Some Comments on Camera Systems, Image Distorsions and Gas Curtain Thickness

S. Udrea

GSI Helmholtzzentrum für Schwerionenforschung

Signal Intensity Estimation

$$N_\gamma = \sigma \cdot \frac{I \cdot \Delta t}{e} \cdot n \cdot d \cdot \frac{\Omega}{4\pi} \cdot T \cdot T_f \cdot \eta_{pc} \cdot \eta_{MCP}$$

$n = 2.5 \cdot 10^{10}\ cm^{-3}$
$d = 5 \cdot 10^{-2}\ cm$
$\Omega = 4\pi\ 10^{-3}\ sr$
$T = 70\%$
$T_f = 80\%$
$\eta_{MCP} = 50\%$

N_γ = average number of photons detected during time Δt
σ = cross section of the photon generation process
I = electron or proton current (electrical)
e = elementary charge
n = gas density
d = distance traveled through gas (curtain thickness)
Ω = solid angle of the optics
T = transmittance of the optical system
T_f = transmittance of the optical filter
η_{pc} = quatum efficiency of the photocathode
η_{MCP} = detection efficiency of the MCP

Projectile	Emitter	λ [nm]	σ [cm²]	I [A]	η_{pc}	N_γ [s^{-1}]	$1/N_\gamma$ [s]
electron	N_2^+	391.4	$9.1\cdot10^{-19}$	5	0.2	$2.0\cdot10^{6}$	$5.0\cdot10^{-7}$
proton	N_2^+	391.4	$3.7\cdot10^{-20}$	1	0.2	$1.6\cdot10^{4}$	$6.1\cdot10^{-5}$
electron	Ne	585.4	$1.4\cdot10^{-20}$	5	0.05	$7.7\cdot10^{3}$	$1.3\cdot10^{-4}$
proton	Ne	585.4	$4.7\cdot10^{-22}$	1	0.05	50	0.02

Conclusion: Single photon detection capability is needed

Camera Systems to be Considered (1)

Intensified CCD or CMOS (ICCD)

- amplification achieved through Micro Channel Plates (MCP) preceded by a photocathode used for photon detection
- MCPs can be stacked, thus double or triple MCP variants exist, thus huge amplification of up to 10^8 can be achieved
- quantum efficiency (QE) and dark counts (DC) level depend on photocathode material (high QE and low DC are important)
- can be modular with exchangeable (cheap) CCD or CMOS camera, which are usually much stronger affected by radiation
- intensifier unit may have relatively simple analog electronics and thus be better suited for radioactive environments
- relatively old and well known technology and therefore usually cheaper

Electron Bombarded CCD (EBCCD)

- is a hybrid of the image intensifier and the CCD
- photons are detected by a photocathode like in an ICCD
- the released electrons are accelerated and impact on the rear side of a back-thinned CCD
- moderate gain of a few hundred is achieved
- has higher spatial resolution than a CCD
- no experience at GSI with this kind of camera
- not suited for a modular design

Camera Systems to be Considered (2)

Electron Multiplying CCD (emCCD)

- amplification achieved through avalanche processes in appropriate semiconductor structures
- CCD cooling is needed for low noise levels
- usually much better QE in the visible and near-infrared than ICCD
- the model tested at GSI didn't prove to be definitely better than the a double MCP ICCD routinely in use
- monolithic camera system with much digital electronics and thus most probably less radiation hard than an ICCD
- relatively new technology usually more expensive than a ICCD

Scientific CMOS (sCMOS)

- newest technology on the market
- high dynamic range, low noise (comparable with the one of a emCCD), high frame rate
- QE similar to the one of the emCCD
- monolithic design
- not so expensive as a emCCD
- testing ongoing at GSI, preliminary result: sCMOS nearly as sensitive as emCCD, simpler technical system, easier to use

Camera System Choice

Modular, Double MCP Intensified System with Lens Relay and Flexible Choice of CCD or CMOS Camera built by ProxiVision

