Gas Jet Monitor:
Progress with Luminescence Detection

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With thanks to the consortium:
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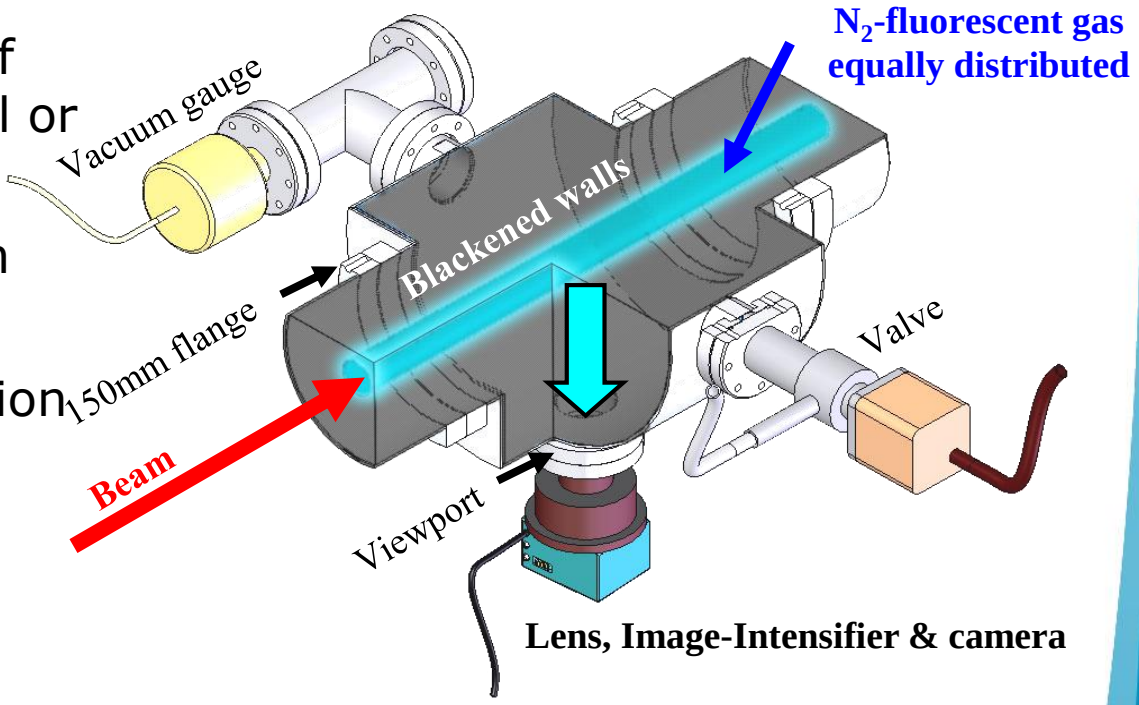
Outline

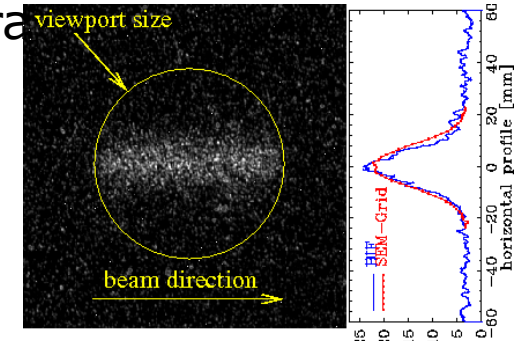
- Beam Induced Fluorescence (BIF) working principle and features
- N_2 and Ne working gases
- Optics set-up and Image intensifier
- Test set-up and results at the Cockcroft Institute
- Conclusions and outlook

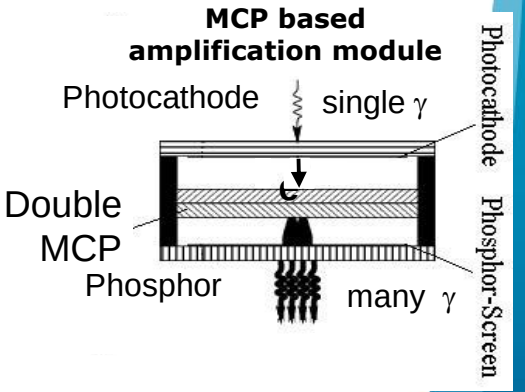
Principle of Beam Induced Fluorescence (BIF)

- Based upon the detection of photons emitted by residual or injected (low pressure) gas
- Little influence on the beam
- Spatial resolution can be matched to application by appropriate optics
- Single pulse observation e.g. ≈ 1 µs time resolution (depending on photon flux)
- Commercial intensifier & camera
- Compact insertion,

  e.g. 15 cm for both planes

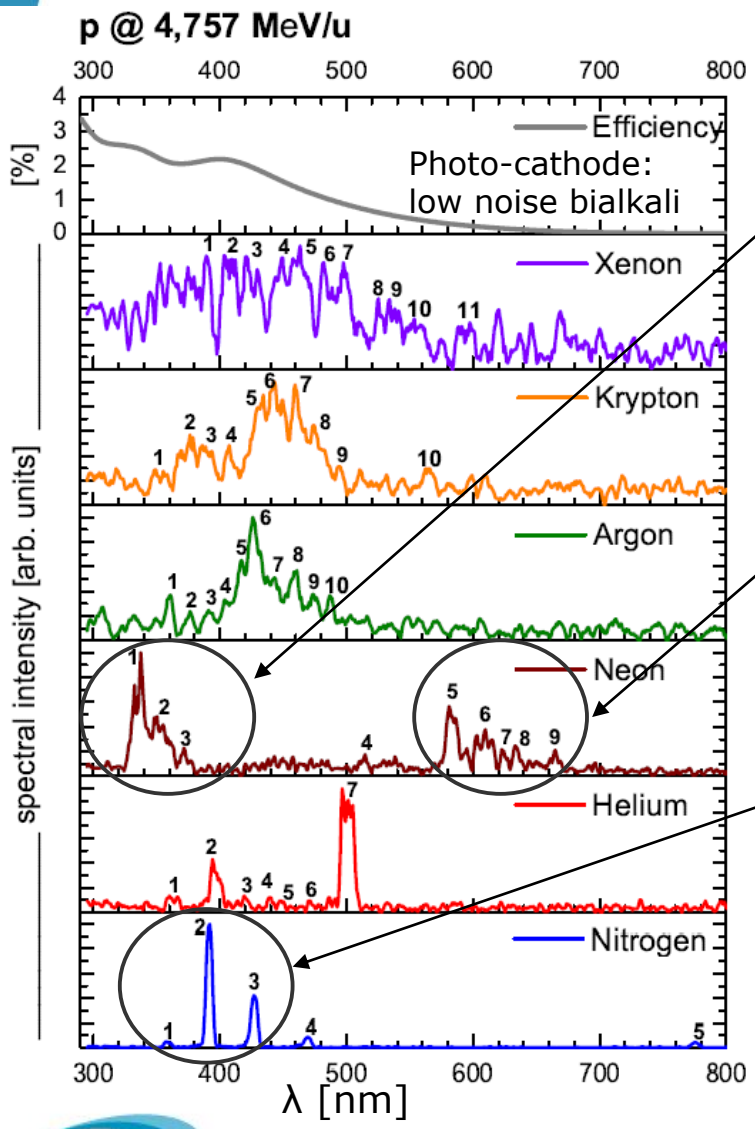






Beam for target experiment: 4x10^{10} Xe^{48+} at 200MeV/u, p=10^{-3} mbar

Fluorescence of different gases



Beam: protons at 4.7 MeV at GSI-LINAC

UV-lines:
Several Ne^+ lines mainly corresponding to different $[2s^2 2p^4(^3P)]3p \rightarrow 3s$ transitions, life times below 10 ns.

Yellow lines:
Several Ne lines mainly corresponding to different $[2s^2 2p^5(^2P)]3p \rightarrow 3s$ transitions, life times of about 20 ns.

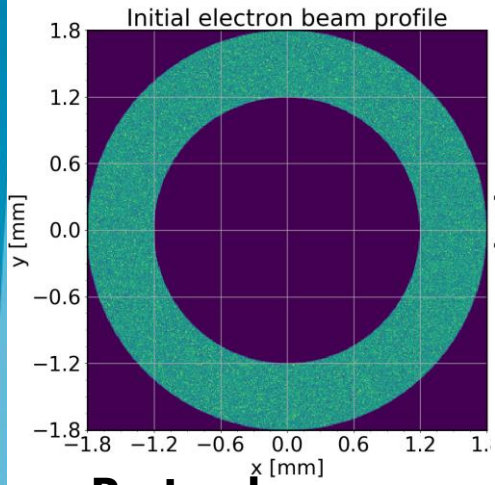
Blue lines:
The strong lines correspond to the $B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$ electronic transition band of N_2^+, life times of about 60 ns.

F. Becker (GSI) et al., Proc. DIPAC'09 , F. Becker, Ph.D. thesis, T.U. Darmstadt, 2009

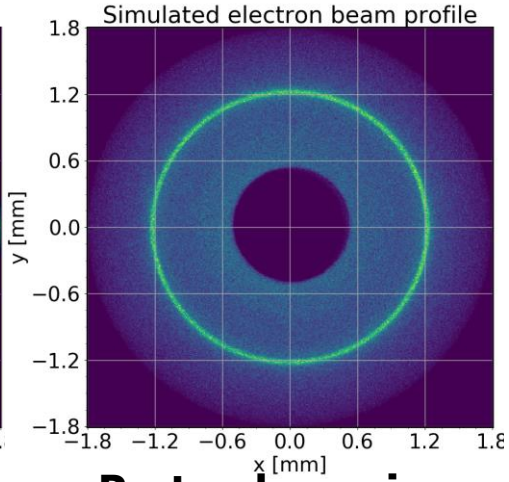
N_2^+ as emitter: distortions due to em-fields

Gas N_2^+ (blue lines): Lifetime τ = 60 ns (exponential), mass ***m*** =28 amu,
Beams: p $2 \cdot 10^{11}$/bunch, width σ = 1mm, length σ = 0.6ns, I_{ele}= 5A (dc), B_{sol} = 4T

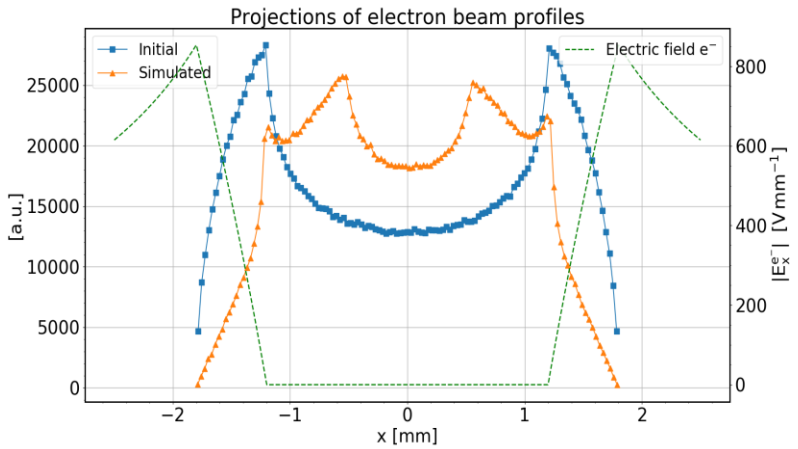
Electron beam:



