Fluorescence Profile Monitor for the CERN e-Lens

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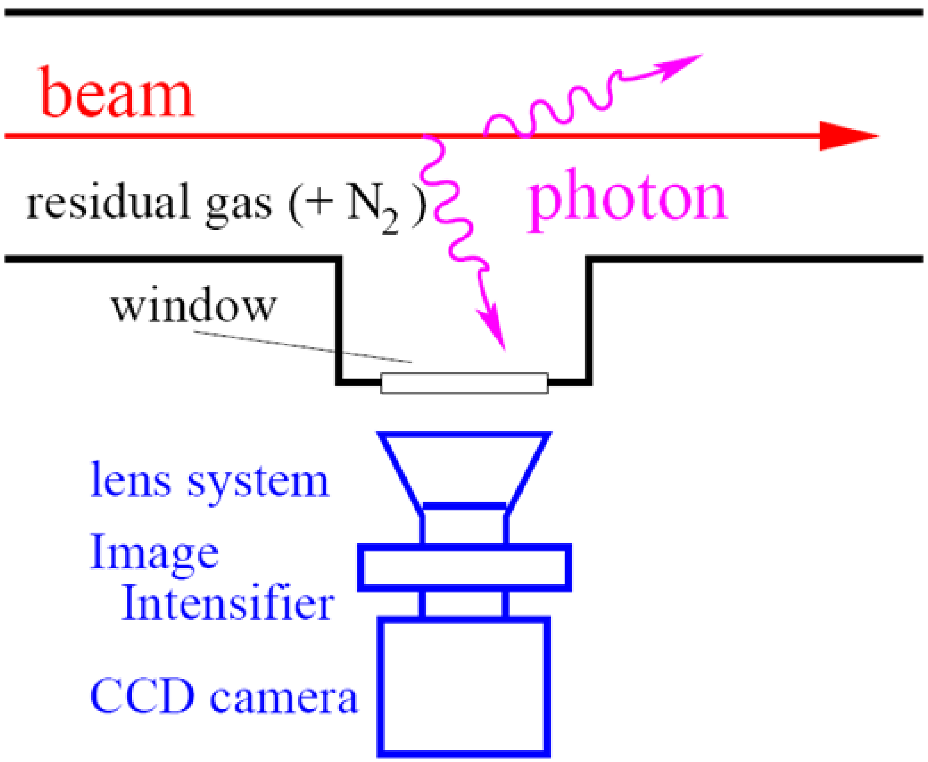
Outline

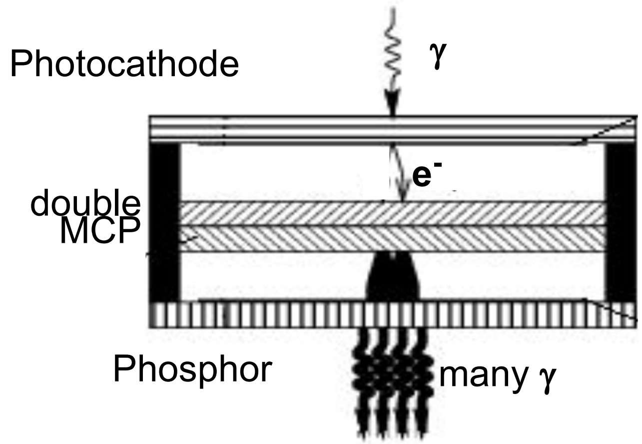
- Beam Induced Fluorescence (BIF) working principle and features
- Characteristics of the CERN e-lens setup
- N_2 as working gas
- Ion and electron dynamics
- Ne as working gas
- Optics
- Open questions
- Conclusions

Beam Induced Fluorescence Features @ GSI

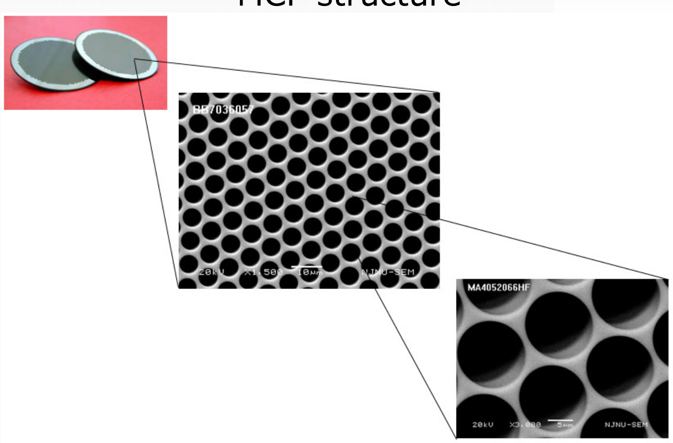
- Based upon the detection of photons emitted by residual or injected (low pressure) gas molecules
- Little influence on the beam
- Single pulse observation possible; down to ≈ 1 μs time resolution
- High resolution, e.g. 0.2 mm/pixel, can be easily matched to application
- Commercial image intensifier available
- Compact installation, e.g. 25 cm for both planes



Intensified CCD working principle



MCP structure



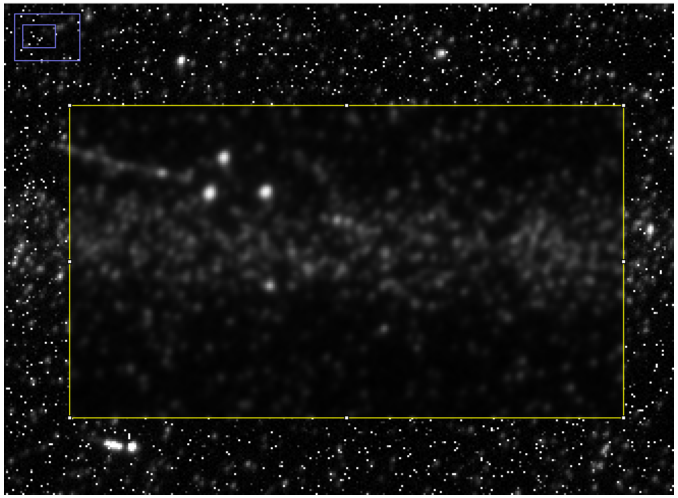
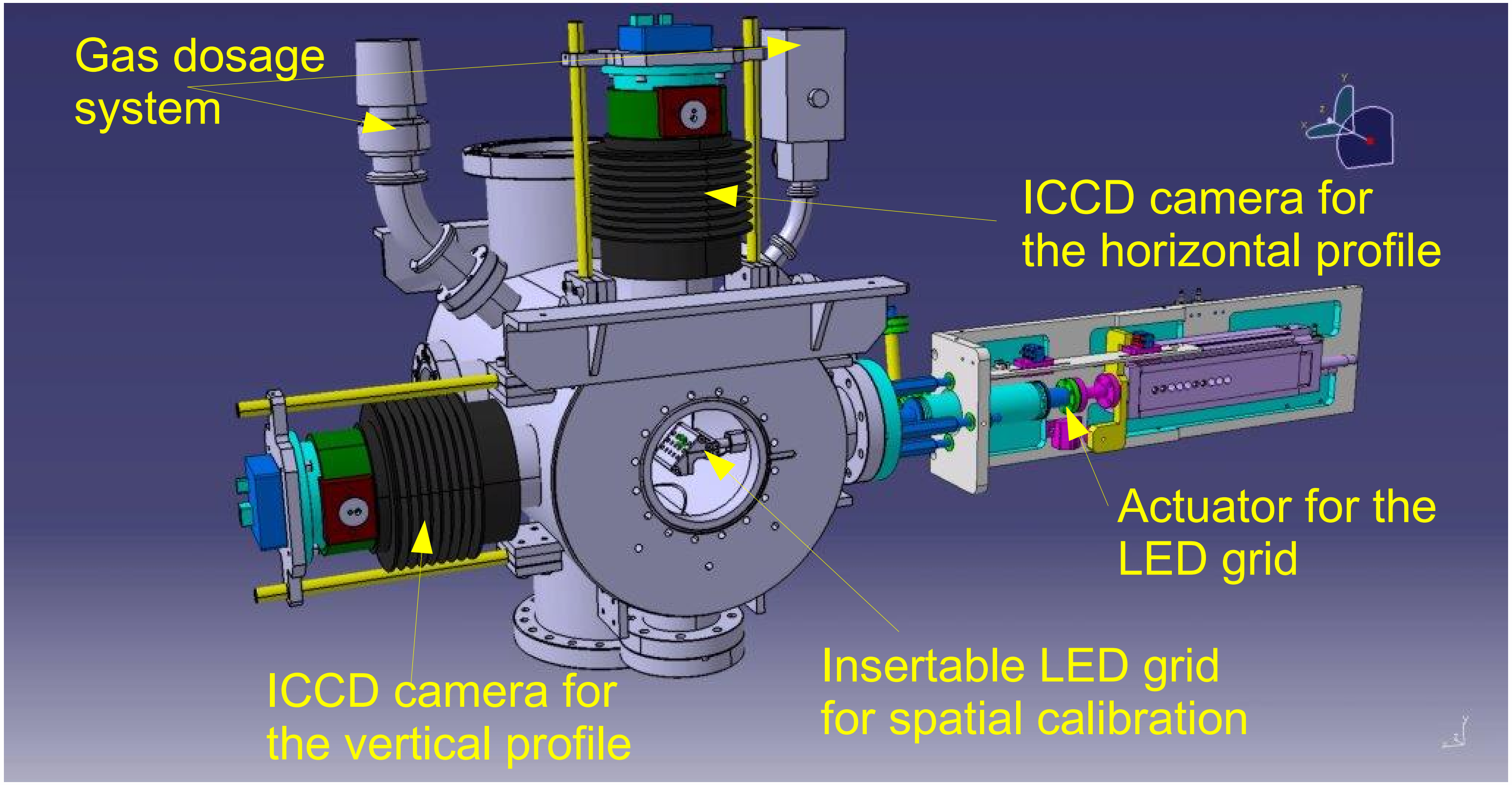


Image from $5\cdot10^8$, 300 MeV/u $^{238}U^{73+}$ ions in N_2, p= $5\cdot10^{-3}$ mbar.

