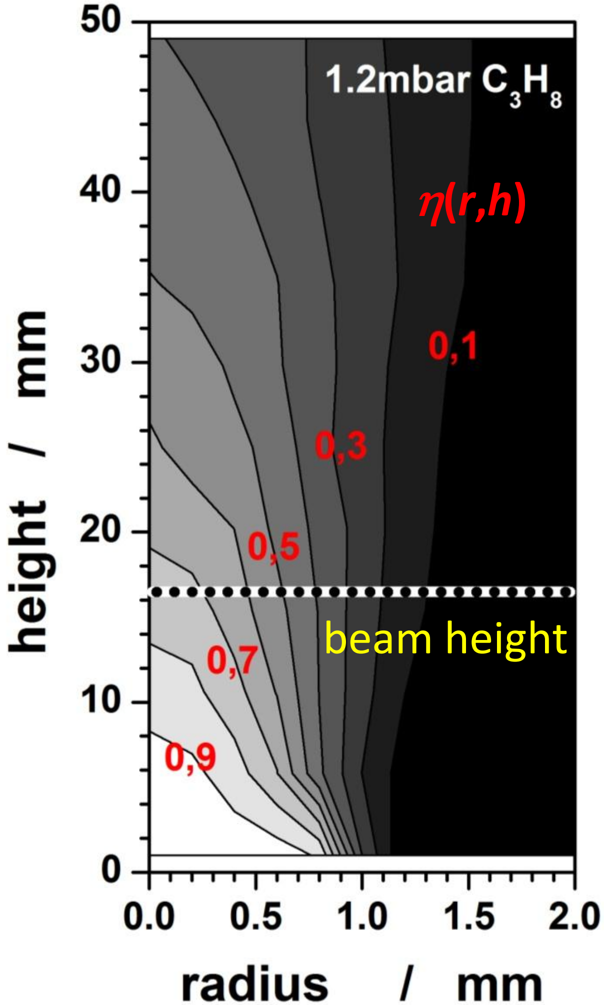
Ionization clusters; narrow + broad beam





broad beam geometry

Radius sensitive volume



detection efficiency η is position dependent:
$\eta(r,h)$ (radius r, height h)

radius r_{eff} of sensitive volume in height h
= radius of cylinder with $\eta = 1$, for which $\eta_{cyl} = \eta_{SV}$

= detection efficiency integrated along particle track

for 1.2 mbar C_3H_8 in nominal beam height:

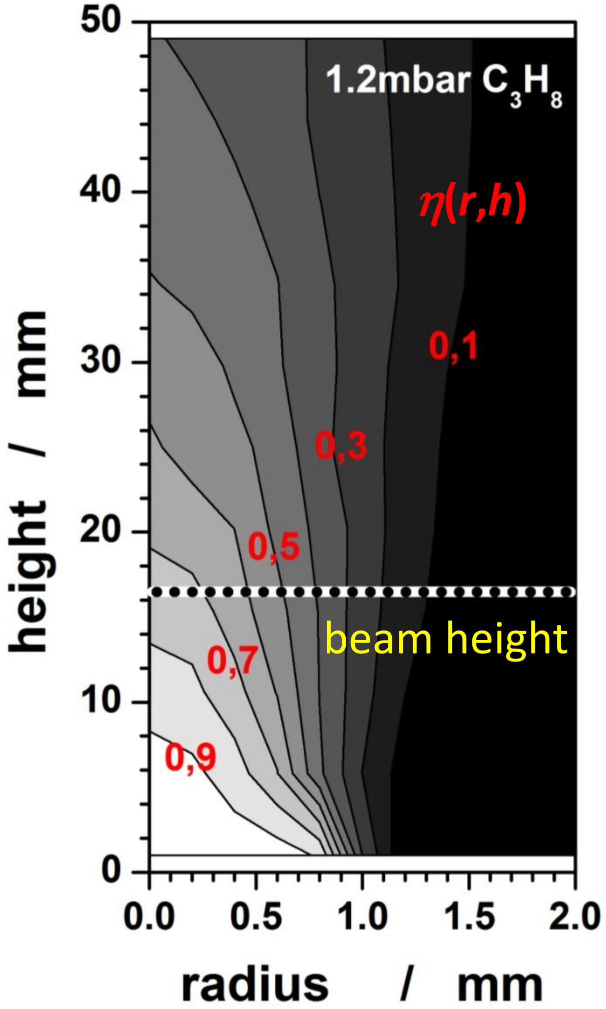
$$r_{eff}(h = 16.25\,\text{mm}) = \int_{r=0}^{l} \eta(r, h = 16.25\,\text{mm}) \cdot dr = 0.6\,\text{mm}$$

$$\triangleq 0.135\,\mu\text{g/cm}^2$$

for 1.2 mbar N_2 in nominal beam height :