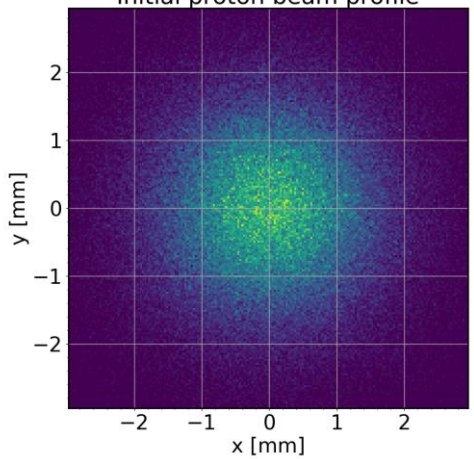
Electron beam image



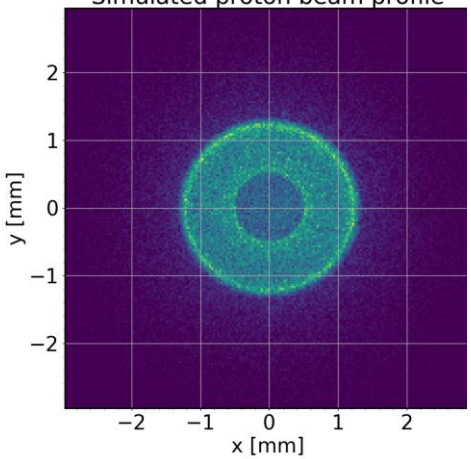
Electron beam: Profile by projection



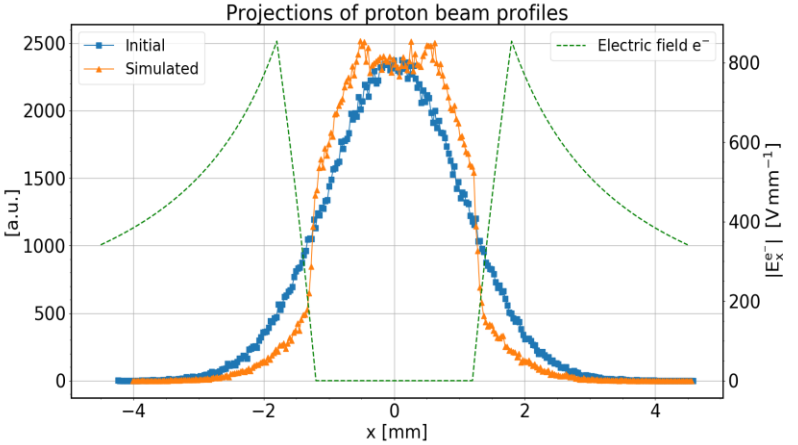
Proton beam:



Proton beam image



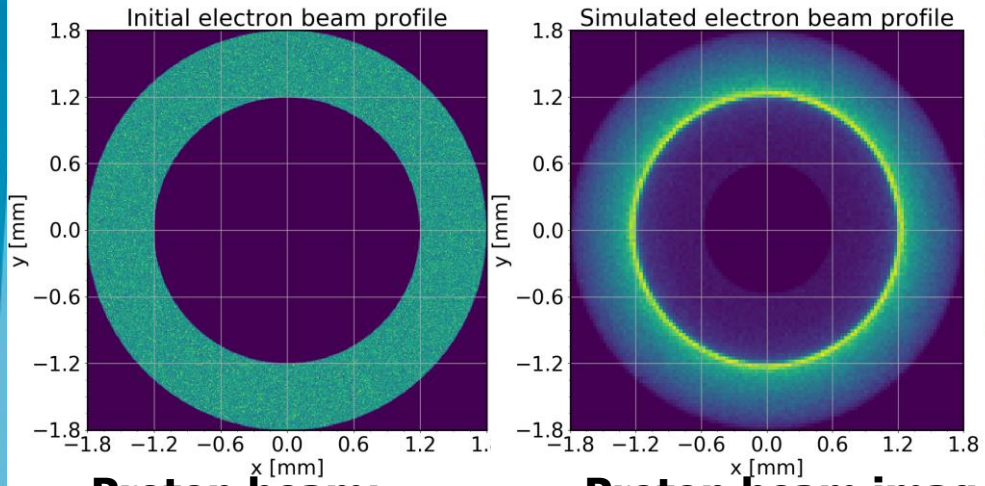
Proton beam: Profile by projection



Ne^+ as emitter: distortions due to em-fields

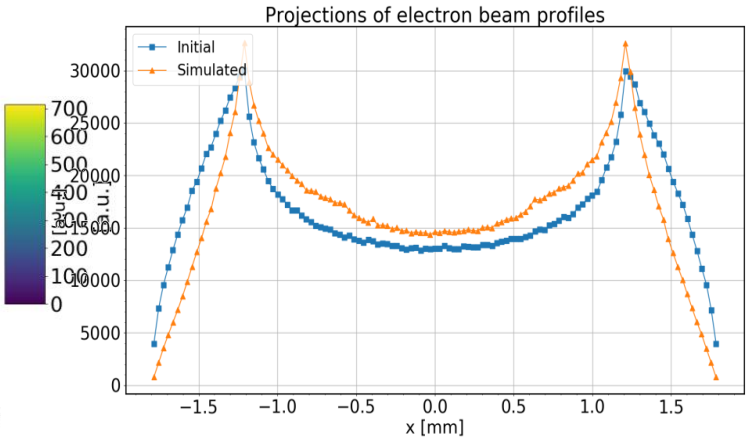
Gas Ne^+ (UV lines): Lifetime τ = 11 ns (exponential), mass m = 20 amu,
Beams: p $2.2 \cdot 10^{11}$/bunch, width σ = 1mm, length σ = 0.6ns, I_{ele} = 5A (dc), B_{sol} = 4T

Electron beam:

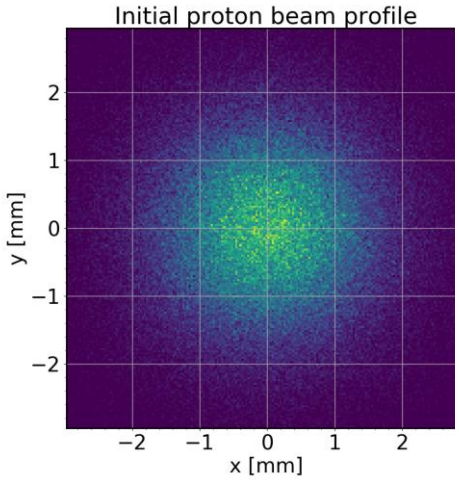


Electron beam image

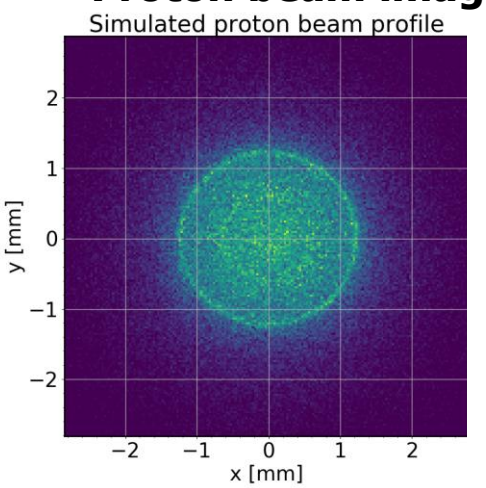
Electron beam: Profile by projection



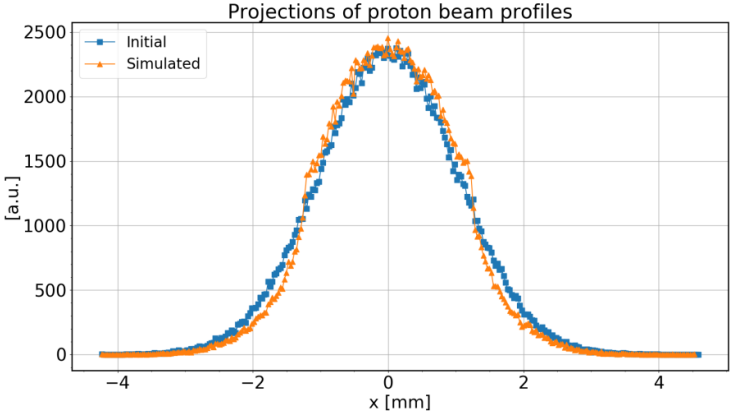
Proton beam:



Proton beam image



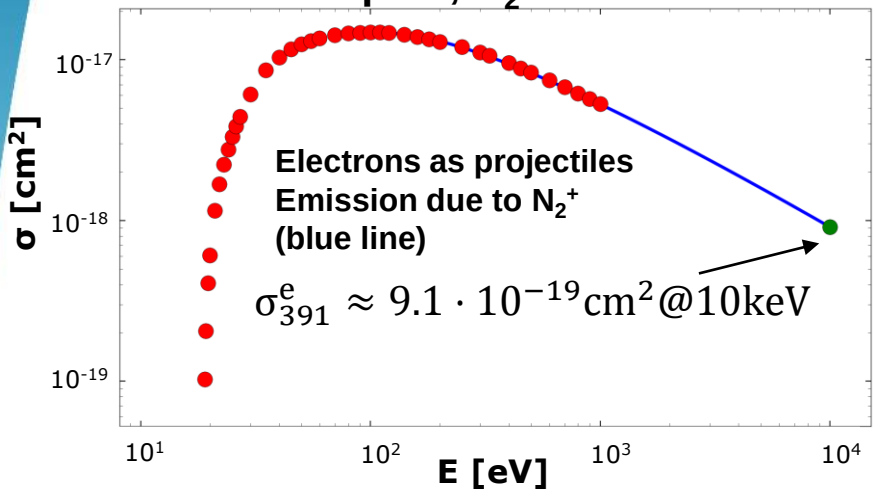
Proton beam: Profile by projection



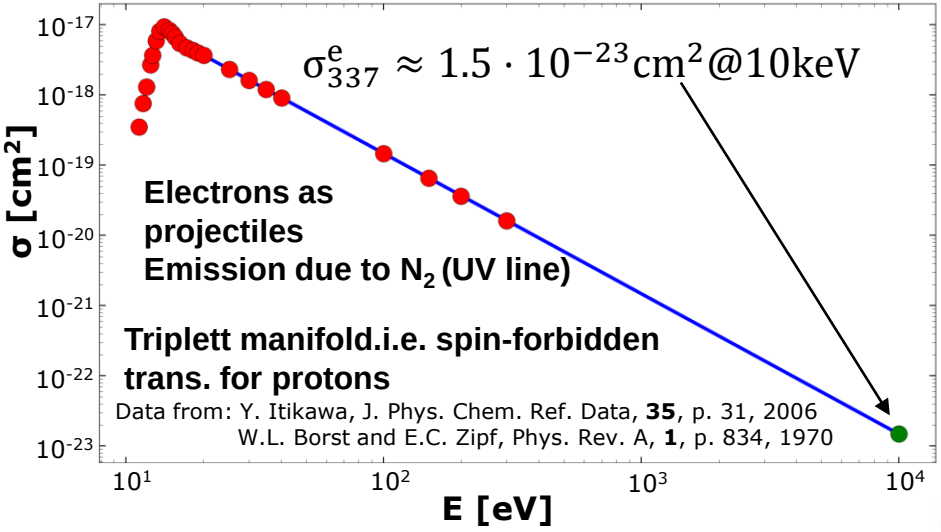
Remark: Neutral Ne (yellow lines) is not influenced by beam's space charge ⇒ 'ideal' working gas!