Advantages

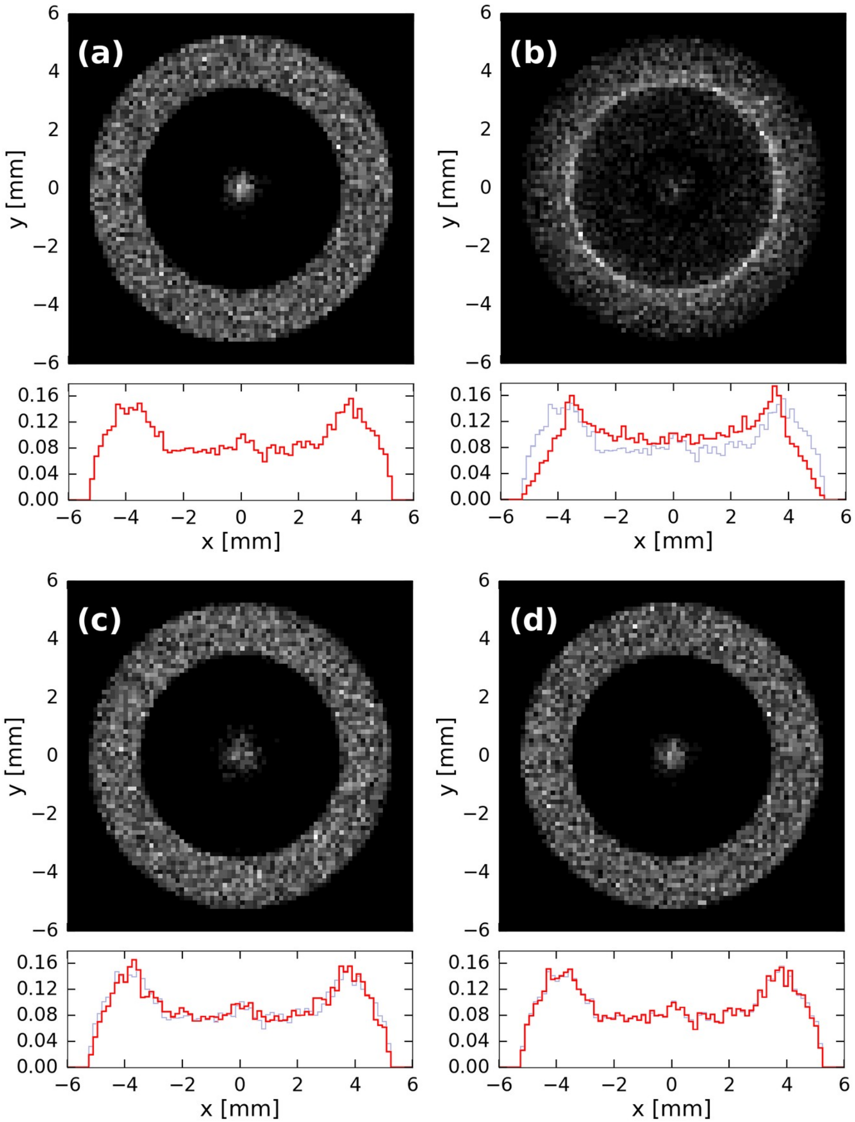
- wide choice of photocathodes, a new type has been developed for the BGC measurements (test results at Cockcroft?)
- very large gain up to 10^6, well suited for single photon detection, basically no noise
- the image intensifier is fully analog and thus radiation hard
- spatial resolution can be comparable with emCCD or sCMOS through proper image processing
- by using photon counting gain non-linearity gets well compensated
- basically no smearing even with a CCD
- no need for high dynamic range
- the CCD or CMOS camera can be easily exchanged and be cheap
- gate time min. 25 μs is shorter than revolution time in LHC
- bright phosphor screen: P43

Disadvantages

- photocathodes are better at short wavelengths, as needed for N_2, than at larger, as for Ne
- QE lower by a factor 5-10 than emCCD
- background due to charged particle impact probably larger
- repetition rate limited by intensifier electronics (1 kHz), P43 decay time (1 ms), and camera frame rate (42 fps)

Simulations of expected images for N_2^+, Ne^+ and Ar^+

Simulations performed with the **virtual-ipm** code
pypi.org/project/virtual-ipm



2D and 1D histograms of the detected photons assuming **ideal gas curtain and optics with unit magnification**. The bin size is 0.15 mm. The 1D histograms are normalized.