BIF-Monitors at the GSI UNILAC

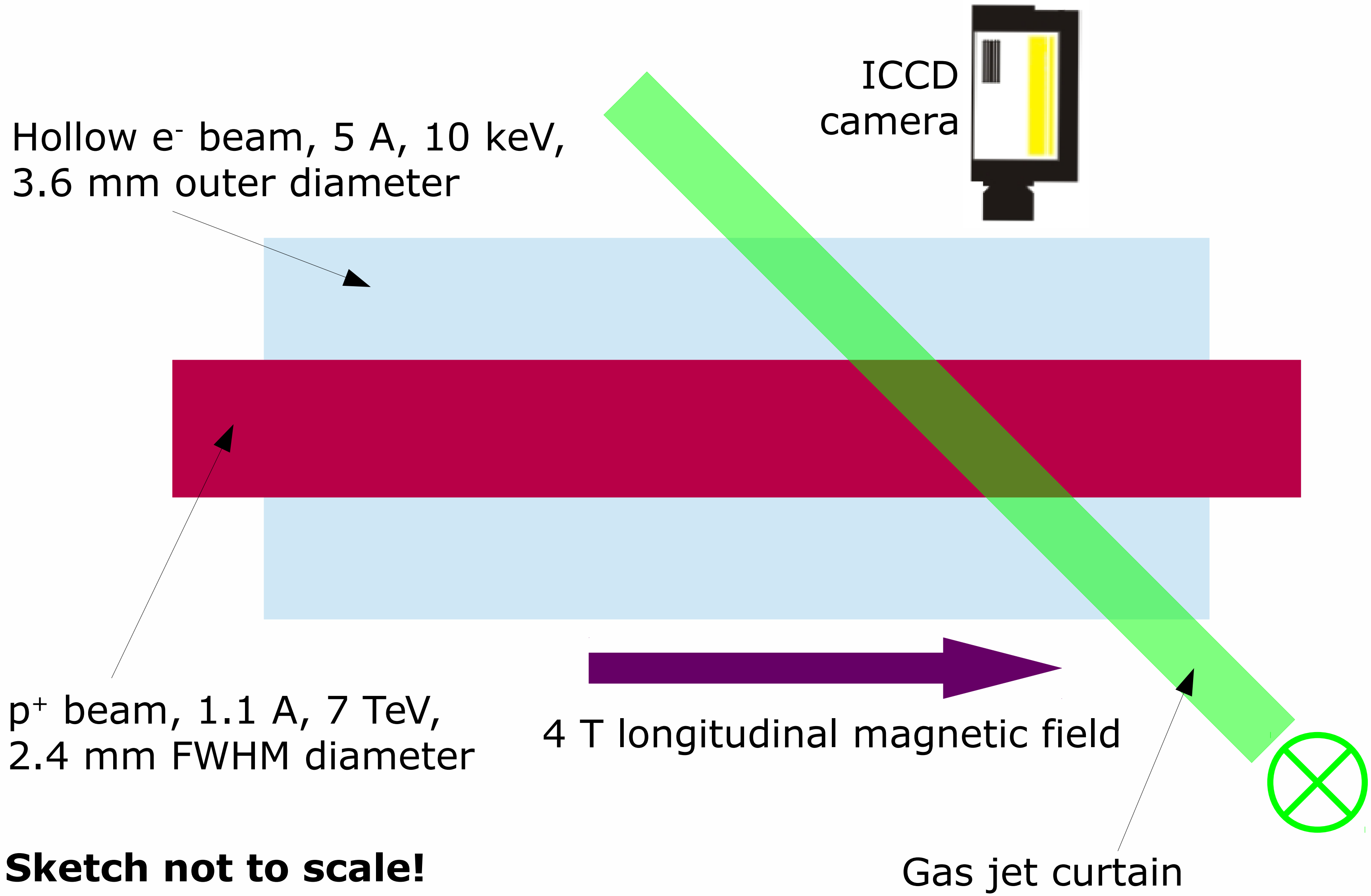
Six BIF stations at the GSI LINAC:

- 2 x image intensified CCD cameras each
- Optics with reproduction scale 0.2 mm/pixel
- Insertion length 25 cm for both directions only
- Single macro-pulse observation



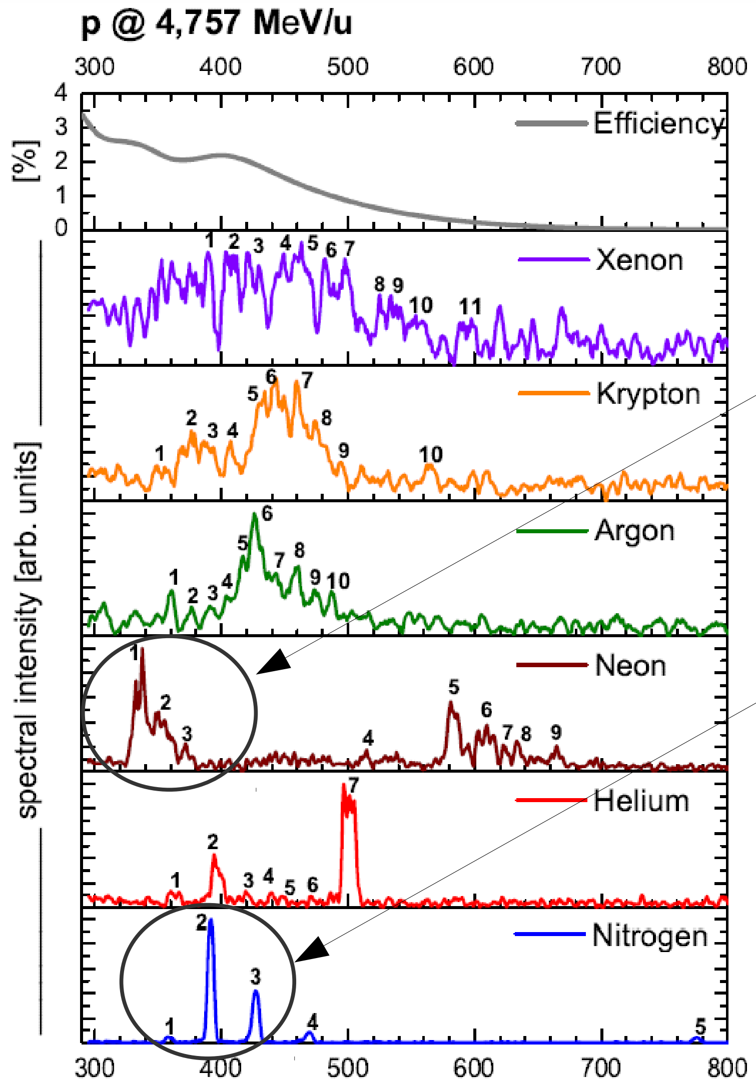
F. Becker (GSI) et al., Proc. DIPAC'07, C. Andre (GSI) et al., Proc. DIPAC'11, IBIC'14

E-Lens and BIF @ CERN



Sketch not to scale!

Fluorescence of different gases



Several Ne^{+} lines mainly corresponding to different $[2s^2 2p^4(^3P)]3p \rightarrow 3s$ transitions and with life times below 10 ns.

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

Note: Nitrogen has a higher photon yield than noble gases; scaling intensity by energy loss results in an almost constant value for noble gases.

F. Becker, Ph.D. thesis, T.U. Darmstadt, Germany, 2009

N_2 as working gas: excitation and emission

$N_2 + p/e^- \rightarrow (N_2^+)^* + e^- + p/e^- \rightarrow N_2^+ + \gamma + e^- + p/e^-$

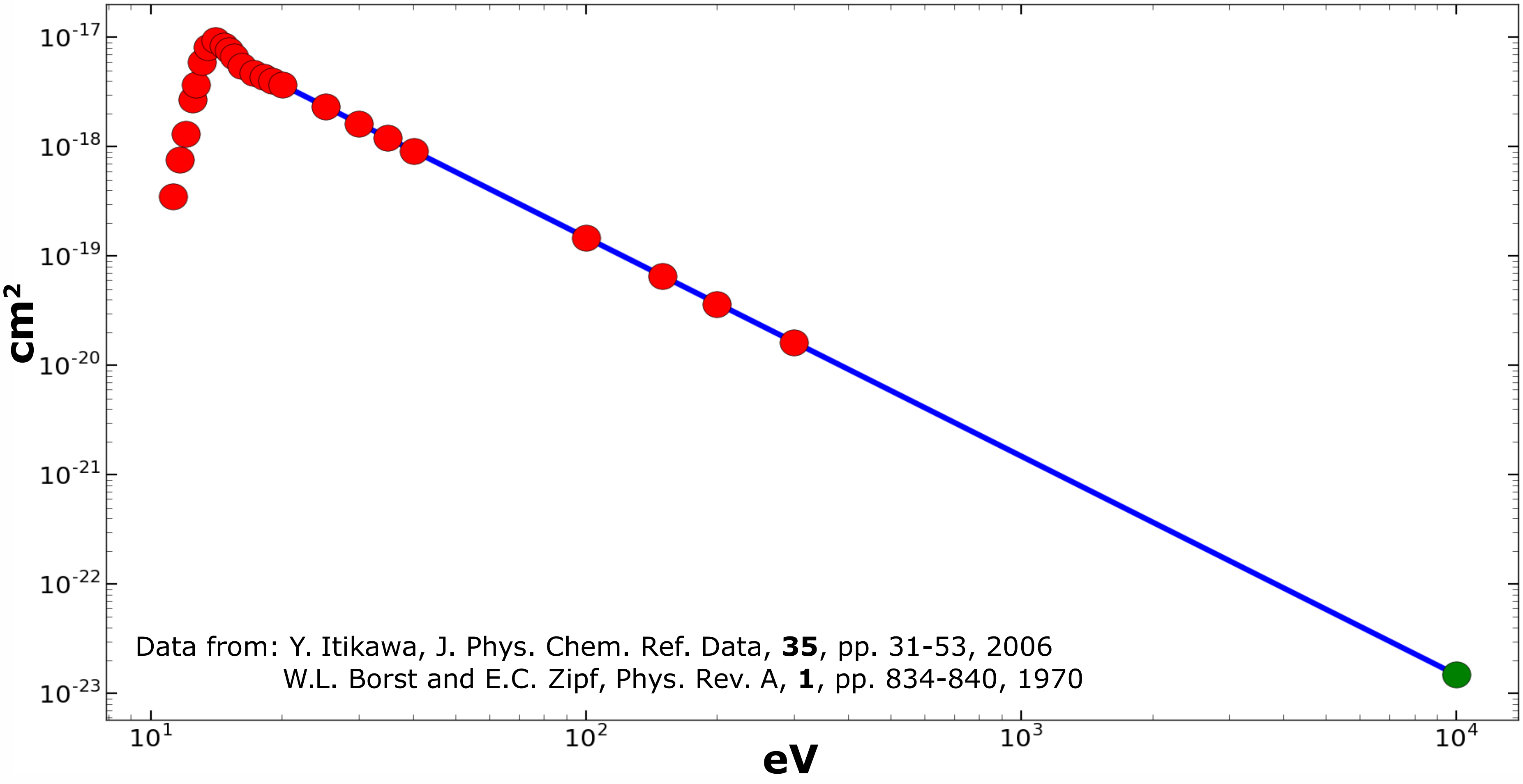
Leads to the electronic transition $B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$ of the molecular ion with wavelengths around 391 nm, depending upon involved vibrational and rotational states

$N_2 + e^- \rightarrow (N_2)^* + e^- \rightarrow N_2 + \gamma + e^-$

Drives the electronic transition $C^3\Pi_u \rightarrow B^3\Pi_g$ of the neutral molecule with wavelengths around 337 nm. This process cannot be initiated directly by protons.