N_2 as working gas: cross sections

Electron impact, N_2^+ blue lines:



Electron impact, neutral N_2 UV range

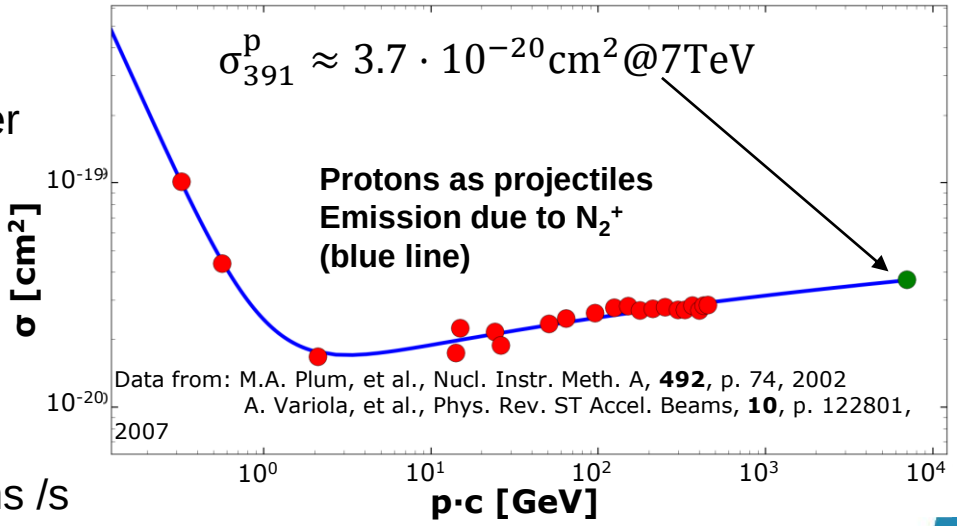


Results of N_2, electron impact:

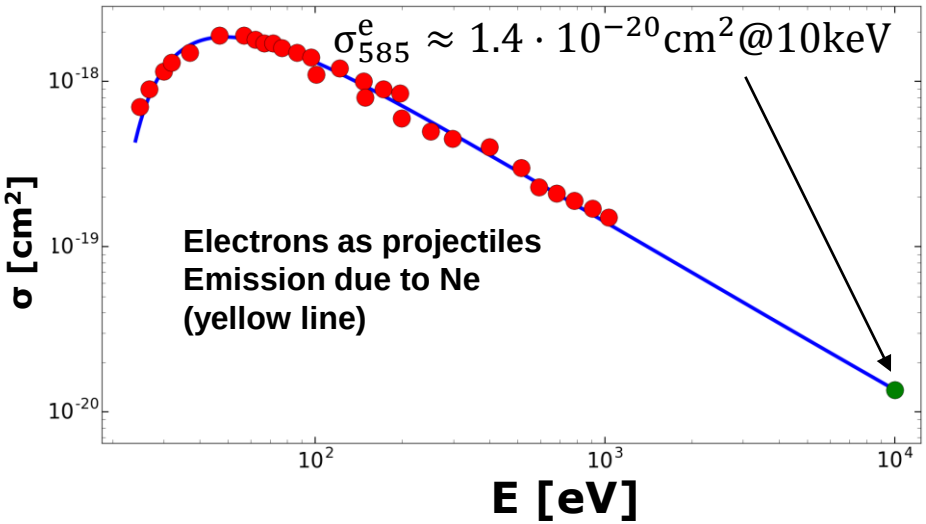
- Cross section extrapolated from 1 keV
- $\sigma^{e}_{391} \approx 9.1 \cdot 10^{-19}\mathrm{cm}^2$ correspond to N = 7· 10^4 photons /s for e-lens parameter
  ⇔ one profile per ≈ 0.1 s
- Transition of neutral N_2 (only e^- excitation): $\sigma^{e}_{337} \approx 1.5 \cdot 10^{-23}\mathrm{cm}^2$ i.e much smaller

Proton impact:

- cross section extrapolated from 450 GeV
- $\sigma^{p}_{391} \approx 3.7 \cdot 10^{-20}\mathrm{cm}^2$ corr. N = 600 photons /s
  ⇔ one profile per ≈ 1 s



Ne as working gas: cross sections



Data from:
J.E. Chilton et al. Phys. Rev. A, **61**, p. 052708, 2000
F.A. Sharpton et al. Phys. Rev. A, **2**, p. 1305, 1970

Results of Ne, electron impact (yellow line):

- Cross section extrapolated from 1 keV
- $\sigma^{e}_{585} \approx 1.4 \cdot 10^{-20}\mathrm{cm}^2$ correspond to N = 300 photons /s (factor 200 less as N_2)
  for e-lens parameter, gas jet and chosen photon cathode ⇔ one profile per ≈ 1 s
- Transition of neutral Ne^+ (UV-lines): cross section not known

Proton impact (yellow line):

- Cross section estimated by the principle of equal velocities:

$\sigma^{p}_{585}(7\mathrm{TeV}) \approx \sigma^{e}_{585}(3.8\mathrm{GeV}) \approx 4.7 \cdot 10^{-22}\mathrm{cm}^2$

correspond to N = 2 photons /s (factor 300 less as N_2) ⇔ one profile per ≈ 1 min

Several yellow lines increases statistics by a factor ≈ 3 ⇔ one profile per ≈ 20 s

Ne as working gas: some comments

Advantages:

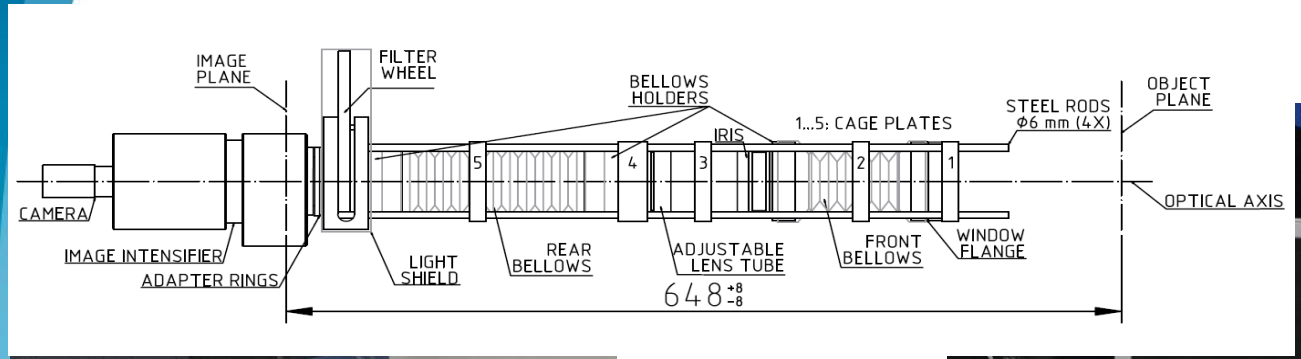
- Fluorescence due to **neutral** Ne (yellow lines), but lower than N_2
- Ne^+ fluorescence (UV lines) from levels with short life times (< 10 ns)
- Mass comparable with that of N_2

Disadvantages:

- Emission by neutrals at long wavelengths (yellow $\lambda > 580$ nm);
  $\Rightarrow$ photo-cathode with for yellow lines leads to a larger dark counts rate
- No experimental cross section for relativistic protons (UV & yellow lines)
- Experimental cross section for e^- only for the neutral Ne (yellow lines),
- No data for Ne^+ (UV lines)

$\Rightarrow$ **Installation of BIF Profile-Monitor at LHC or SPS would be helpful**

Optics test set-up at GSI



CMOS camera

Filter wheel within light shield

Lens: UV apochromatic triplet, f = 160 mm, optimized for 1:-1 imaging

Iris (f/8,Ø 20 mm)

Image intensifier:
chevron double MCP
for single photon detection
gate-able, 25 µs min to ∞
1 kHz max. rep. rate

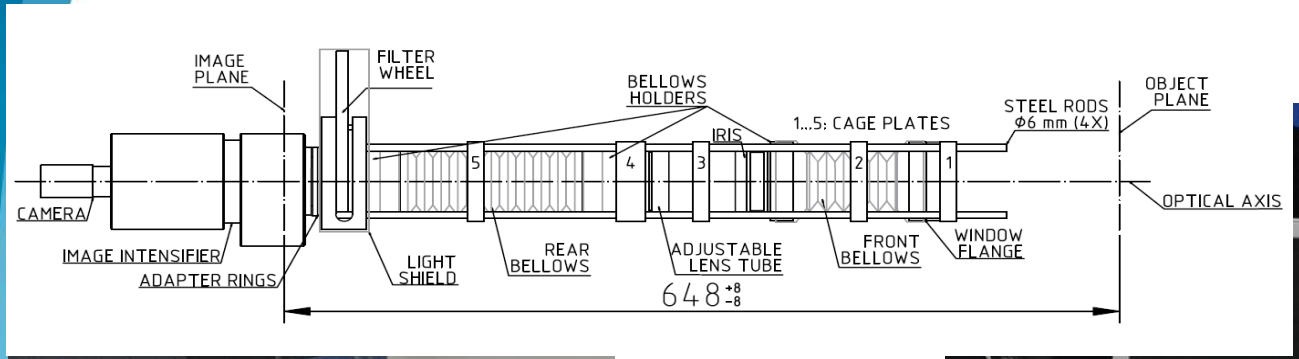
0,5 m

USAF resolution test patterns

Light foil

Acknowledgement to C. Andre.