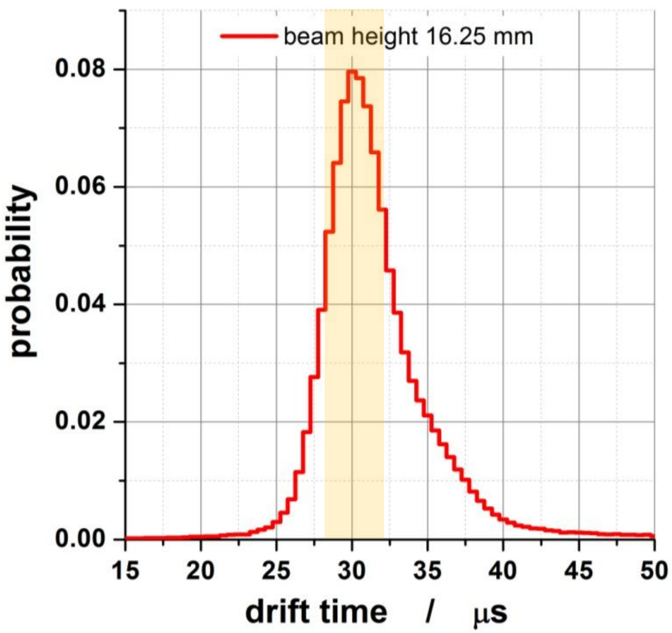
$r_{eff} = 0.46$ mm $\triangleq 0.068\ \mu g/cm^2$

Height sensitive volume

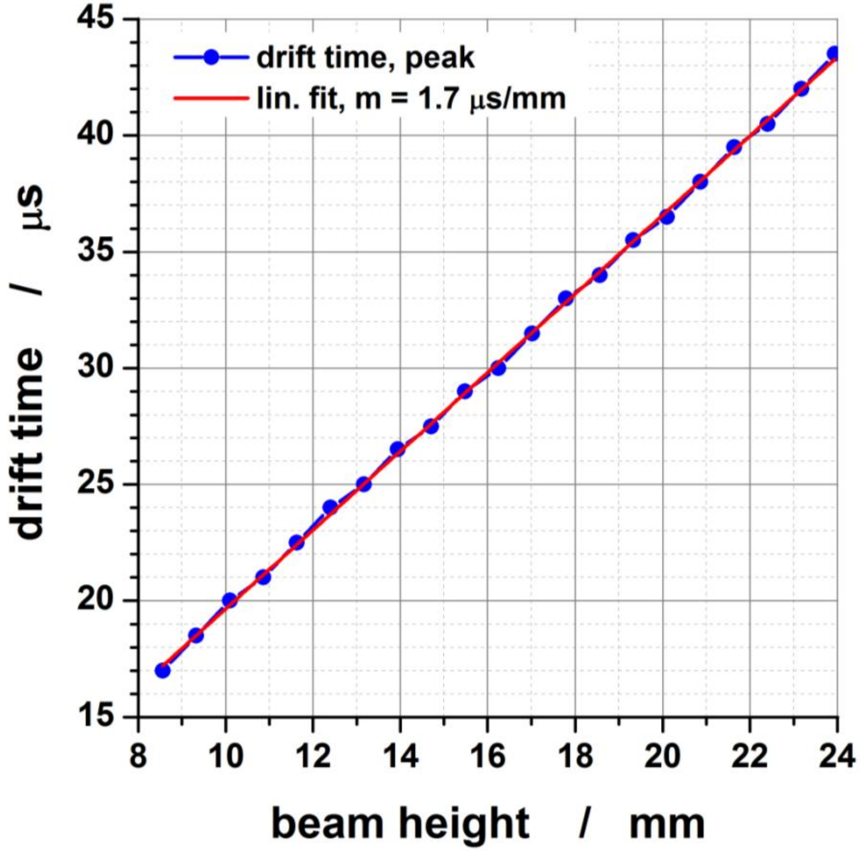


total height of sensitive volume: 50 mm

reduction of effective height of sensitive volume possible by reduction of the drift time window for the target gas ions