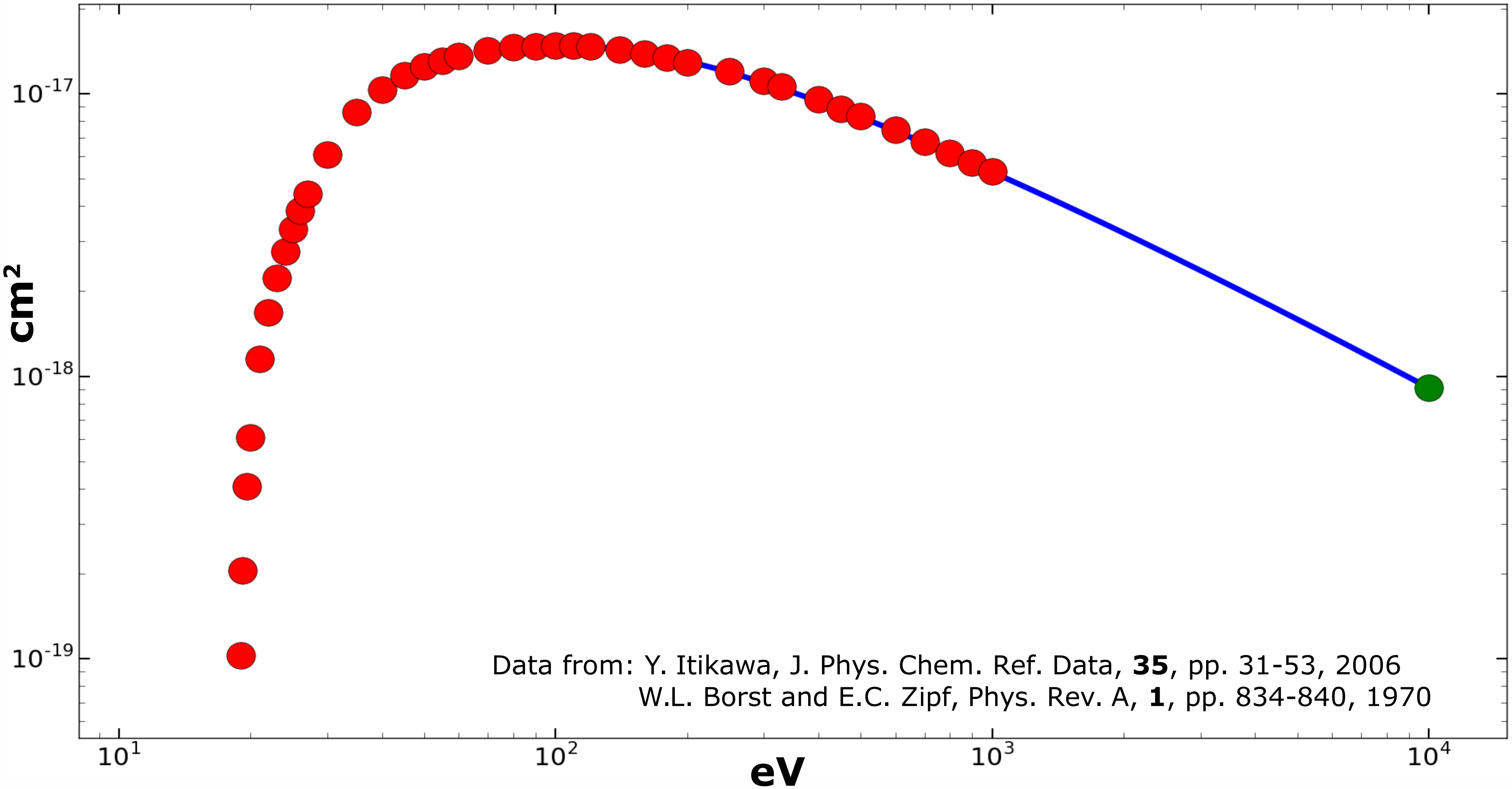
Note: Ionization is relevant too, due to the generation of secondary low energy electrons with high cross sections for excitation and/or ionization of N_2.

N_2 as working gas: $C^3\Pi_u \rightarrow B^3\Pi_g$ cross section for e^-



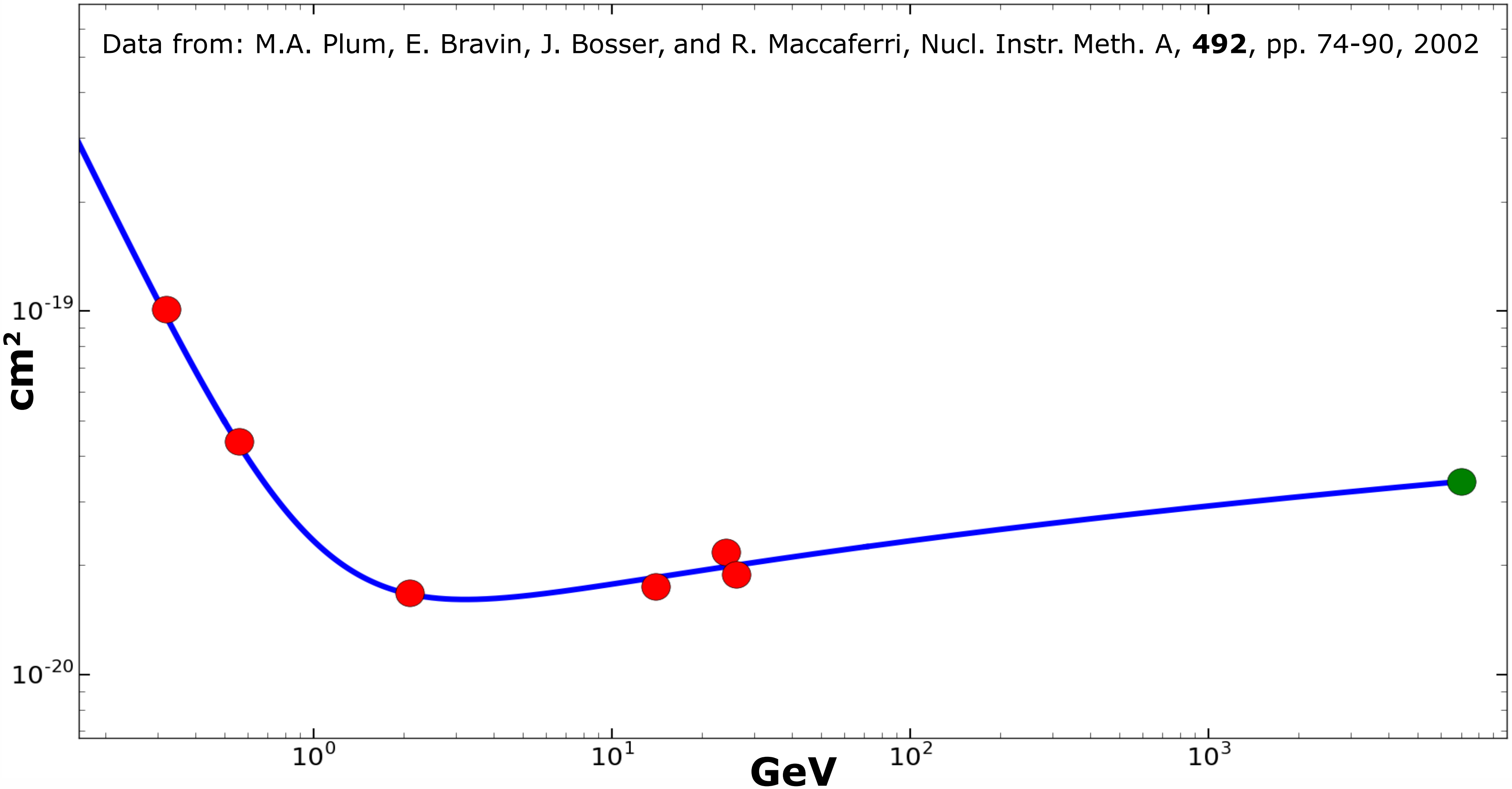
$$\sigma^{e}_{337} \approx 1.48 \cdot 10^{-15} \cdot E^{-2}\, cm^2 = 1.48 \cdot 10^{-23}\, cm^2 @ 10\, keV$$

N_2 as working gas: $B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$ cross section for e⁻