Optics test set-up at GSI



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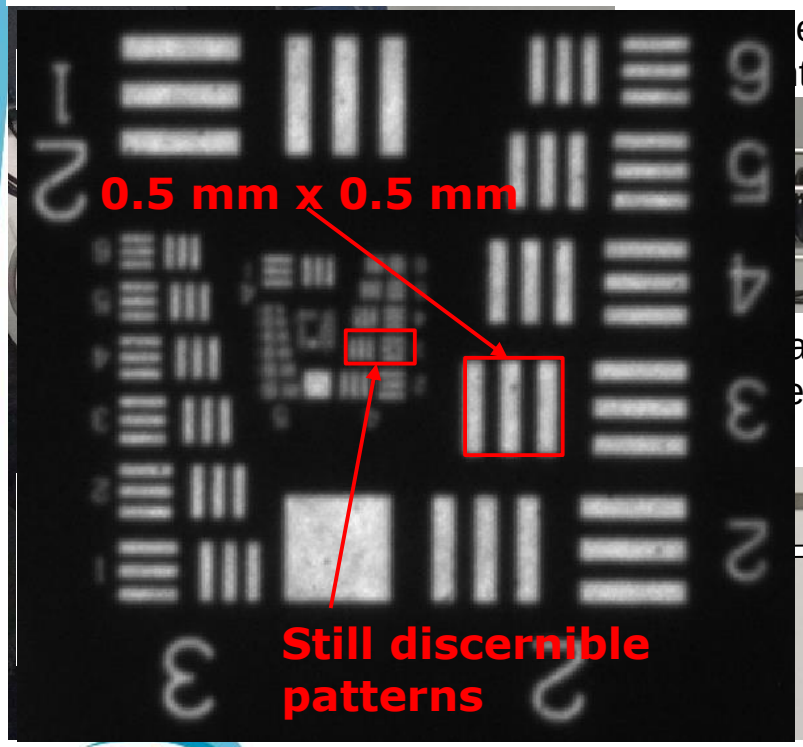
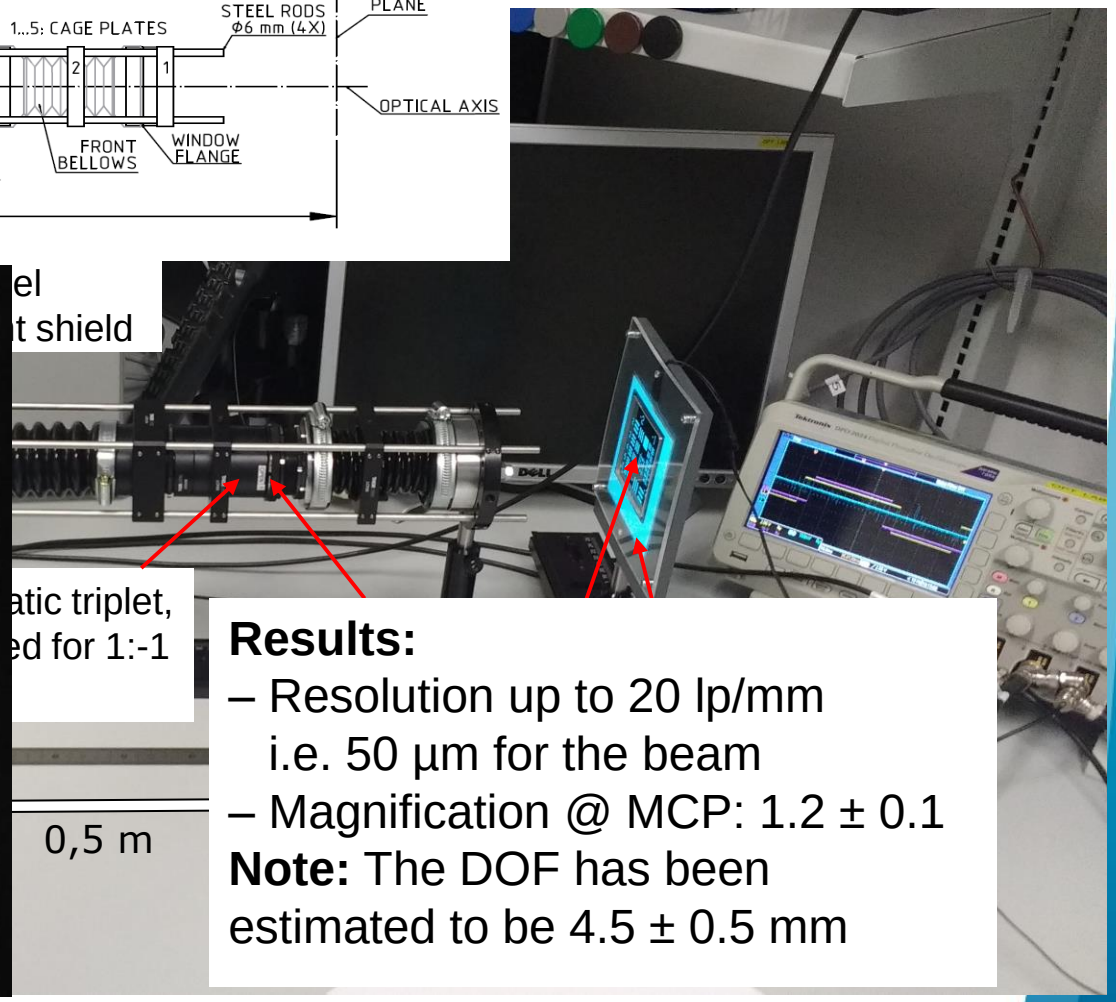


atic triplet,
ed for 1:-1



Results:
– Resolution up to 20 lp/mm
i.e. 50 µm for the beam
– Magnification @ MCP: 1.2 ± 0.1
Note: The DOF has been estimated to be 4.5 ± 0.5 mm

Acknowledgement to C. Andre.

Photo cathode and Camera

Photo cathode S20:

- ➢ High quantum efficiency
- ➢ Sensitive for Ne yellow lin
- ➢ Medium dark counts
- ➢ Availability

⇒ S20 chosen

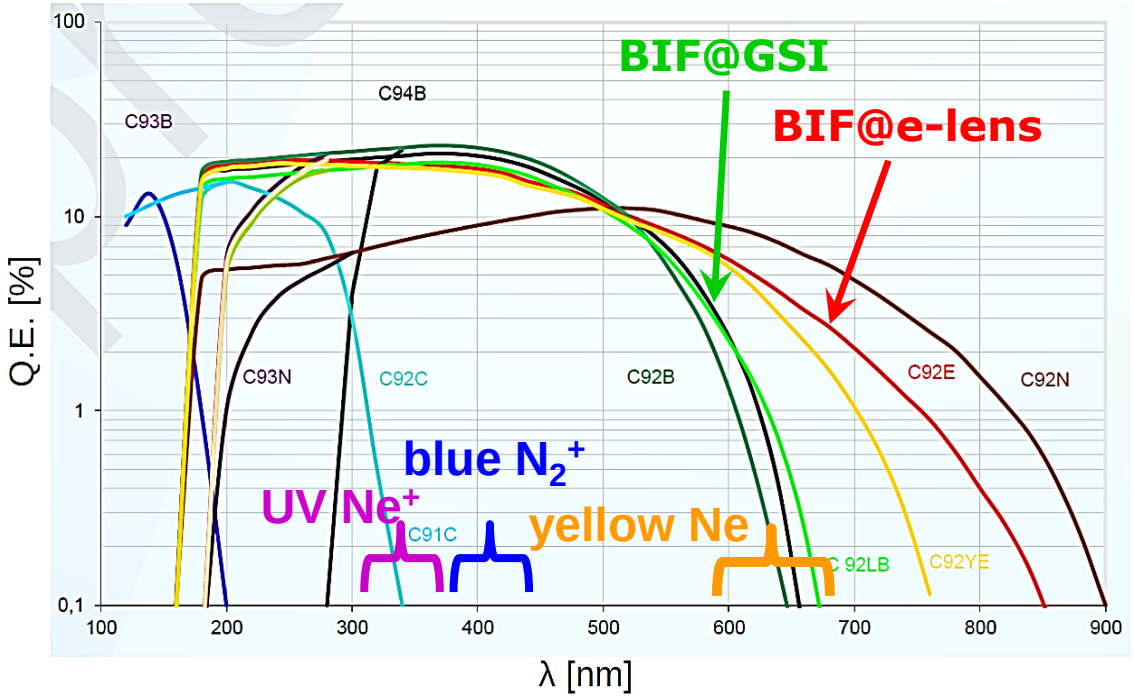


Image intensifier:

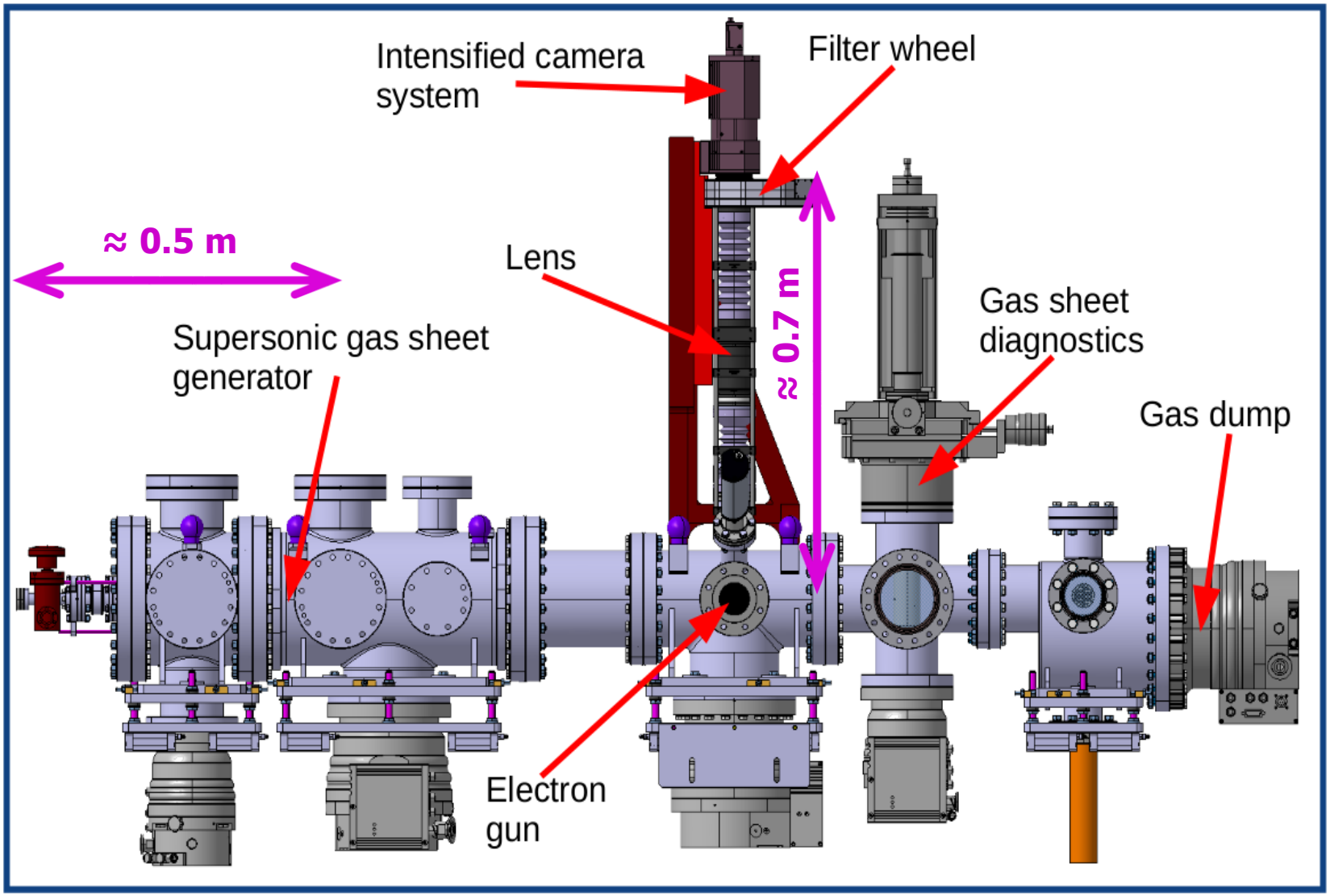
- ➢ double MCP for single photon counting i.e. 10^6 amplification