Height sensitive volume



slope drift time: 1.7 µs/mm

drift time window: ± 2.5 µs
→ ± 1.45 mm

detection efficiency $\eta(r,h) \cong 0{,}7$
($r = 0 - r_{eff}$, h = 14.8 mm – 17.7 mm)
h_{eff} = 2 mm

for 1.2 mbar C_3H_8 in nominal beam height:
$h_{eff} \hat{=} 0.46\ \mu g/cm^2$

Ionization clusters; physical / biological aspects

physics: take into account all primary particles (events), including those which do not interact

→ $P_\nu(Q,d)$ for all ν ($\nu = 0, \ldots, \infty$)

$P_\nu(Q,d)$ reflects the (absolute) track structure of the radiation quality Q

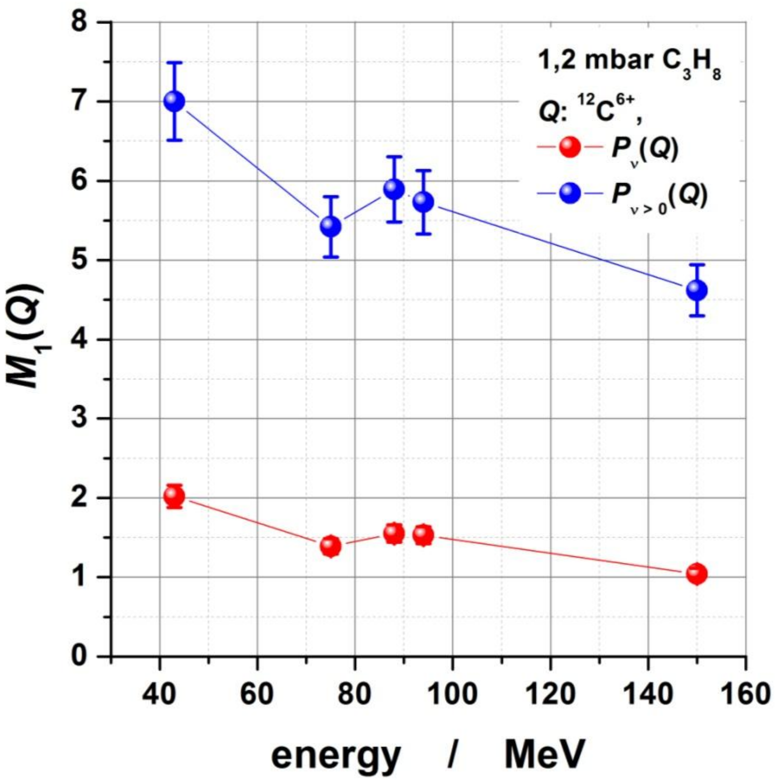
biology: all primary particles which do not interact (i.e. events with cluster size $\nu = 0$) do not produce a biological damage, i.e. they have no biological effect
take into account only events with at least one interaction (here: ionization), i.e. events with cluster size $\nu > 0$

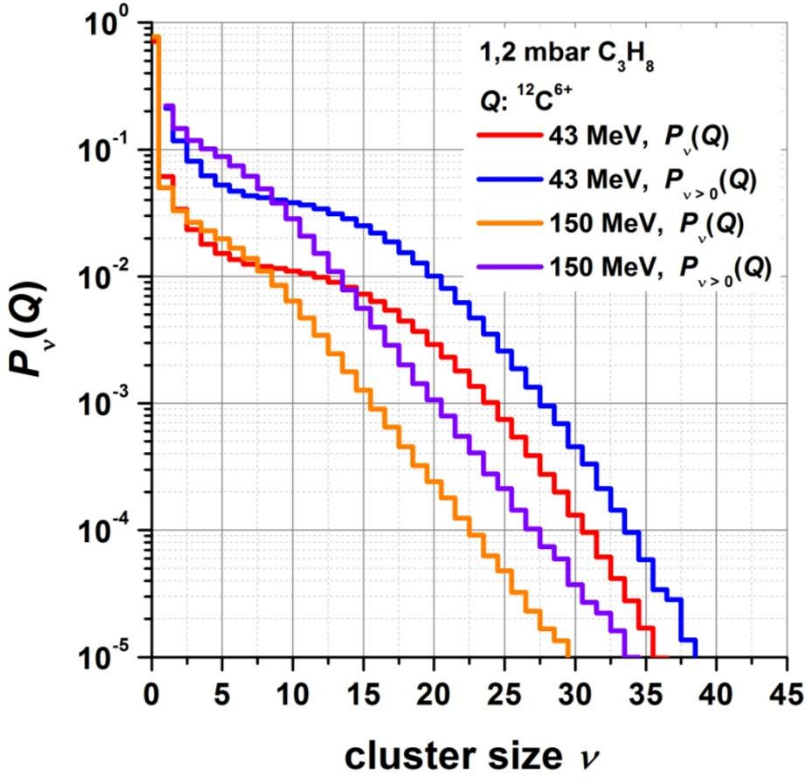
→ $P_\nu(Q,d)$ for all $\nu > 0$ → $P_{\nu>0}(Q,d)$