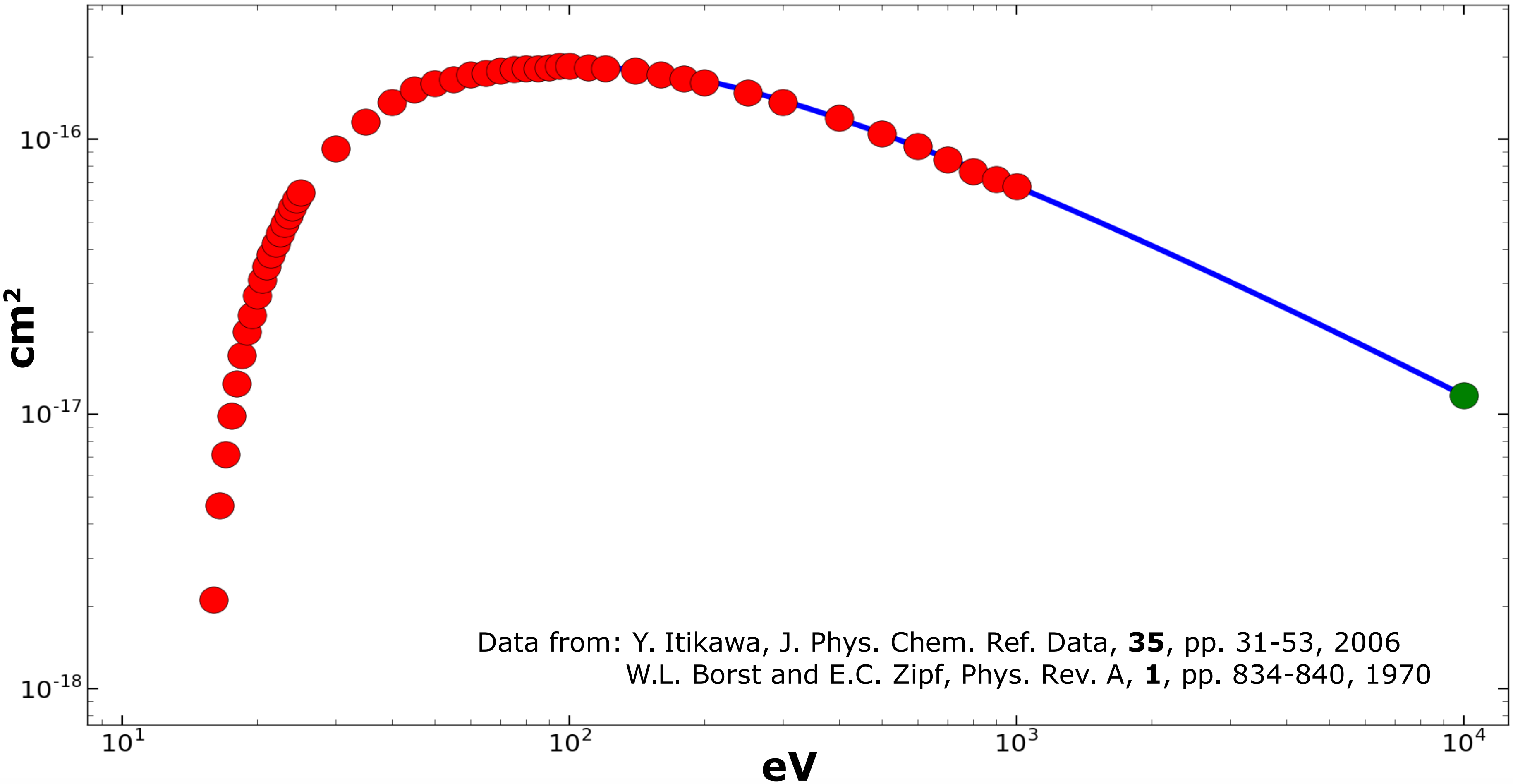
$$\sigma_{391}^{e} \approx \frac{1.66\cdot 10^{-15}}{E}\cdot \ln\left(2.4\cdot 10^{-2}\cdot E\right) cm^2 = 9.1\cdot 10^{-19}\, cm^2 @ 10\, keV$$

N_2 as working gas: $B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$ cross section for p^+



$$\sigma_{391}^{p} \approx 1.3 \cdot 10^{-21} \cdot \left[\left(1 + \left(\frac{0.94}{p \cdot c}\right)^2\right) \cdot \left(2 \cdot \ln\left(\frac{p \cdot c}{0.94}\right) + 10.3\right) - 1 \right] cm^2 = 3.4 \cdot 10^{-20}\, cm^2 @ 10 keV$$

N_2 as working gas: ionization cross section for e-



$$\sigma_{ion}^{e} \approx \frac{2.15 \cdot 10^{-14}}{E} \cdot \ln\left(2.3 \cdot 10^{-2} \cdot E\right) cm^2 = 1.2 \cdot 10^{-17} cm^2 @ 10\,keV$$

N_2 as working gas: detected photons

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

N_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

N_2 as working gas: specific detection time

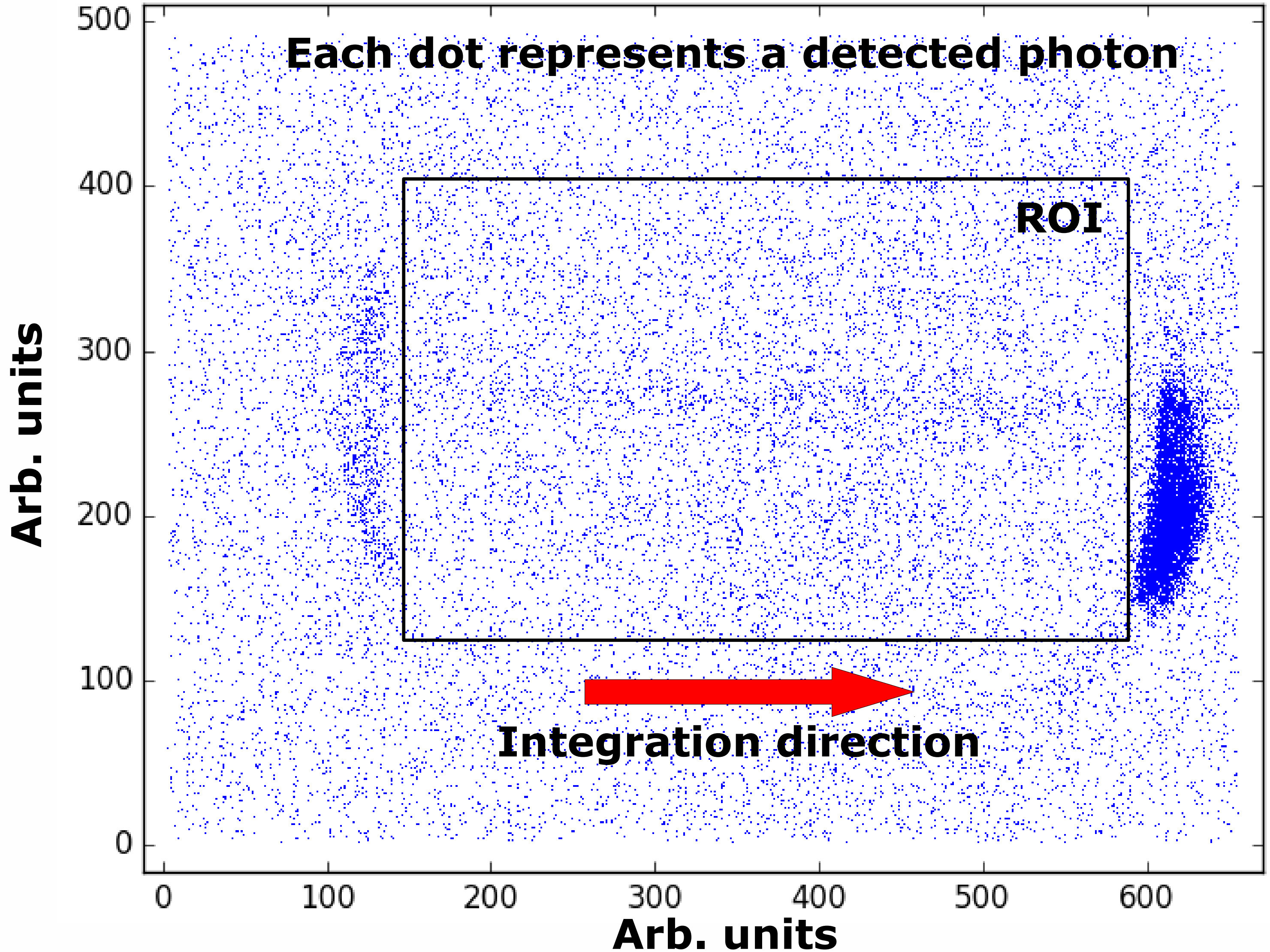
$$N_\gamma = \sigma \cdot \frac{I \cdot \Delta t}{e} \cdot n \cdot d \cdot \frac{\Omega}{4\pi} \cdot T \cdot T_f \cdot \eta_{pc} \cdot \eta_{MCP}$$

$I = 1$ A
$n = 2.5 \cdot 10^{10}$ cm^{-3}
$d = 5 \cdot 10^{-2}$ cm
$\Omega = 4\pi\ 10^{-5}$ sr
$T = 65\%$
$T_f = 30\%$
$\eta_{pc} = 20\%$
$\eta_{MCP} = 50\%$

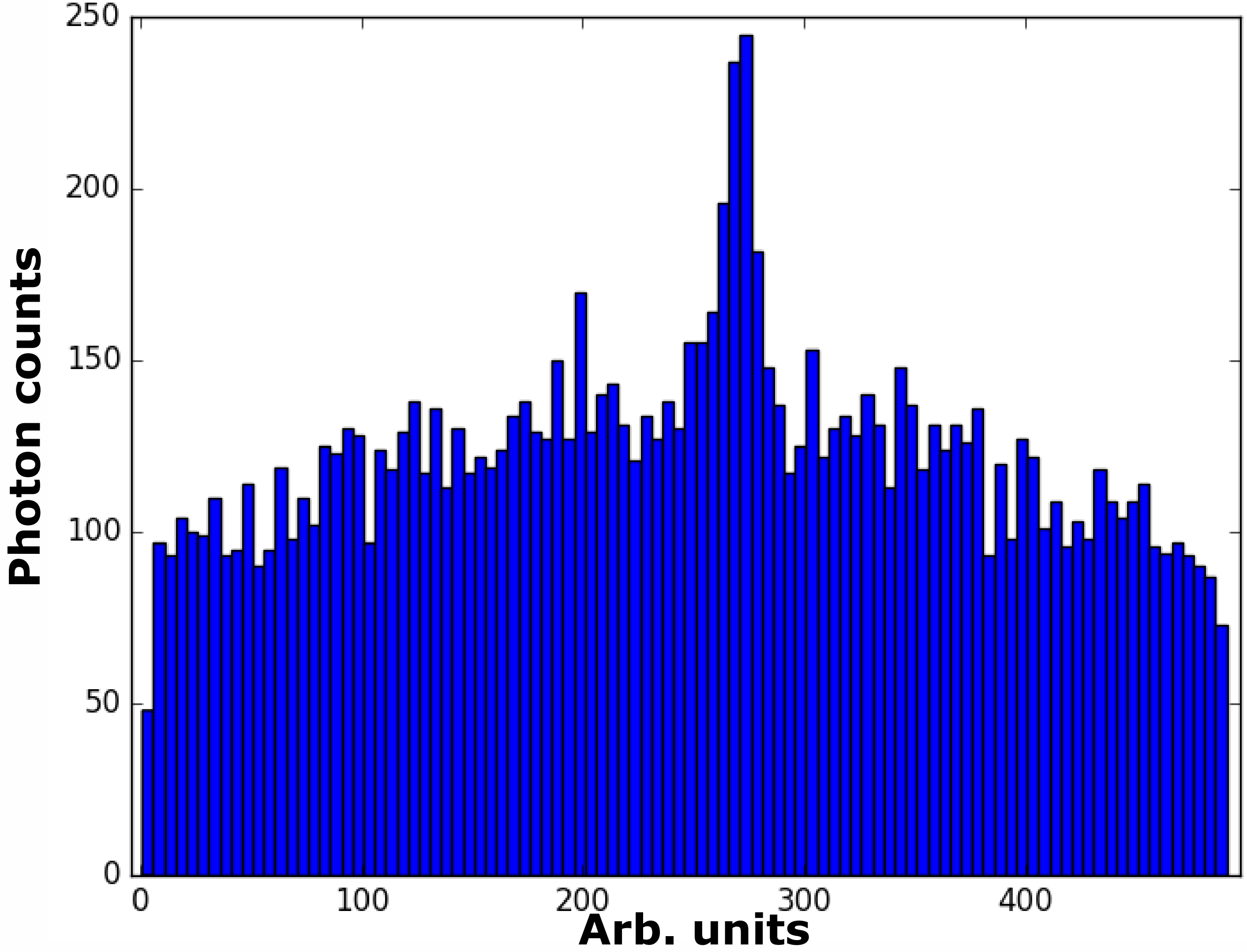
$\Delta t_s(391, p^+) \approx 20$ ms/photon
$\Delta t_s(391, e^-) \approx 0.7$ ms/photon
$\Delta t_s(337, e^-) \approx 46$ s/photon