Camera:

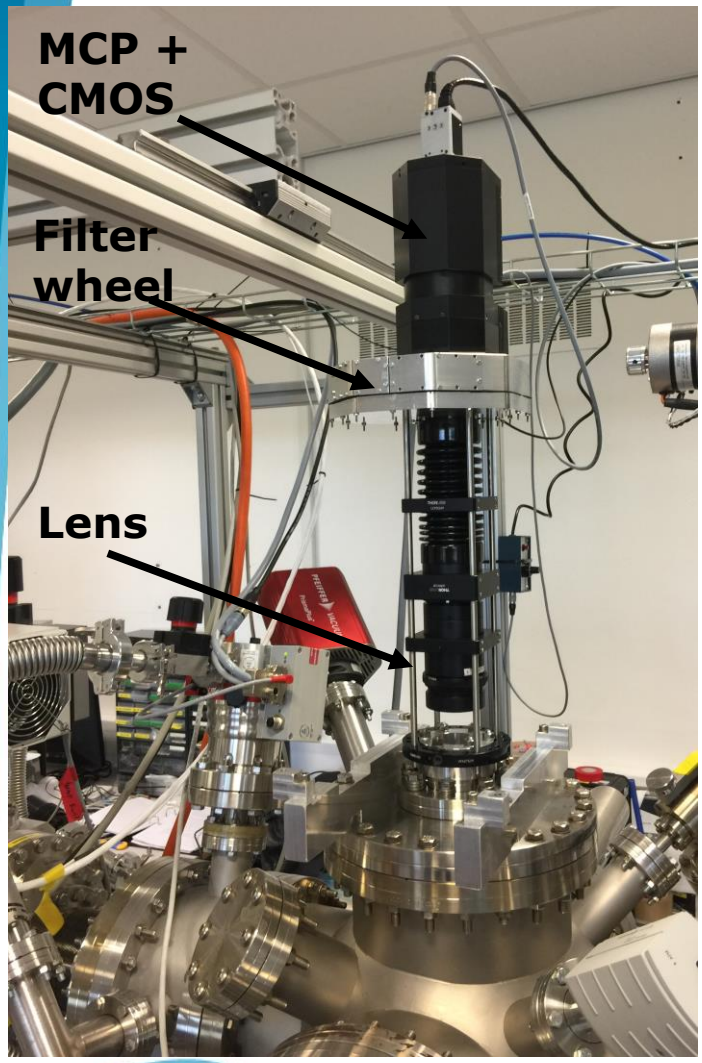
- ➢ Simple CMOS
- ➢ Coupling II to CMOS by relay optics for easy maintenance

	Designation	Material	Peak Q.E. [%]	Dark counts [1/s/cm²]
BIF@e-lens	C92E	S20	20	600
BIF@GSI	C92LB	Low noise bialkali	20	15
	C92B, C93B, C94B	Bialkali	20	60
	C92N, C93N	S25	10	3000
	C92YE	Yellow enhanced	20	60

Overview of future setup



Actual BIF set-up at Cockcroft



Components:

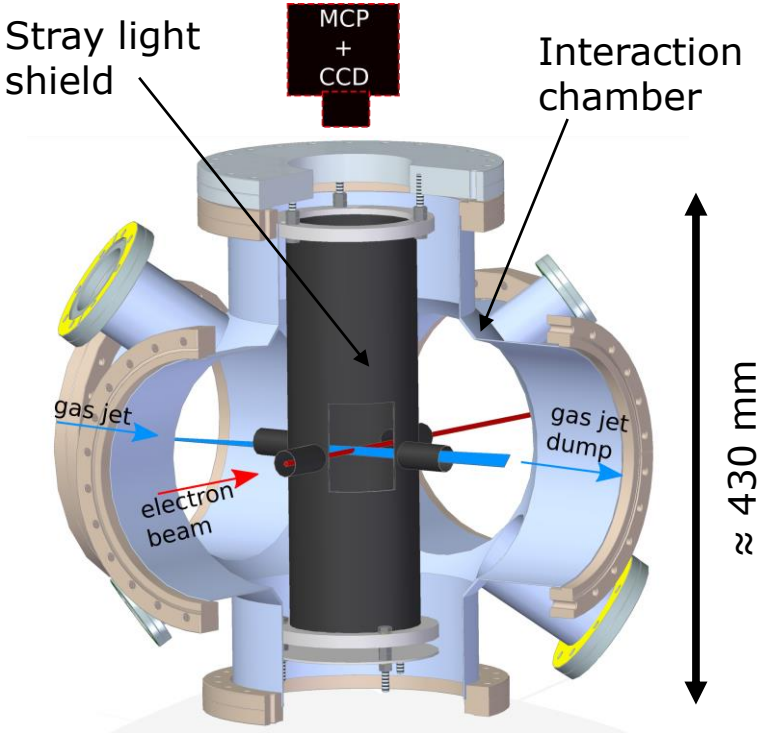
- Proxivision image intensifier with chevron double MCP
- Basler acA1920-40gm CMOS camera
- UV-Apochromat, f=160 mm
- Filter wheel with 10 nm bandwidth filters at 337, 390 & 430 nm, and a broadband filter for 550 to 600 nm

Gas:

- N_2, Ne
- Density ≈ $2.5 \cdot 10^{10}$ cm^{-3}
- Thickness ≈ 0.4 mm
- Width ≈ 4 mm

Electron beam:

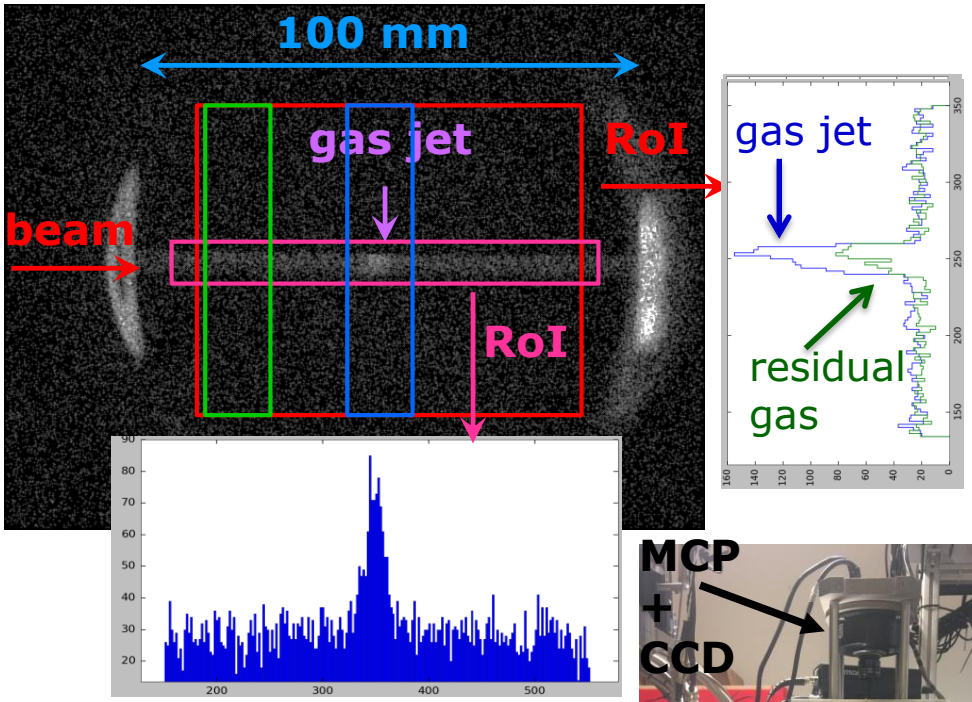
- E < 10 keV
- I < 100 µA
- ∅ ≈ 1 mm



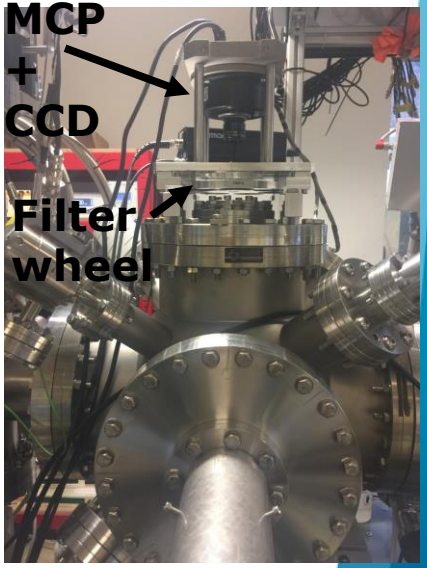
Detection of the e⁻ – gas curtain interaction

Test at existing installation at Cockcroft Institute:
Pressure: $4 \cdot 10^{-8}$ mbar
e-beam: 3 keV, ≈10 µA,
Integration time: 8000 s
Filter @390 nm, 10 nm FWHM
Emitter: N_2^+ @ 391.4 nm
Single photon detection

100 mm = 480 pixel, 4.8 pixels/mm



Results:
- Functionality proven
- e⁻ beam recorded from residual gas
- Effective jet density about 4-fold
- Technical improvements required for jet generation and electron beam



Data acquisition and processing

Image intensifier in single photon detection mode:

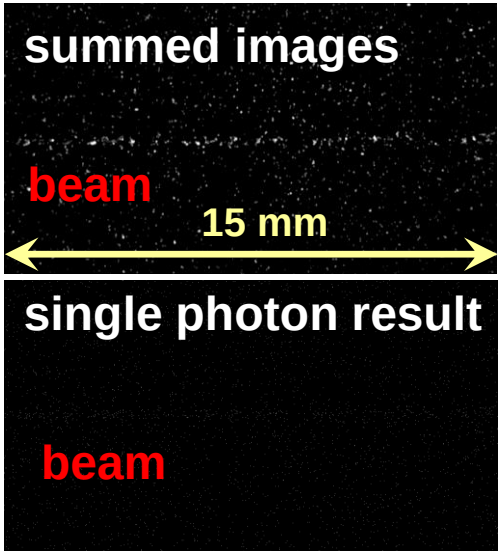
- Exposure time: distinguishing single photons → typ. 1 s
- Single photons: maxima above a threshold i.e. 'spot'
- For each maxima its coordinates is stored
- a image rotation can be performed if needed
- The final image: one dot for each identified photon
- 1D histogram by integration along predefined axes