$P_{\nu>0}(Q,d)$ reflects the (relative) distribution of damages (ionizations > 0) of the radiation quality Q

Ionization clusters; broad beam

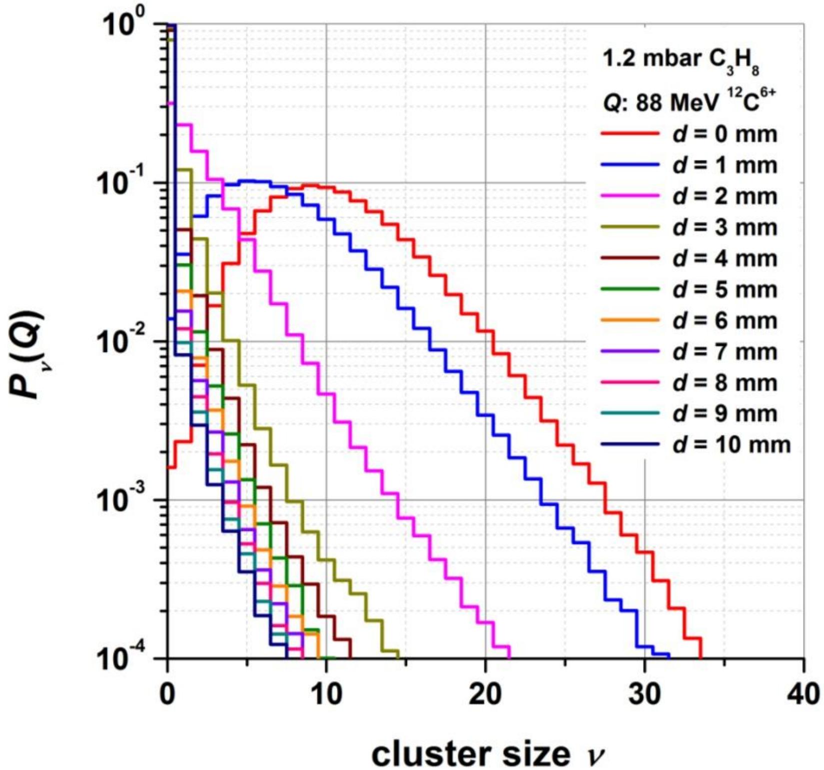
$P_{\nu>0}(Q)$ vs. $P_{\nu}(Q)$