(a) No distorsions
(b) N_2^+, τ_{BIF} = 60 ns
(c) Ne^+, τ_{BIF} = 11 ns
(d) Ar^+, τ_{BIF} = 9 ns

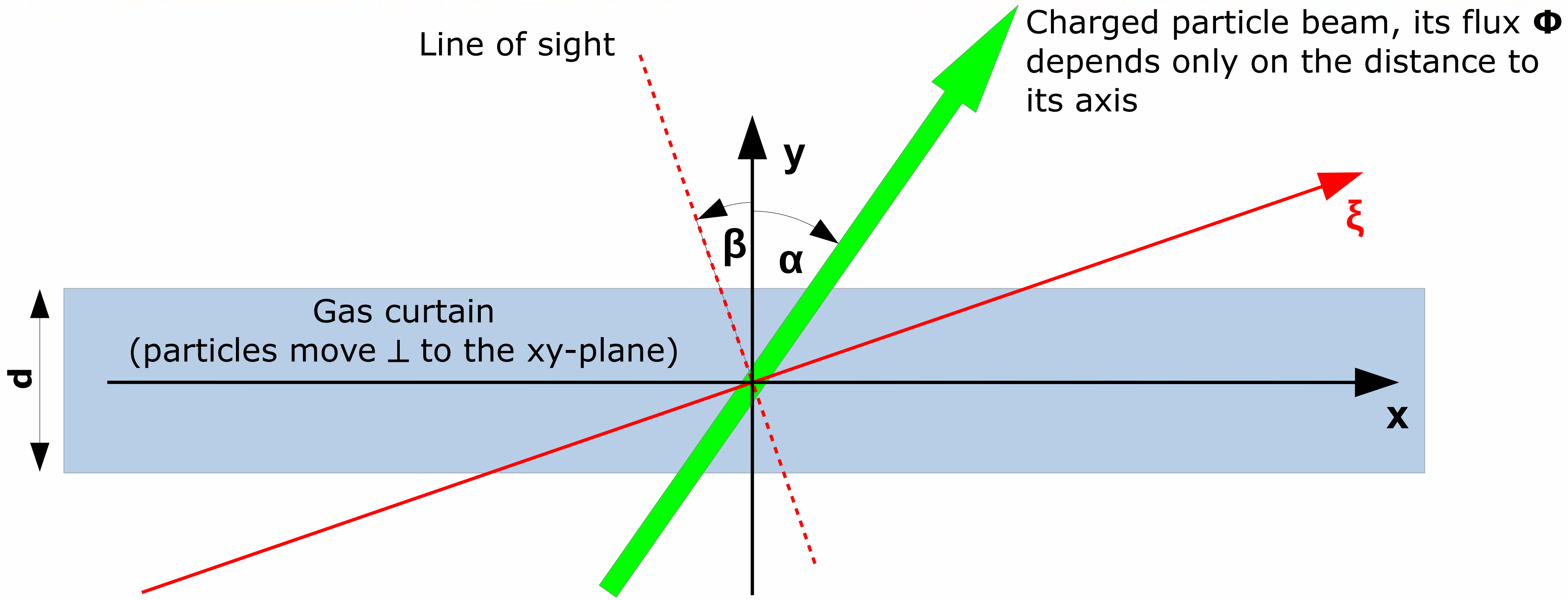
The 1D histogram from (a) is reproduced in grey in all the others.

Simulation parameters

B_{sol} = 1 T
I_e = 5 A
D_e = 10.5 mm
d_e = 7 mm
$\langle I_p \rangle$ = 1 A
σ_{tp} = 0.3 mm
$4 \cdot \sigma_{lp}$ = 1.01 ns
$N_\gamma^e \approx 12500$
$N_\gamma^p \approx 250$

Such simulations should be performed with a realistic gas curtain too for a better reproduction of the image to be expected.