Note: For the present setup at the Cockroft Institute the cross section @ 391 nm is twice as high, the solid angle at an f-ratio of 5.6 is as considered above but the electron current is approx. 10 μA. This results in $\Delta t_s(391, e^-) \approx 35$ s/photon.

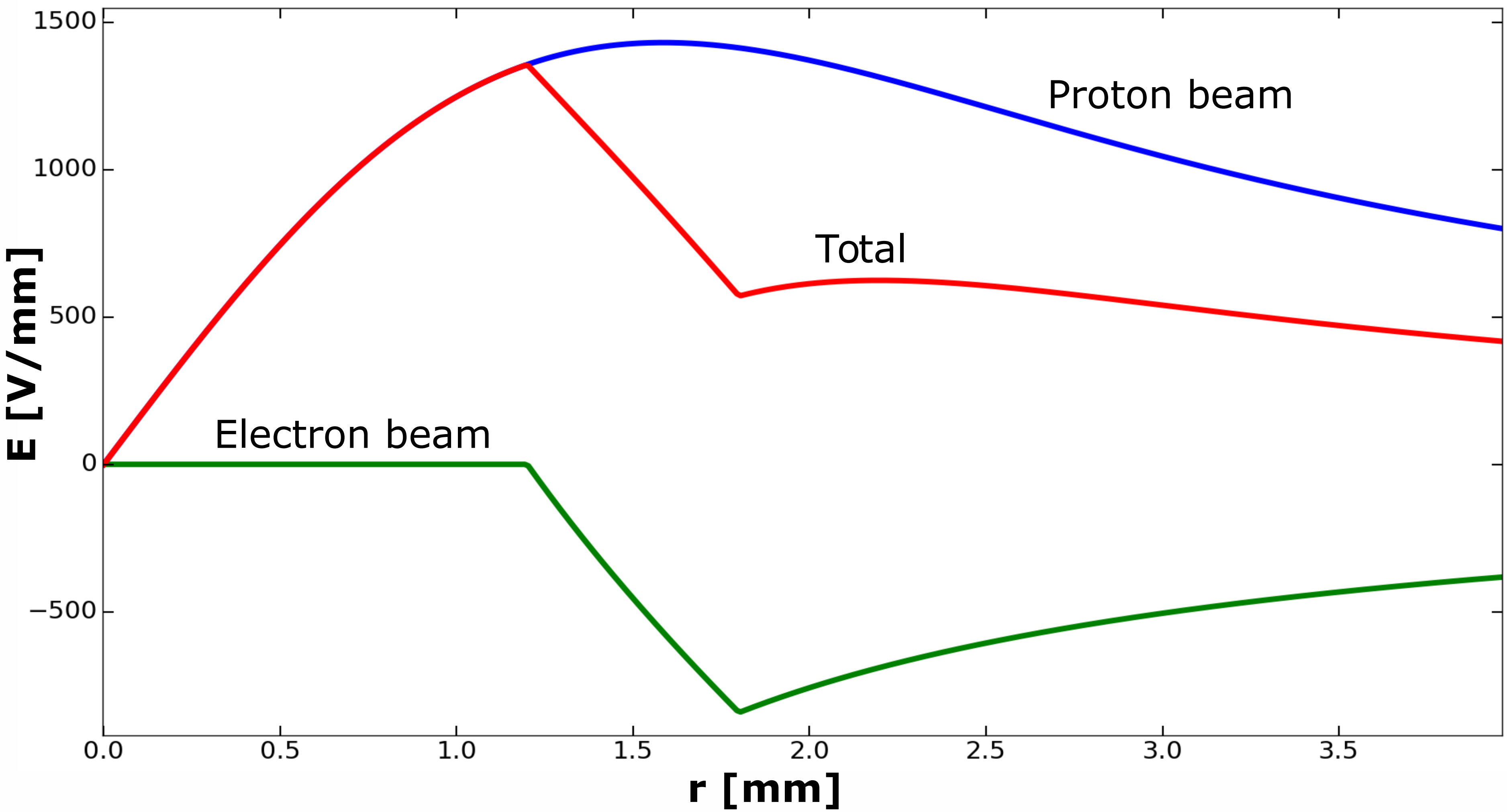
First signal at Cockroft (part 1)



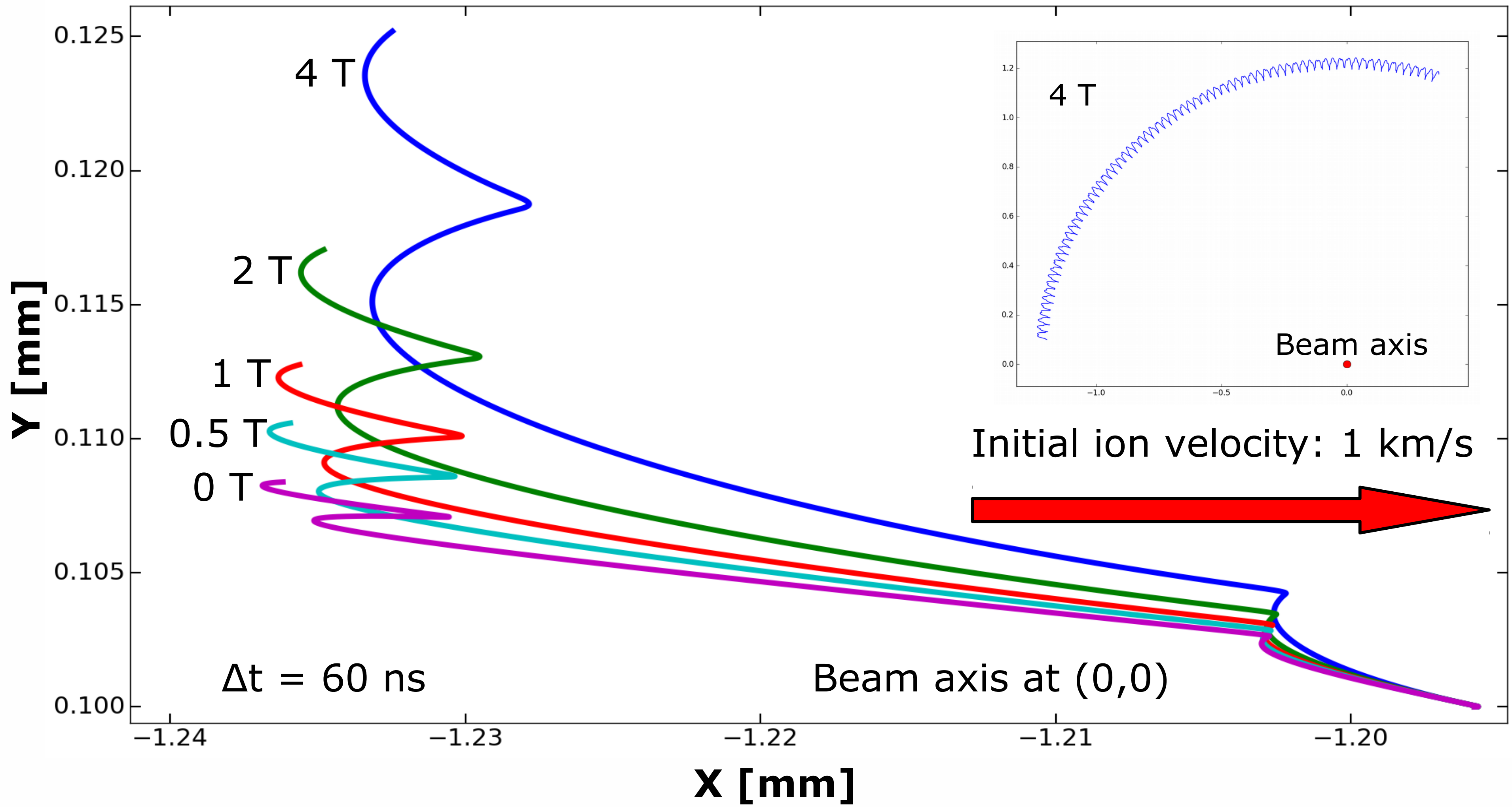
First signal at Cockroft (part 2)