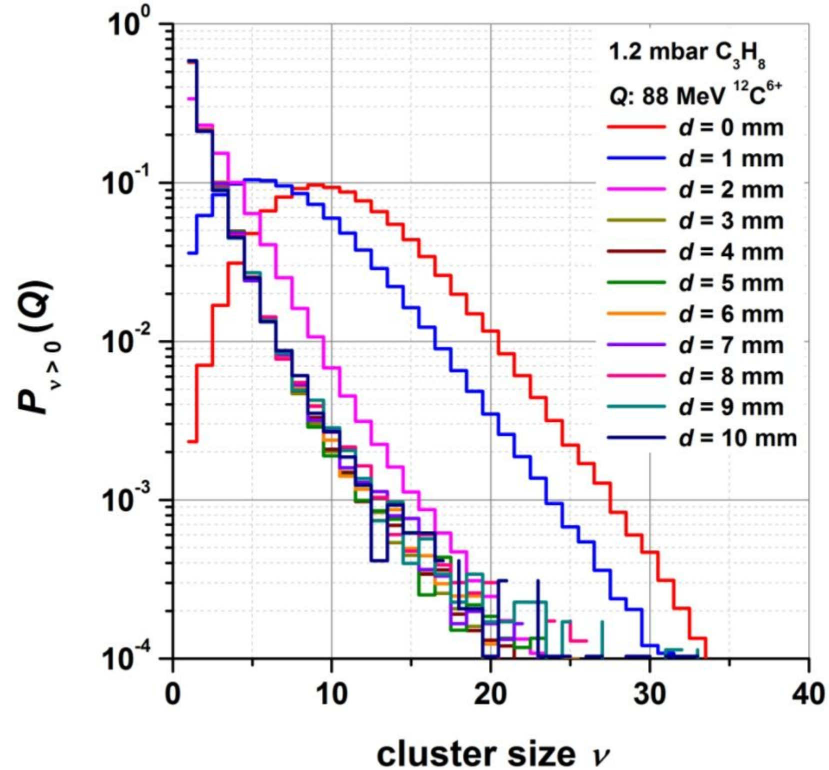




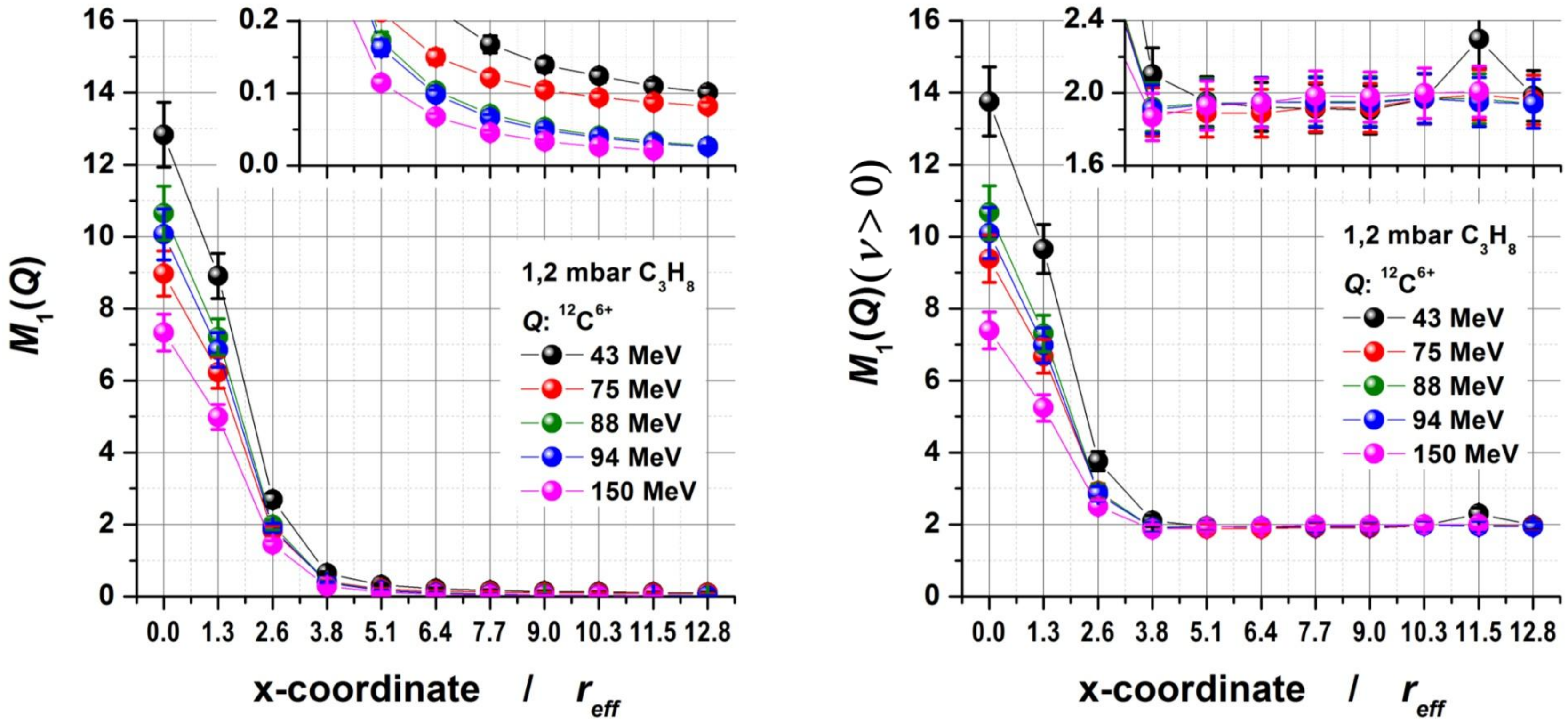
Ionization clusters; narrow beam

$P_{\nu>0}(Q)$ vs. $P_{\nu}(Q)$





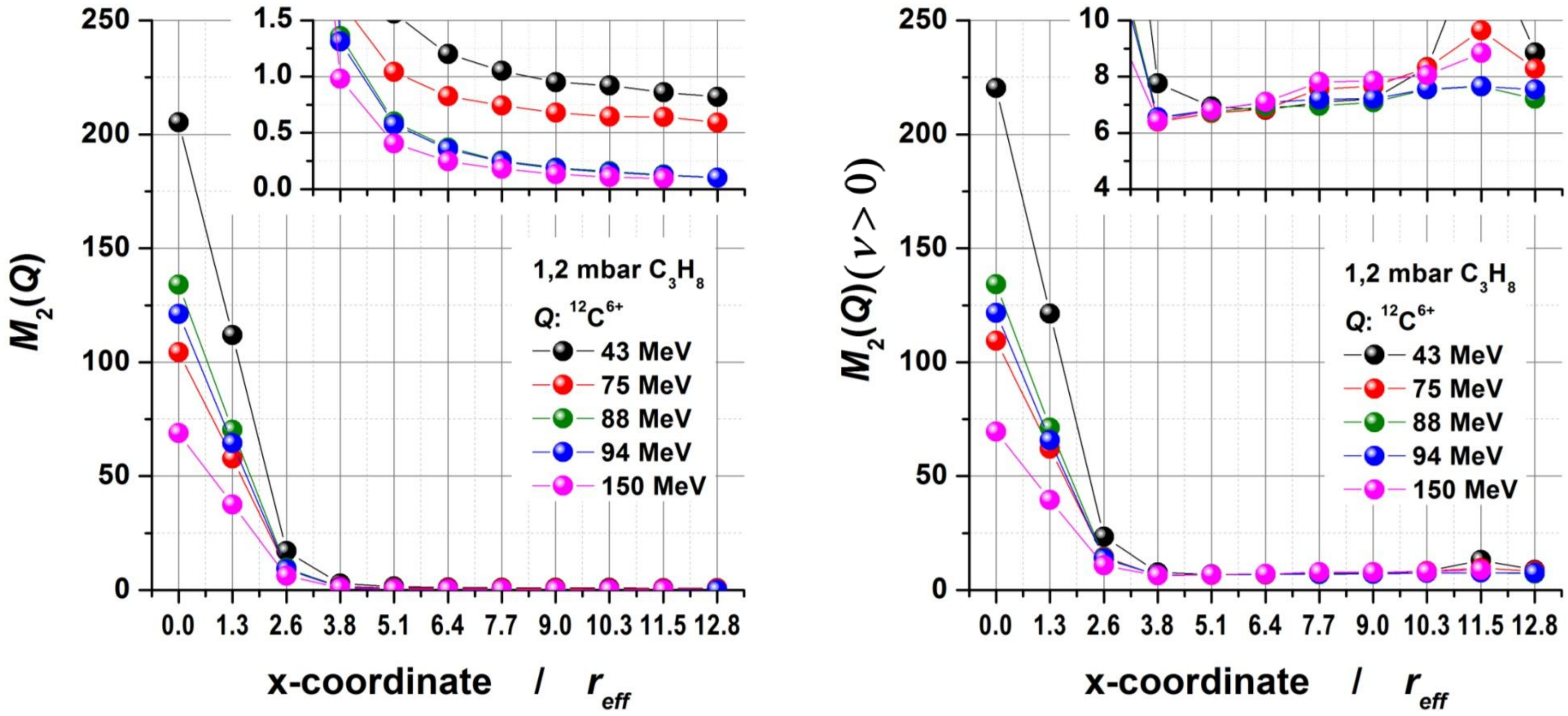
Ionization clusters; narrow beam $P_{\nu>0}(Q)$ vs. $P_{\nu}(Q)$: $M_1(Q)$



$$M_1(T) = \sum_{\nu=0}^{\infty} \nu \cdot P_\nu(T)$$

Ionization clusters; narrow beam

$P_{\nu>0}(Q)$ vs. $P_{\nu}(Q)$: $M_2(Q)$



$$M_2(T)=\sum_{\nu=0}^{\infty}\nu^2\cdot P_{\nu}(T)$$

Conclusion

instrumentation:

- measurement of track structure in nanometric volumes
  - 1.2 mbar N_2 : $r_{eff} = 0.068\ \mu g/cm^2$ ($d_{eff} \cong 1nm\ H_2O$)
  - 1.2 mbar C_3H_8 : $r_{eff} = 0.135\ \mu g/cm^2$ ($d_{eff} \cong 4nm\ H_2O$)
  - height variable with drift time window:
    1.2 mbar C_3H_8 : $\pm 2.5\ \mu s \rightarrow h_{eff} = 0.46\ \mu g/cm^2$ ($h_{eff} \cong 7nm\ H_2O$)
- position sensitive detection allows various irradiation geometries
  - resolution (mean): 60 µm
  - nonlinearity: 0.043 (±7 mm)

physics:

- ionization cluster measurements of carbon ions in 1.2 mbar C_3H_8 (BioQuaRT)
- comparison $P_\nu(Q)$ vs. $P_{\nu>0}(Q)$:
  - ionization cluster size distribution constant for $P_{\nu>0}(Q)$ for large impact parameter d (outside of sensitive volume)
  - $M_1(Q)$ larger for $P_{\nu>0}(Q)$ than for $P_\nu(Q)$

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Thank you for your attention

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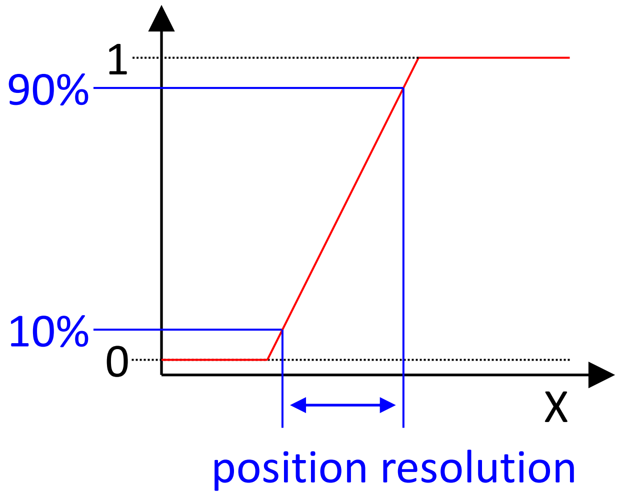
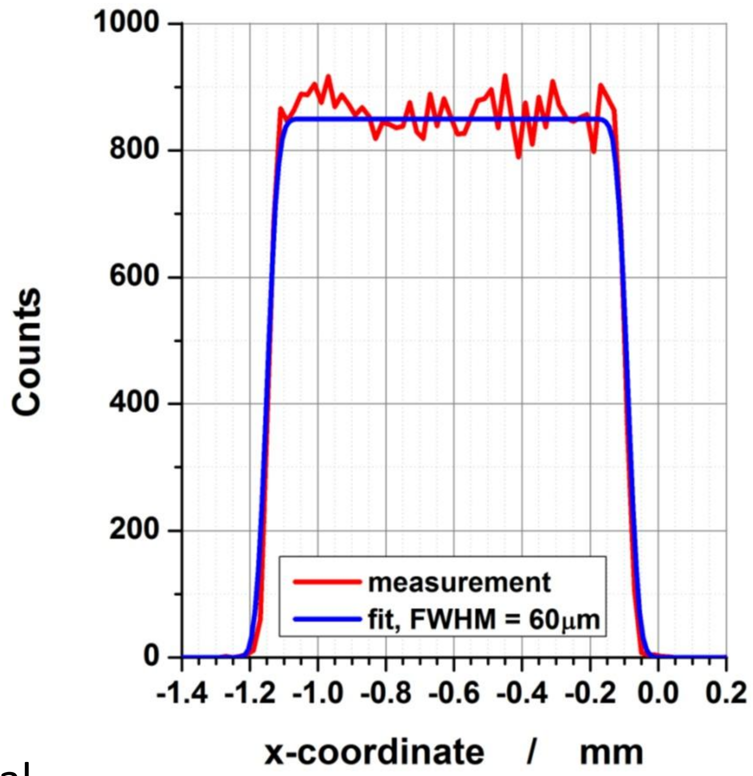
Characterisation PSD