Influence of Curtain Thickness: 2D-Model

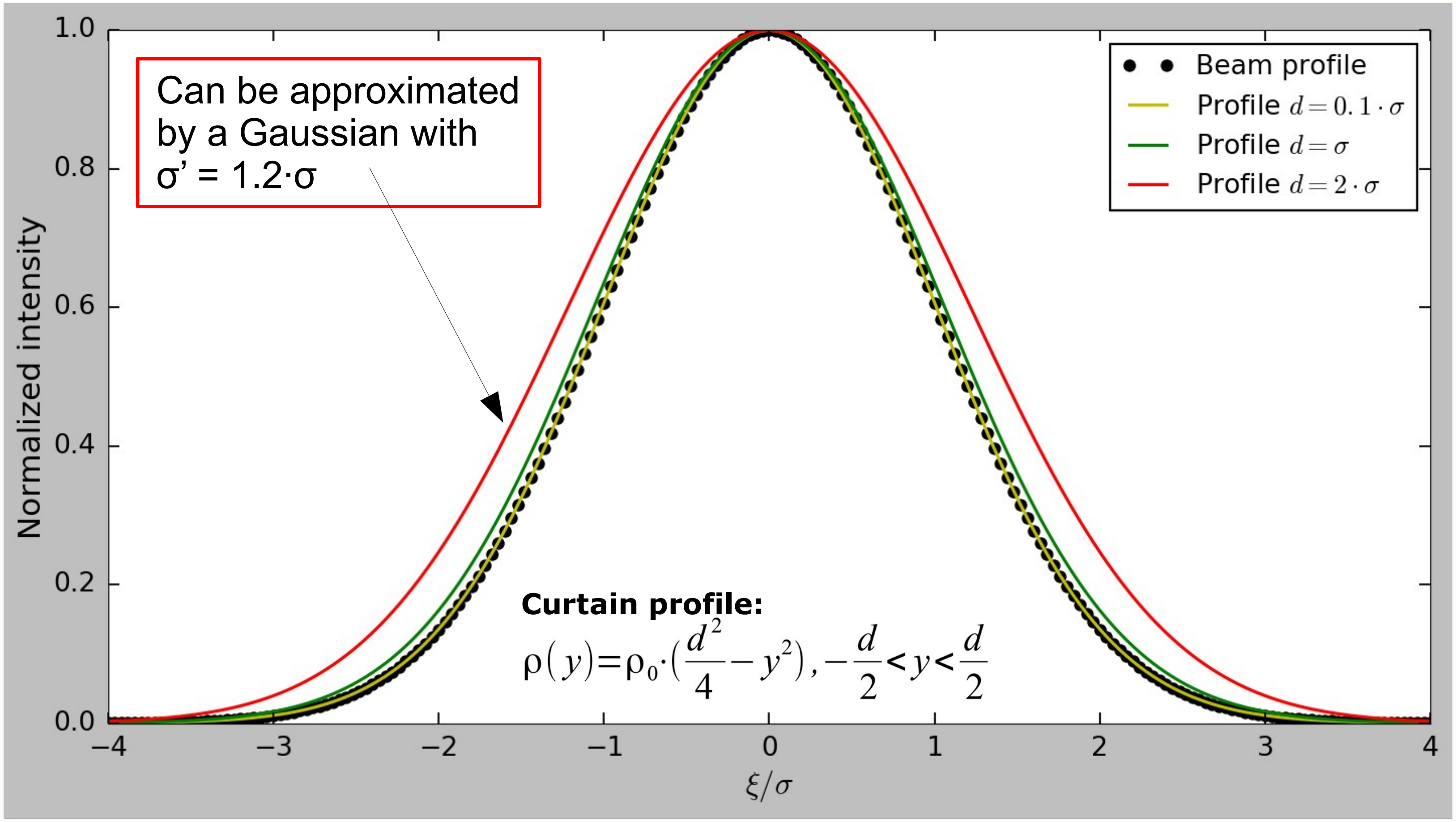


- Gas curtain's density **ρ** depends only on **y**
- Gas curtain's refractive index is 1
- Gas curtain extends from **y** = -d/2 to **y** = d/2
- 1D detector parallel to the **ξ** axis
- Ideal optics placed practically at infinity
- Practically infinite depth of field
- 0 ≤ **β** < 90° **(presently 45°)**
- -90° < **α** < 90° **(presently 45°)**

R. Ischebeck, et al., Phys. Rev. ST Accel. Beams, vol. 18, 2015

$$I(\xi)\propto\int_{-d/2}^{d/2}\rho(y)\cdot\phi\left(\xi\cdot\frac{\cos(\alpha)}{\cos(\beta)}-\frac{\sin(\alpha+\beta)}{\cos(\beta)}\cdot y\right)dy$$