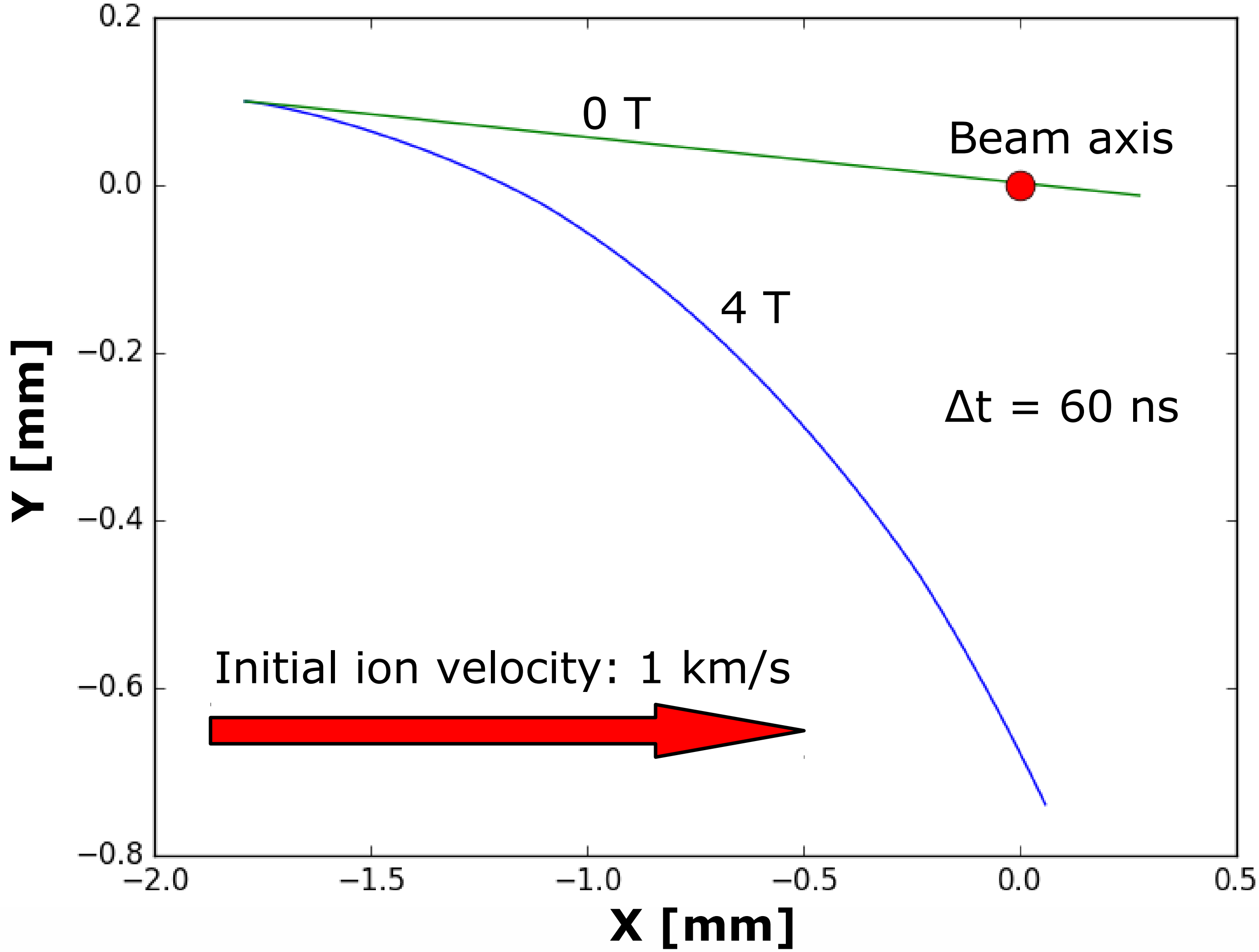
Ion and electron dynamics: electric field



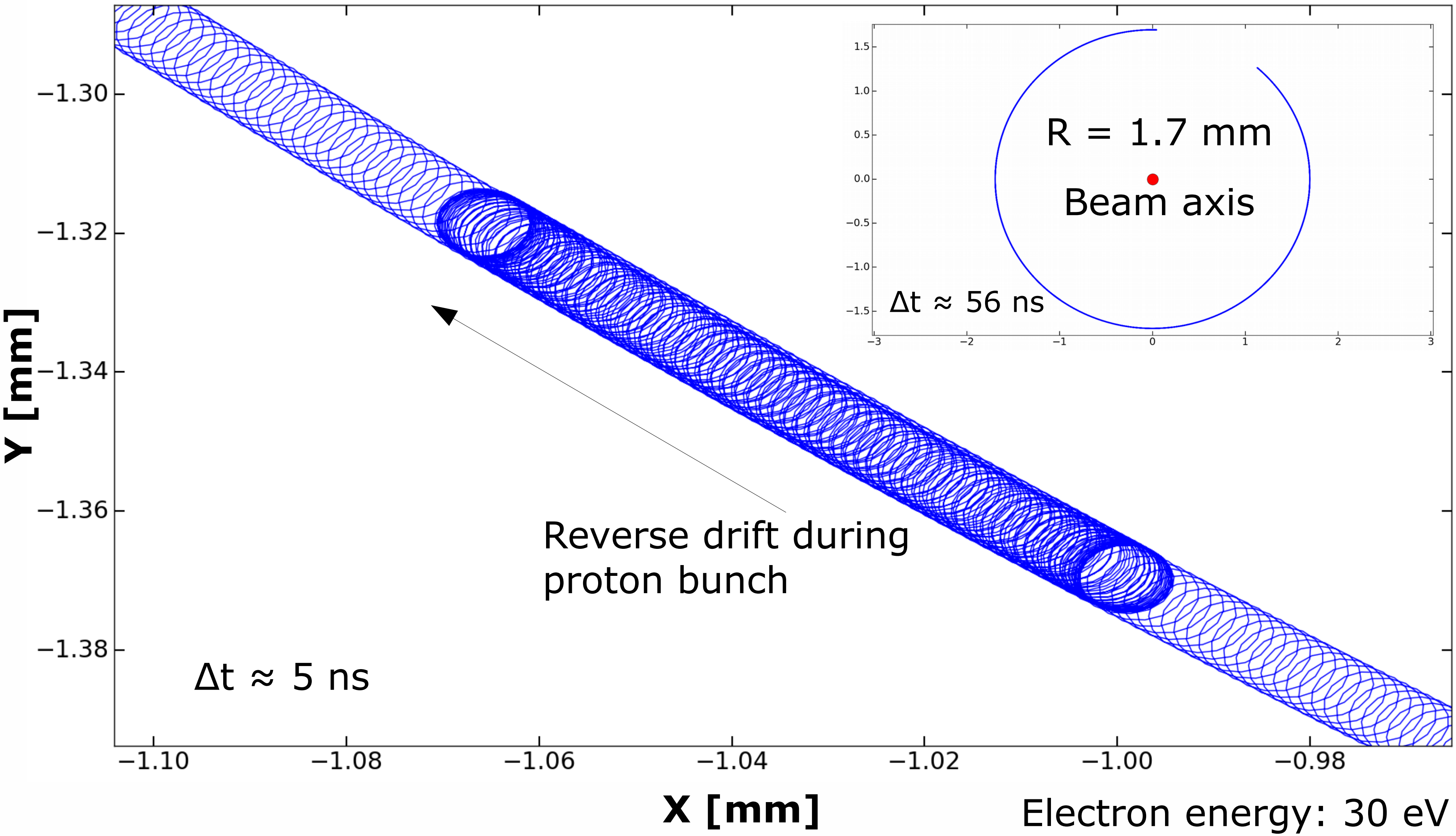
Ion and electron dynamics: N_2 ions (part 1)



Ion and electron dynamics: N_2 ions (part 2)

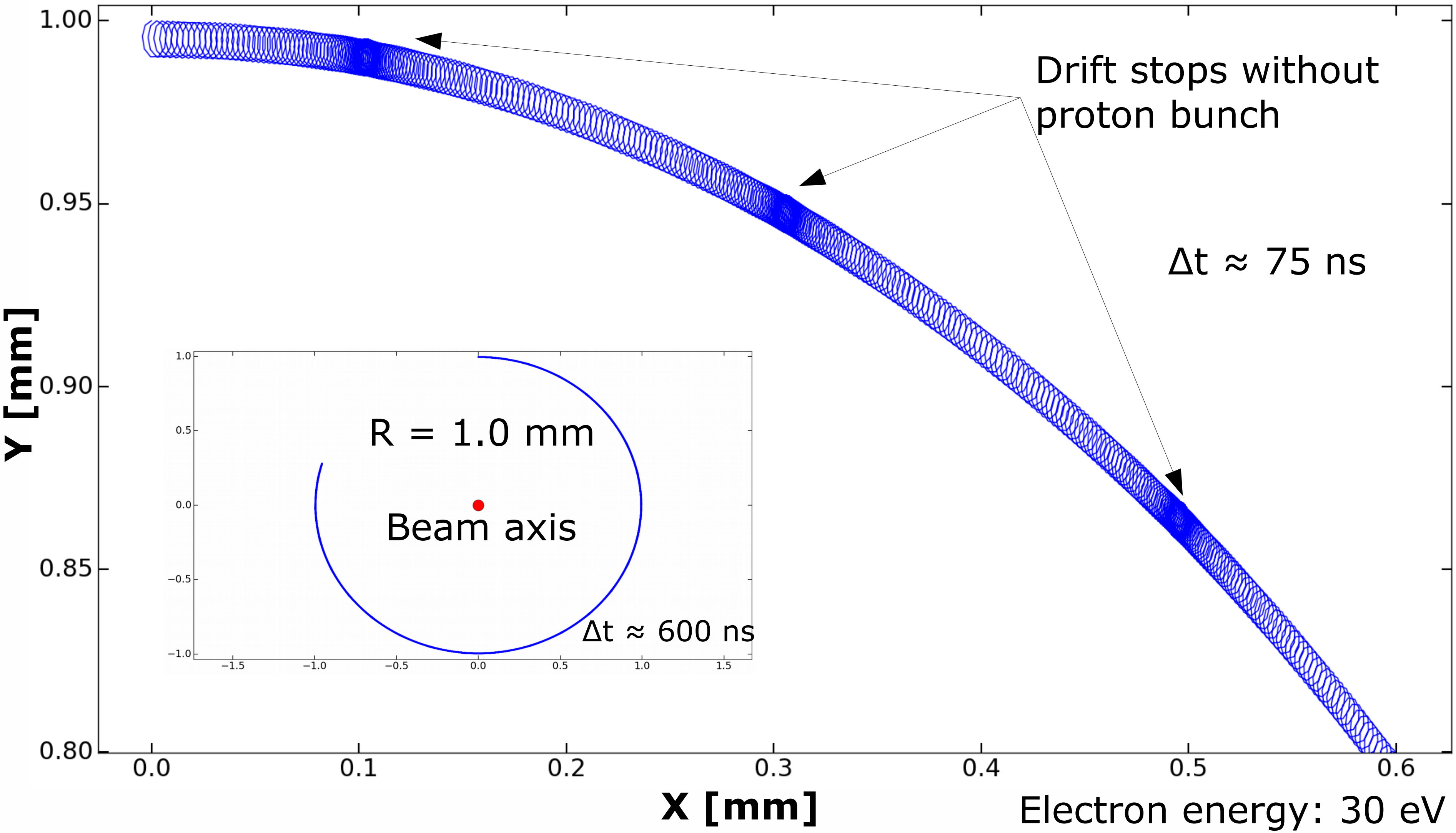


Ion and electron dynamics: electrons (part 1)