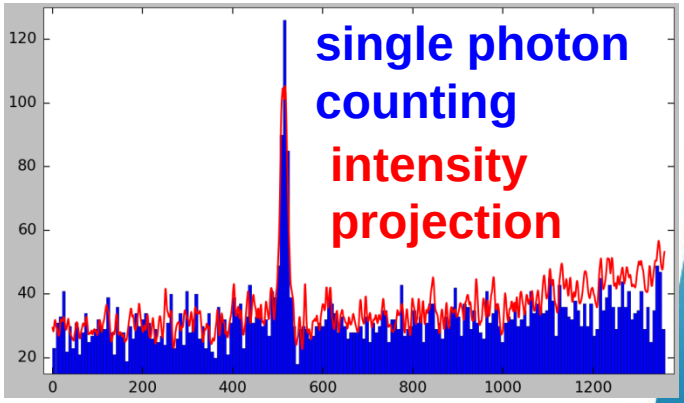
Code realized by macro in ImageJ

Result:

- Beam profile and width
- Total amount of photons are determined
- improved signal-background ratio

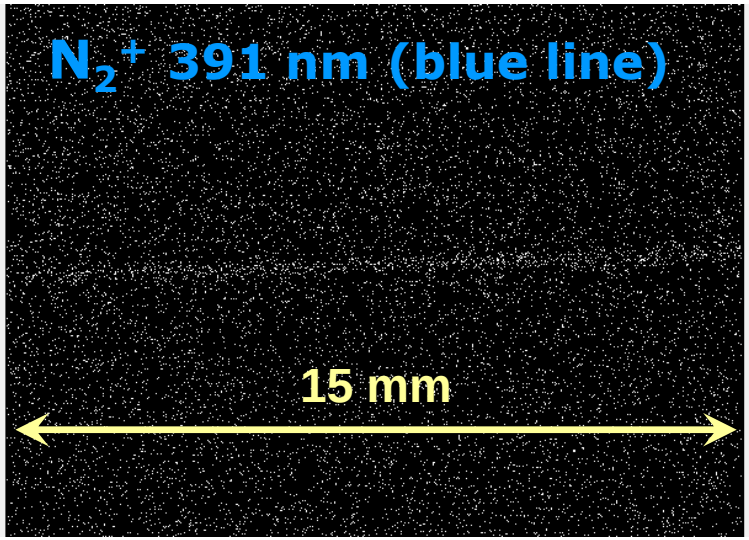
Pressure: $1.4 \cdot 10^{-7}$ mbar
e-beam: 7 keV, ≈30 µA
Readout: 16 images of 1 s



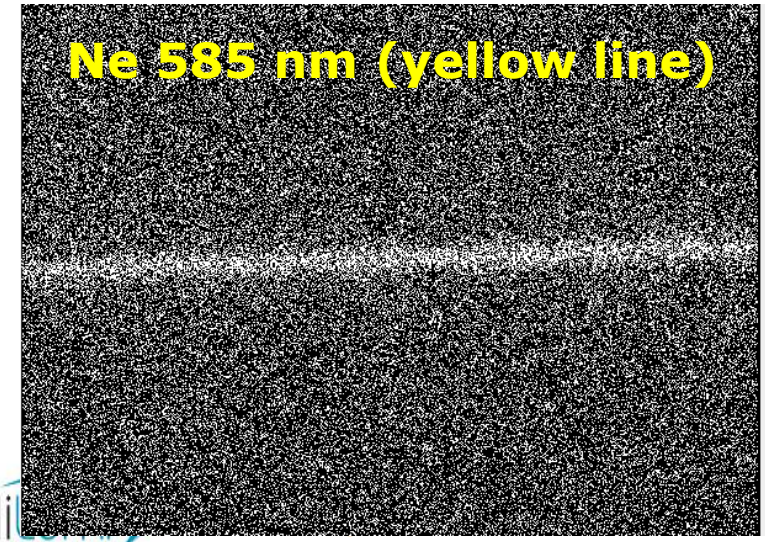


Comparison between Nitrogen and Neon

Residual gas images



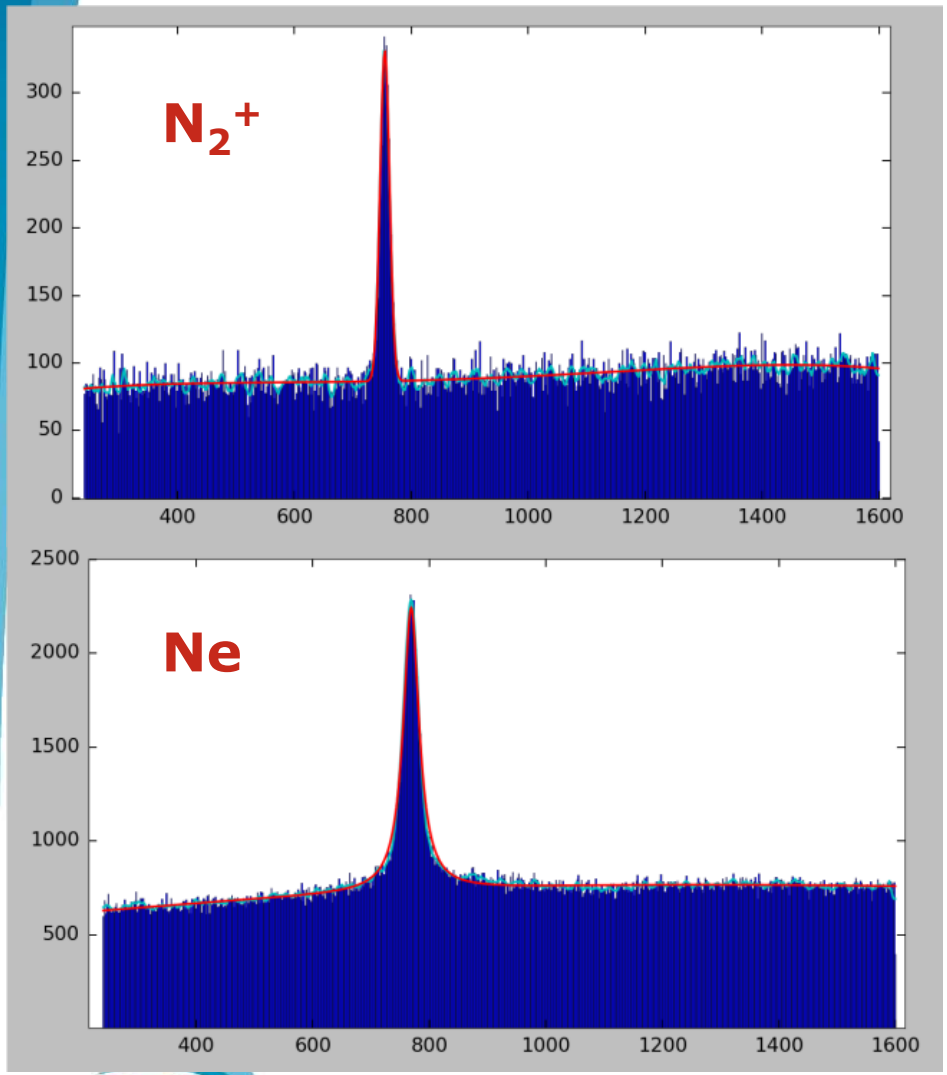
Pressure: $1.4 \cdot 10^{-7}$ mbar
e-beam: 7 keV, ≈30 µA, focused to ≈1 mm
Integration time: 160 s
Filter @390 nm, 10 nm FWHM
Emitter: N_2^+ @ 391.4 nm
Scale: 45 pixels/mm



Pressure: $4 \cdot 10^{-5}$ mbar
e-beam: 7 keV, ≈30 µA, focused to ≈1 mm
Integration time: 400 s
Filter 550-600 nm, flat top
Emitter: Ne @ 585.4 nm

Comparison between Nitrogen and Neon

1D histograms after integration along beam axis



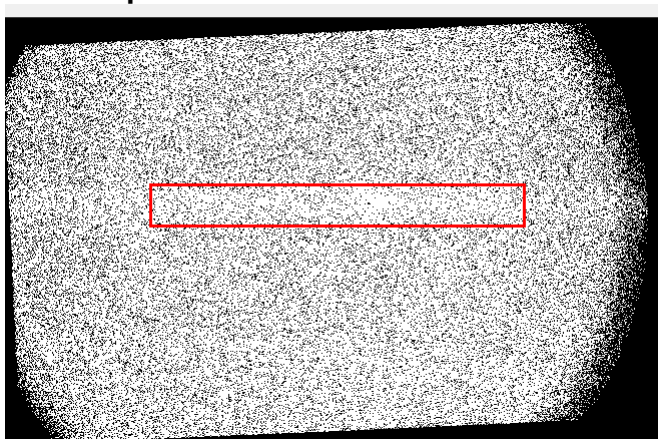
Width: FWHM = 0.42 mm
Signal strength:
N_γ measured: 2500
N_γ estimate: 2000
⇒ **within expected uncertainties!**
Signal-background ratio: As expected !
(pressure is main error)

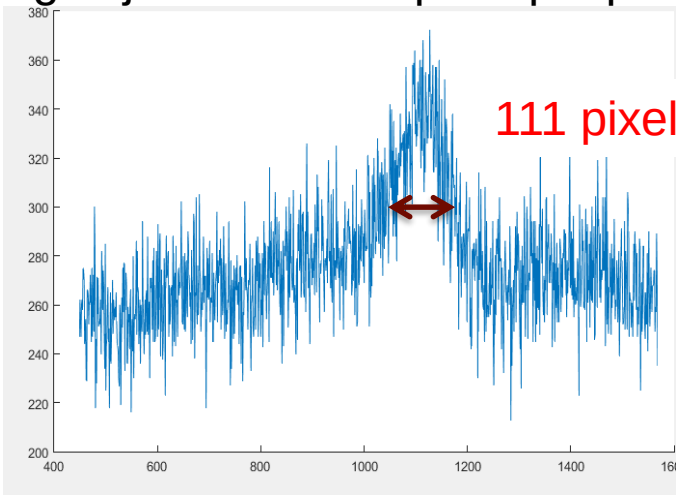
Width: FWHM = 0.75 mm
Signal strength:
N_γ measured: 40000
N_γ estimate: 12700
⇒ **within expected uncertainties!**
Signal-background ratio:
As expected (pressure is main error)