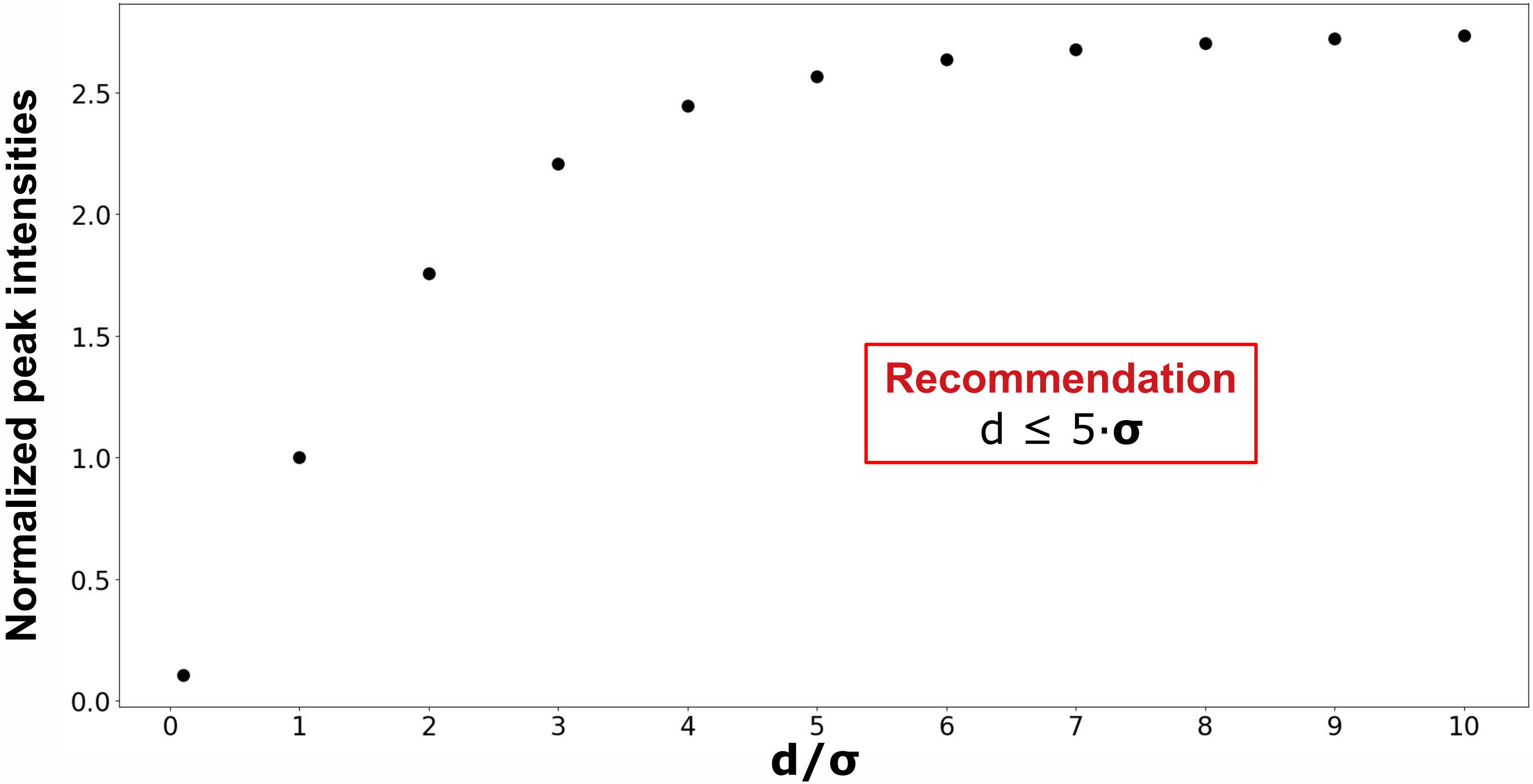
Parabolic Gas Curtain Profile and Gaussian Beam



Line of sight and beam axis are perpendicular to each other, moreover $\alpha = \beta = 45°$
The charged particle beam has a Gaussian profile with standard deviation **σ**, three gas curtain thicknesses **d** are considered: 0.1·**σ**, **σ** and 2·**σ**.