Electron energy: 30 eV

Ion and electron dynamics: electrons (part 2)



Electron energy: 30 eV

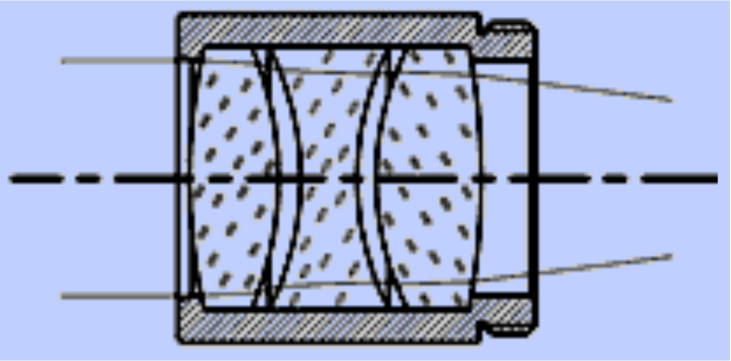
Ne as working gas

- Strong fluorescence due to neutrals
- Ne^+ fluorescence from levels with short life times (< 10 ns)
- Mass comparable with that of N_2
- Emission by neutrals at long wavelengths (λ > 580 nm); photocathodes with higher sensitivity in this region lead to a larger rate of dark counts
- Presently no known data about fluorescence cross sections due to relativistic protons
- Presently known data on cross sections for the interaction with electrons just for the neutral atom, no data regarding combined ionization and excitation

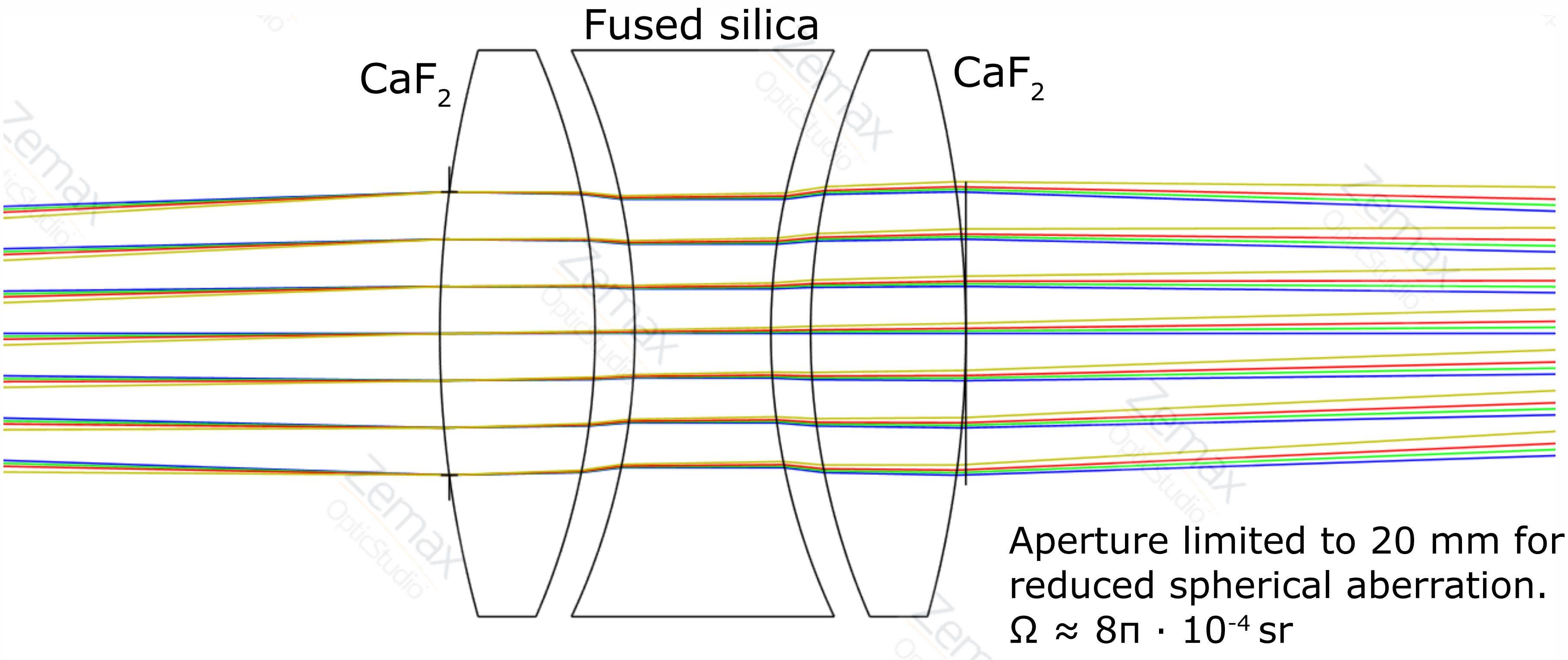
Optics: requirements

- 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 allows 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 up to 15 mm with reasonable blur

Optics: commercially available lens (part 1)

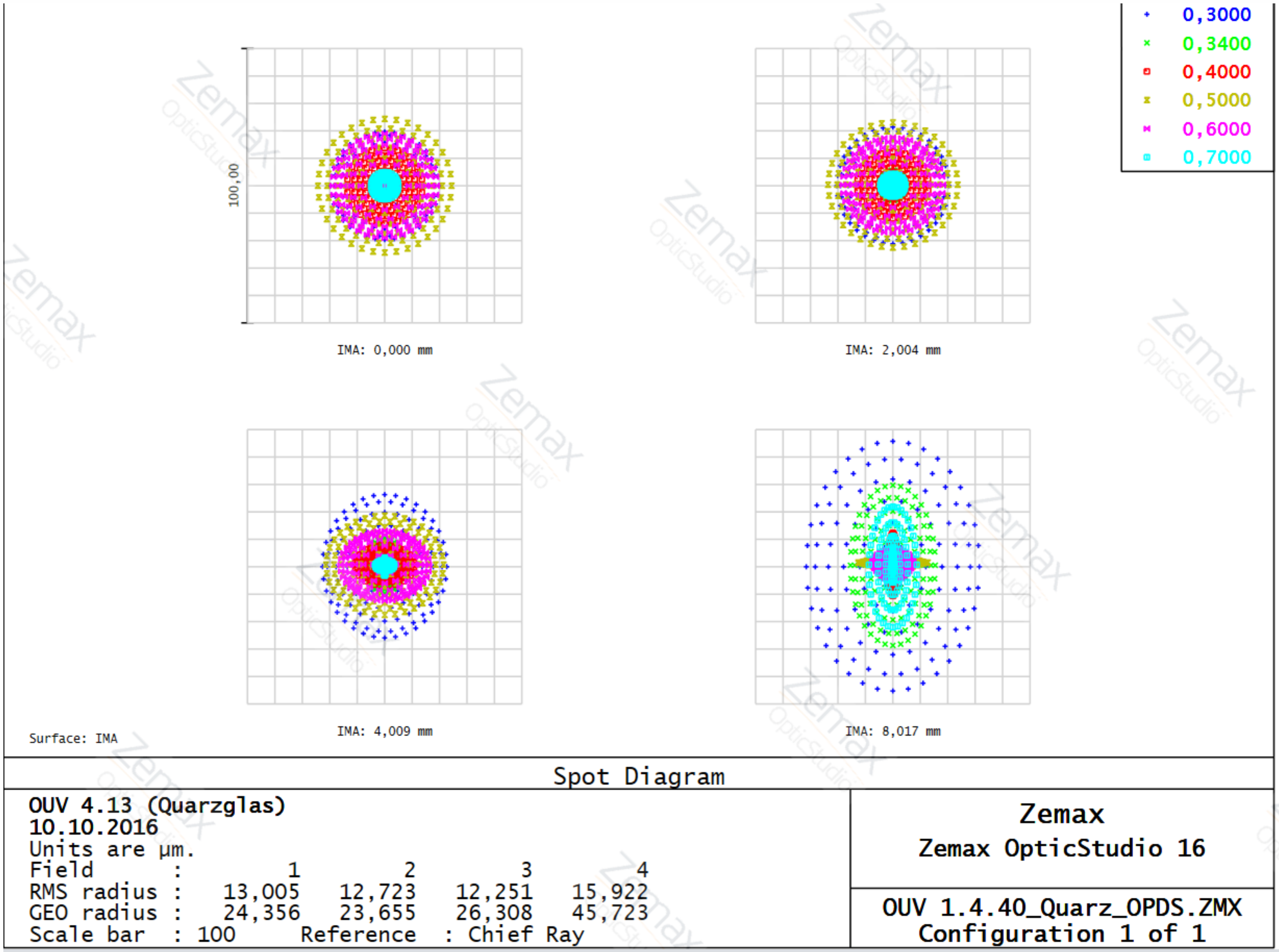


Optimized for 1:-1 imaging
Focal length (EFL): 160 mm
Maximum aperture: 40 mm
Mount diameter: 50 mm
Mount length: 54 mm
Thread: M48x1