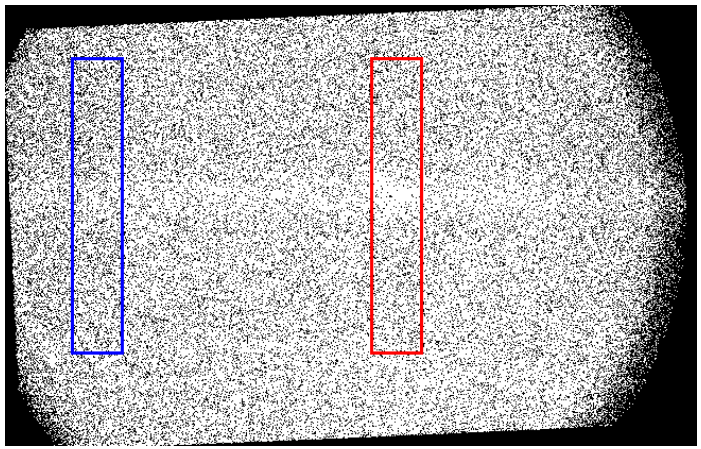
Fit of peak: Voigt profile
Background: 4th oder polynomial
Remark: Voigt profile is a convolution of a Gaussain and a Lorentz-curve

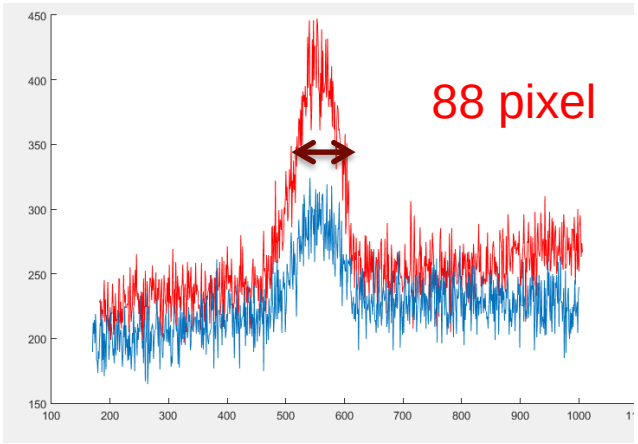
Recent results with improved N_2 gas jet

Parameter: Electron beam energy: 5keV Current: I_{ele} ~ 30µA
Pressure: p ~ 6*10^{-8} mbar, 4000 s integration time
⇒ overlap between electron beam and gas jet found and principle proved !









Conclusions and outlook

BIF for transverse profile at e-lens

- **Optical setup & image intensifier produced at tested**
- First tests at gas curtain performed, but needs improvements
- Pressure range 10^{-9} to 10^{-5} mbar

- **N_2** excited by **p^+**: lines well known up to 400 GeV, considered as reference
- **N_2** excited by **e^-**: well investigated up to 1 keV e^- energy, higher energies have to be investigated experimentally

- **Ne** excited by **p^+**: investigations required e.g. at LHC, **advantage:** neutral Ne
- **Ne** excited by **e^-**: emission due to neutrals well investigated up to 1 keV e^- investigations needed for higher energies

- **Ar** excited by **p^+**: many lines, investigated at some MeV, no extensive literature research until now
- **Ar** excited by **e^-**: no data available yet, no literature search

Outlook

- Further investigations at Cockcroft Institute
- Some measurements at low energy ion accelerators at GSI & TU-München
- Installation of a profile monitor in LHC would be very helpful
- Advantage of Ne (yellow lines): Neutral Ne emitter ⇒ **no** space charge influence

Thank you for your attention

Extra slides

Photon rate estimation for hollow e-lens

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

n = $2.5 \cdot 10^{10}$ cm^{-3}
d = $5 \cdot 10^{-2}$ cm
Ω = $4\pi\ 10^{-4}$ sr
T = 70%
T_f = 30%
η_{MCP}= 50%

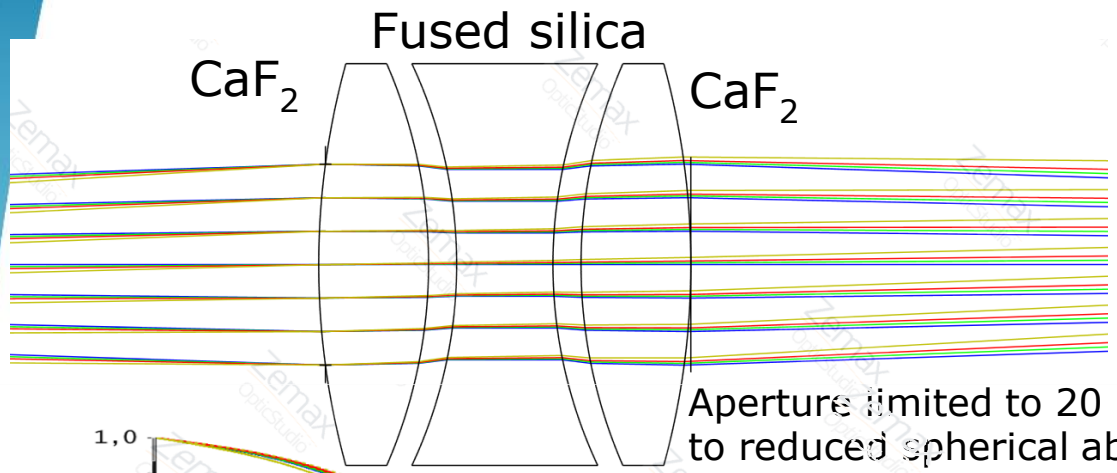
N_γ = average number of photons detected during time Δt
σ = cross section of the photon generation process
I = electron or proton current (electrical)
e = elementary charge
n = gas density
d = distance traveled through gas (curtain thickness)
Ω = solid angle of the optics
T = transmittance of the optical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

Projectile	Gas	λ [nm]	σ [cm^2]	I [A]	η_{pc}	N_γ [s^{-1}]	$1/N_\gamma$ [s]
electron	N_2	337.1	$1.5 \cdot 10^{-23}$	5	0.2	1.2	0.8
electron	N_2	391.4	$9.1 \cdot 10^{-19}$	5	0.2	$7.5 \cdot 10^{4}$	$1.3 \cdot 10^{-5}$
proton	N_2	391.4	$3.7 \cdot 10^{-20}$	1	0.2	$6.1 \cdot 10^{2}$	$1.6 \cdot 10^{-3}$
electron	Ne	585.4	$1.4 \cdot 10^{-20}$	5	0.05	$2.9 \cdot 10^{2}$	$3.5 \cdot 10^{-3}$
proton	Ne	585.4	$4.7 \cdot 10^{-22}$	1	0.05	1.9	0.5

Optics: requirements

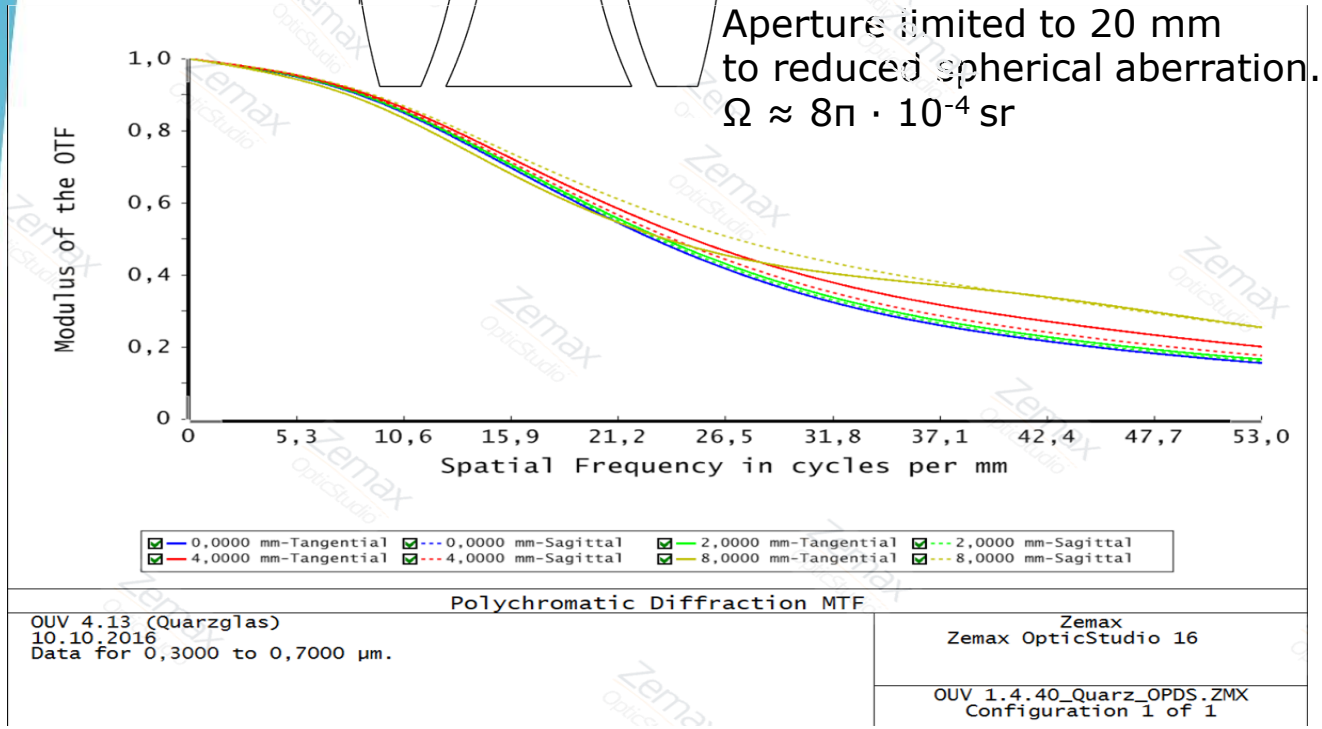
- Good transmission in the near UV, at least in the region 300 to 400 nm
- Good resolution, well corrected geometrical and chromatic aberrations
- A magnification of about 1 (absolute value) due to the relatively low resolution of the double MCP stack of at most 20 lp/mm
- Relatively large working distance to allow the placement of the detector system at d > 400 mm from the beam axis
- Large acceptance, a solid angle of about $4\pi \cdot 10^{-4}$ sr desirable
- Total depth of field (DOF) up to 15 mm with reasonable blur; can be relaxed if an appropriate setup geometry is used: camera looking perpendicular to the curtain plane or application of the Scheimpflug principle