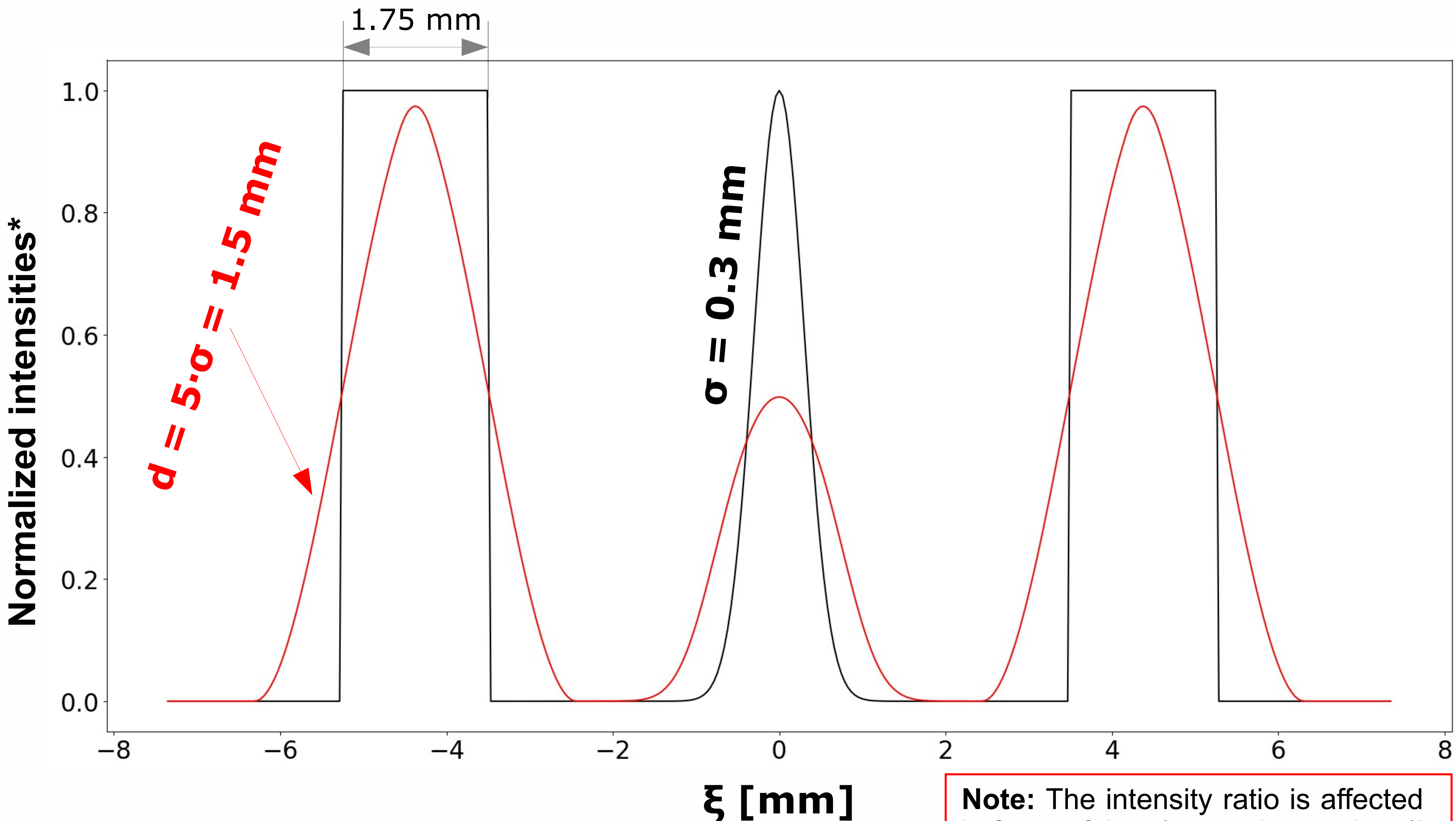
Peak Intensities and Curtain Thickness

Computations performed for a Gaussian beam profile



The recorded profile is basically a convolution of the curtain profile with the beam profile. Thus the recorded profile gets wider with increasing curtain thickness **d** and while the total number of recorded photons also increases the peak of the recorded profile gets into saturation because the photons are spread over the detector.

Curtain Thickness 5·σ



Note: The intensity ratio is affected in favor of the electron beam signal!

(*) Integrals are equal

Final Remarks

- Presently a modular double MCP image intensifier system with customizable CCD or CMOS camera appears to be the best choice
- Strong imagedistortions due to electric and magnetic fields appear just for N2 in case of an ideal curtain (extremely thin, huge density)
- The curtain thickness should be limited to a maximum of about 5 times the RMS transversal size of the proton beam or any small feature to be observed. The smaller the better for resolution. Higher thicknesses do not contribute to peak signal strength but spread the extra photons over the detector.