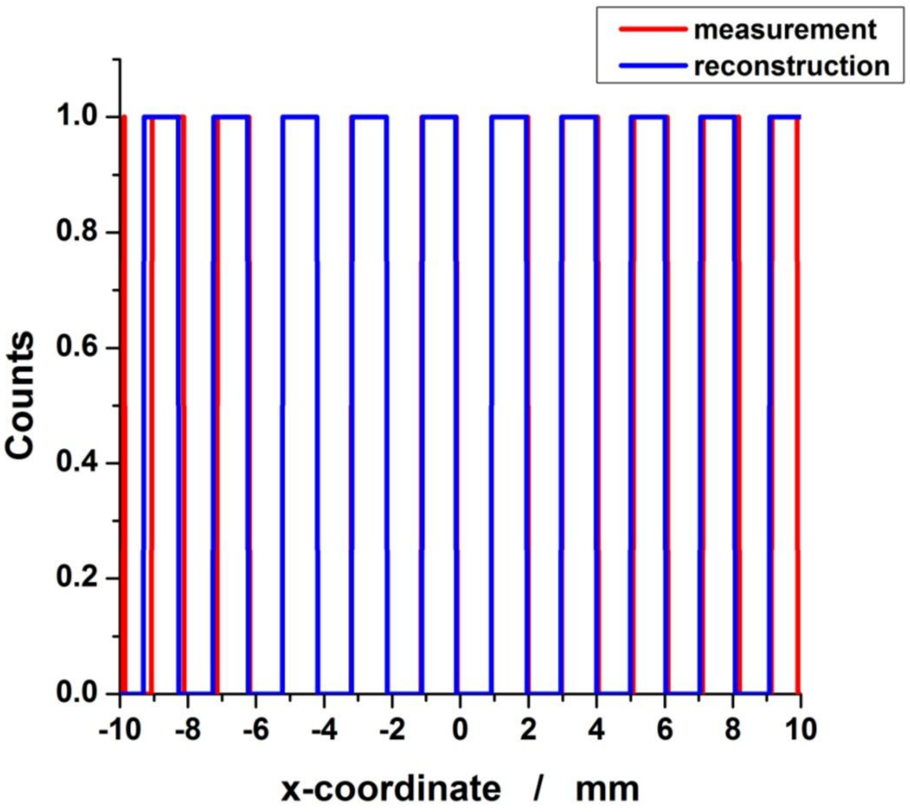




position resolution:
distance: 10% intensity – 90% intensity

identical to:
convolution, rectangular distribution with normal distribution, position resolution = FWHM

Characterisation PSD



nonlinearity: 0.077 (±10 mm)
0.043 (±7 mm)

determination nonlinearity *NL*:

$$NL = \frac{\sum_{i=1}^{n} \left(Y_i^R - Y_i^M\right)^2}{n}$$

measurement:

all „pixel" with counts > mean → $Y^M = 1$
all „pixel" with counts < mean → $Y^M = 0$

reconstruction:

determination of strip center and strip width resp. slit center und slit width (mean values, without boundary area);
„pixel" below slit → $Y^R = 1$
„pixel" below strip → $Y^R = 0$

Size sensitive volume; liquid H_2O

measurement in gas, target is DNA (H_2O-cylinder); → scaling of distributions

mean cluster size: $M_1(Q) \approx \dfrac{D}{\lambda} = \dfrac{D\rho}{\lambda\rho}$

distributions comparable when:

$$M_1(Q)_{material\ 1} = M_1(Q)_{material\ 2} \quad \rightarrow \quad \frac{(D\rho)_{material\ 1}}{(D\rho)_{material\ 2}} = \frac{(\lambda\rho)_{material\ 1}}{(\lambda\rho)_{material\ 2}}$$

with: D = diameter sensitive volume
ρ = density
λ = mean free path for ionization

☞ $\dfrac{(\lambda\rho)_{C_3H_8}}{(\lambda\rho)_{H_2O}} \cong 0{,}66$: **r_{eff} = 0,135 μg/cm² (1,2 mbar C_3H_8) → 0,20 μg/cm² H_2O**

☞ $\dfrac{(\lambda\rho)_{N_2}}{(\lambda\rho)_{H_2O}} \cong 1{,}36$: **r_{eff} = 0,05 μg/cm² (1,2 mbar N_2) → 0,05 μg/cm² H_2O**