Optics: commercially available lens

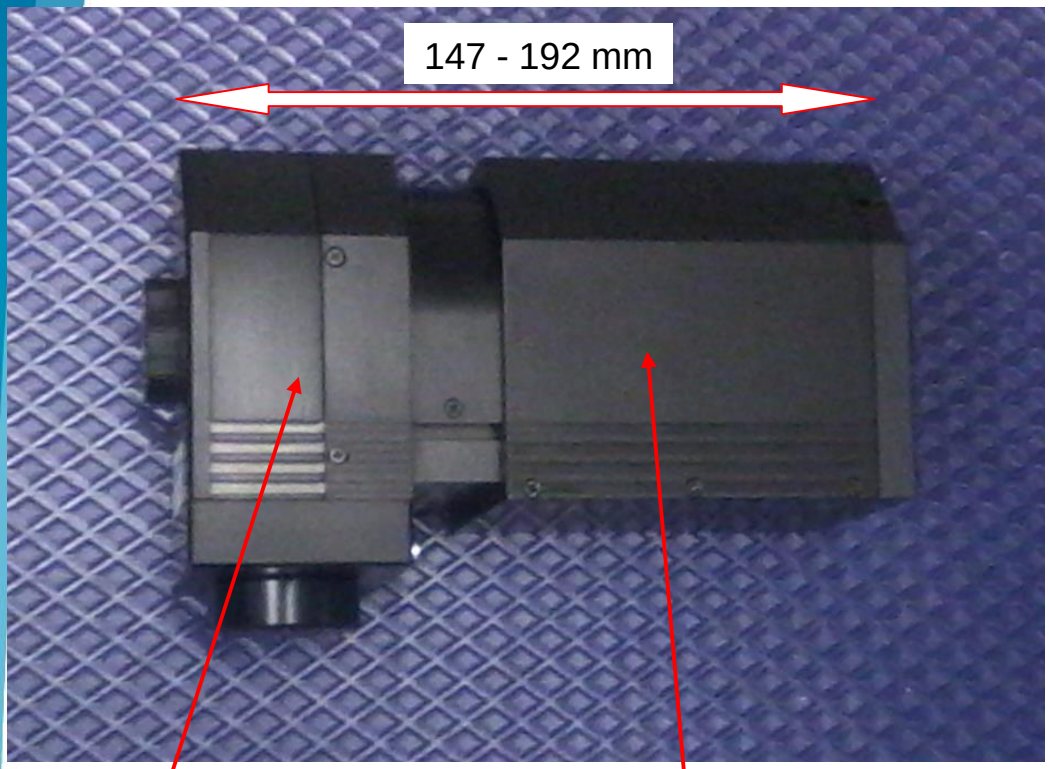


Optimized for 1:-1 imaging
Focal length (EFL): 160 mm
Maximum aperture: 40 mm
Mount diameter: 50 mm
Mount length: 54 mm
Thread: M48x1

Aperture limited to 20 mm to reduced spherical aberration.
$\Omega \approx 8\pi \cdot 10^{-4}$ sr



The ProxiKit PKS 2581 TZ-V 25 µs

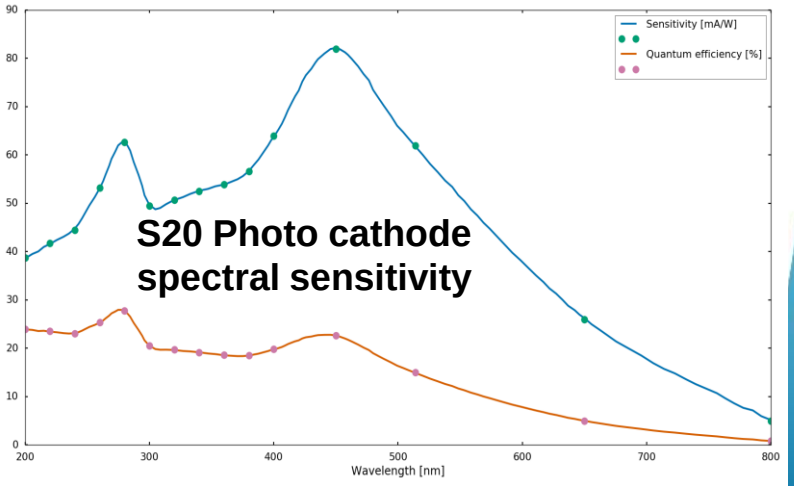


Double MCP based image intensifier and associated electronics modules

Relay optics module to image the phosphor screen onto the camera chip

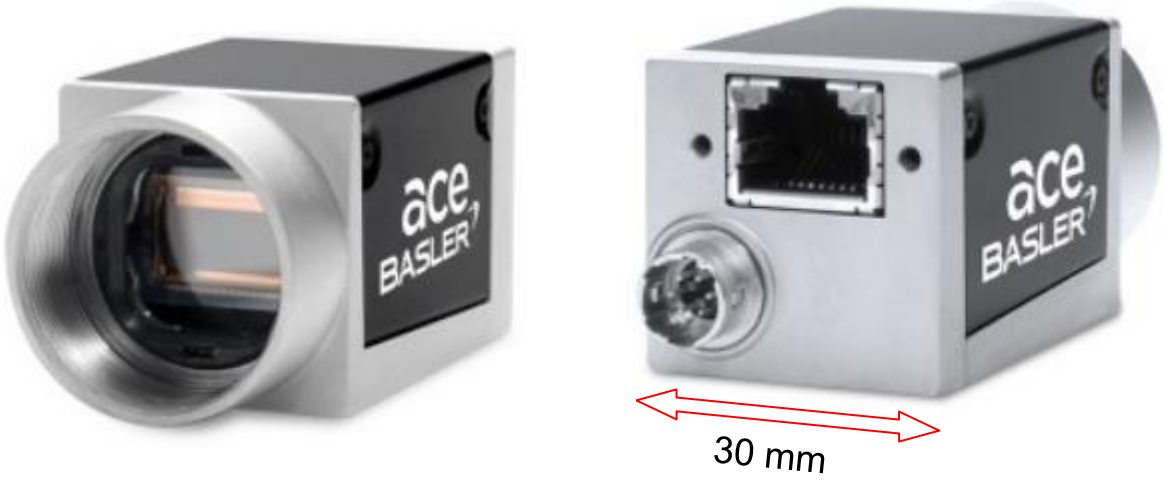
Features:

– UV enhanced S20 photo-cathode
– P43 phosphor screen
– TTL gate: 25 µs to ∞, f_{max} = 1 kHz
– Flexible, user serviceable relay optics based on a Schneider Componon 12 lens offering many image ratios, e.g. 18:11 & 25:11
– Any camera with C-mount mechanics or adaptable to it can be used, as long as the detector is sensitive in the visible wavelength range as emitted by the P43

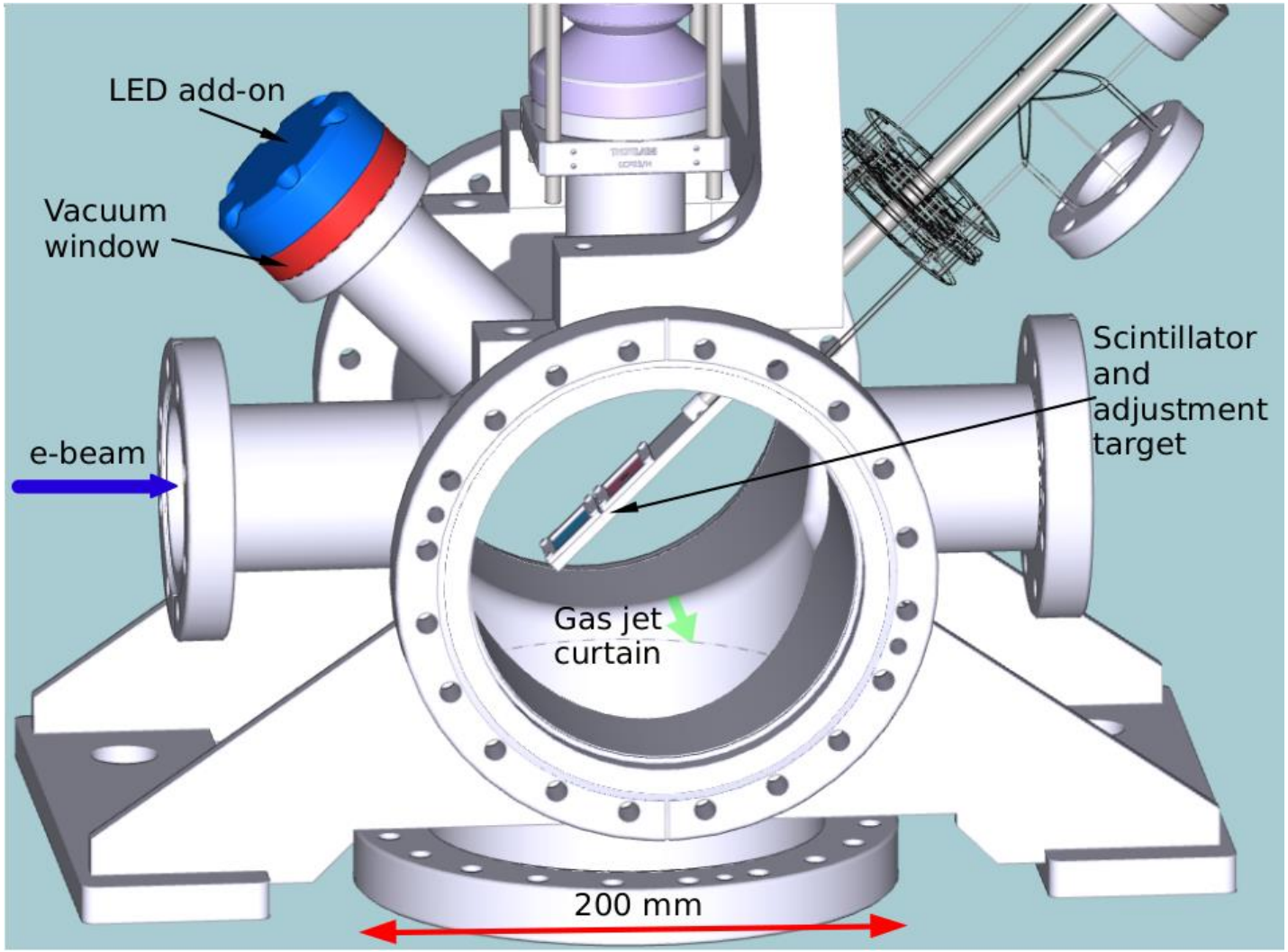


The acA1920-40gm CMOS camera

Seller/ Manufacturer	Sensor	Resolution	Video Output	Exposure time	Trigger	I/O	Power (lowest voltage)
Rauscher/ Basler	Sony 1/1.2" IMX249, CMOS, 5,86x5,86 µm², Global Shutter	1920x1200	Mono 8bit, 12bit, 12bit packed	34 µs @ 8bit/ 40 µs @ 12bit – 10 s or trigger width	*Hardware Trigger:* Pulse-Edge, Pulse-Width *Trigger Modes:* Trigger Width, Sequence	1x ISO IN 1x ISO OUT 1x GP IN/OUT	PoE (36V)/ 12V DC via 6-Pin Hirose



Adjustment target



Note: A solution based on LEDs placed in vacuum, as used successfully at GSI, is not possible because of the much stricter vacuum conditions.