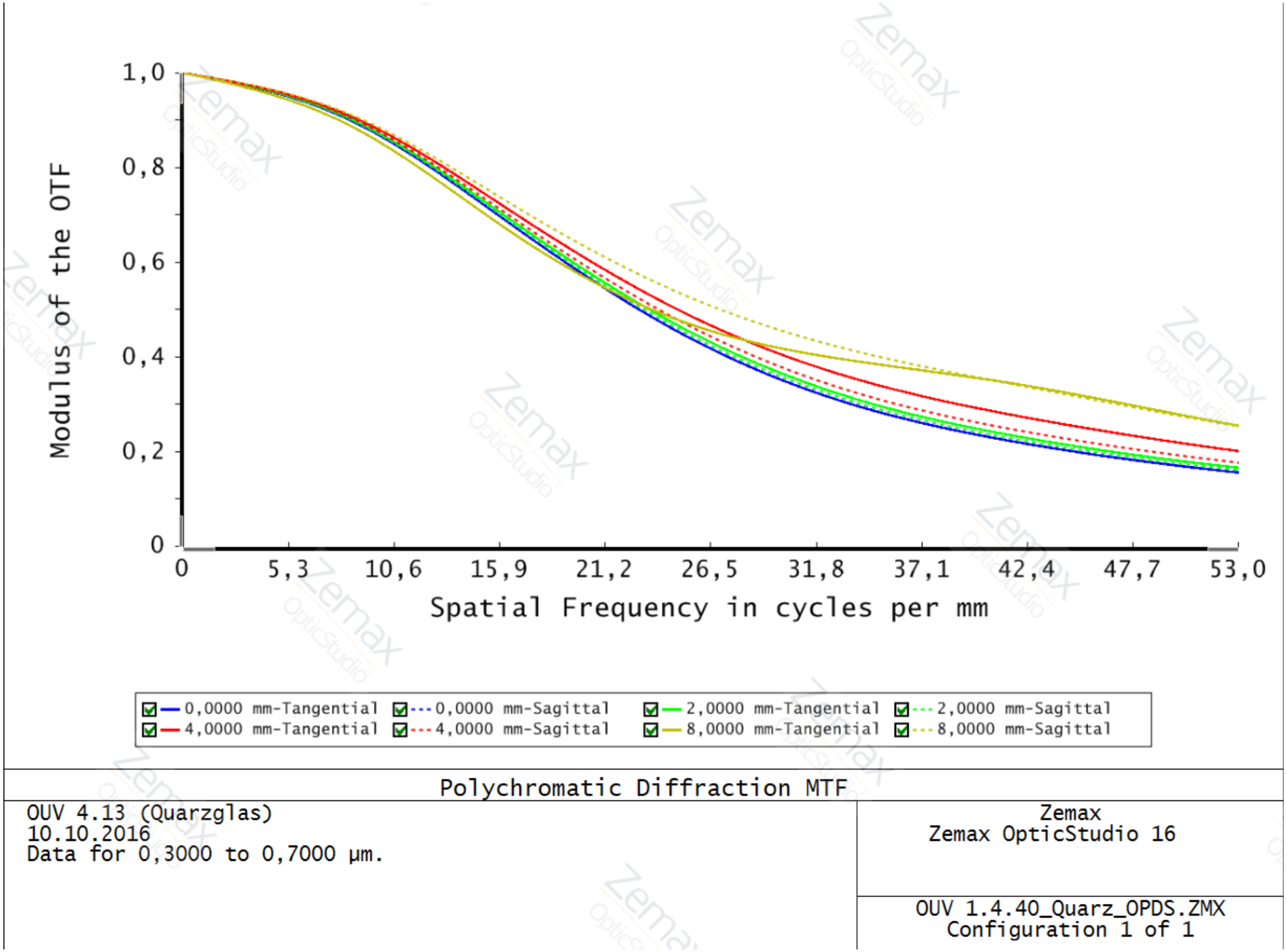


Aperture limited to 20 mm for reduced spherical aberration.
$\Omega \approx 8\pi \cdot 10^{-4}$ sr

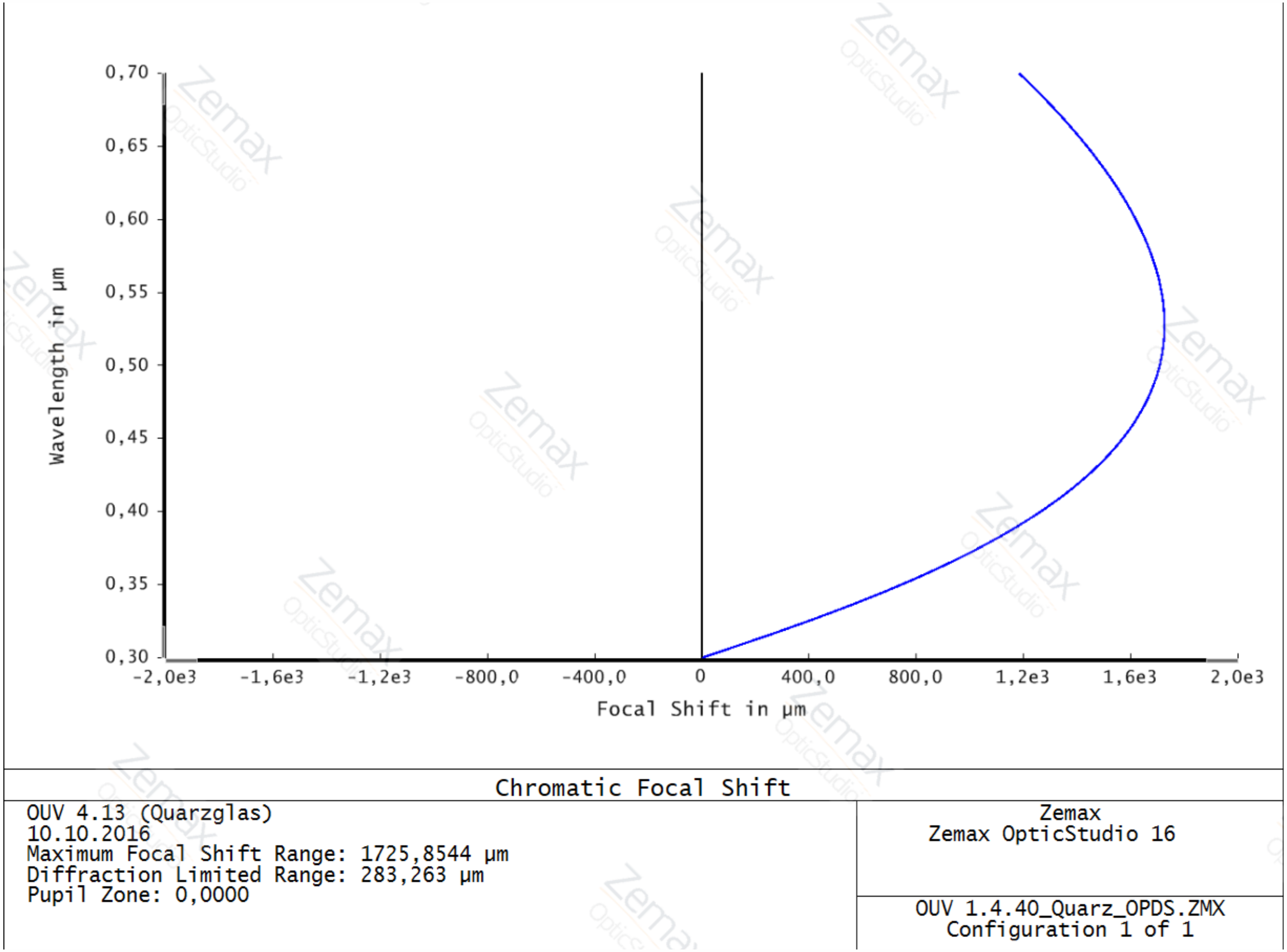
Optics: commercially available lens (part 2)



Optics: commercially available lens (part 3)



Optics: commercially available lens (part 4)

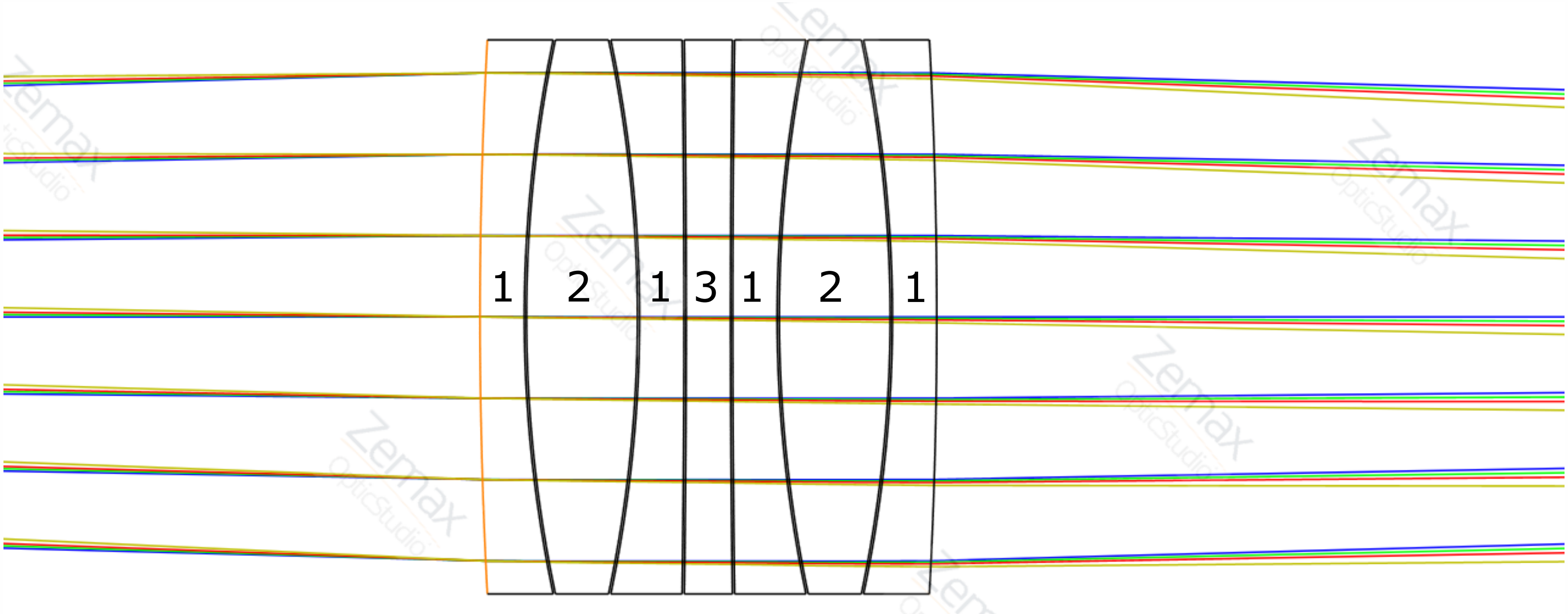


Optics: custom lens (part 1)

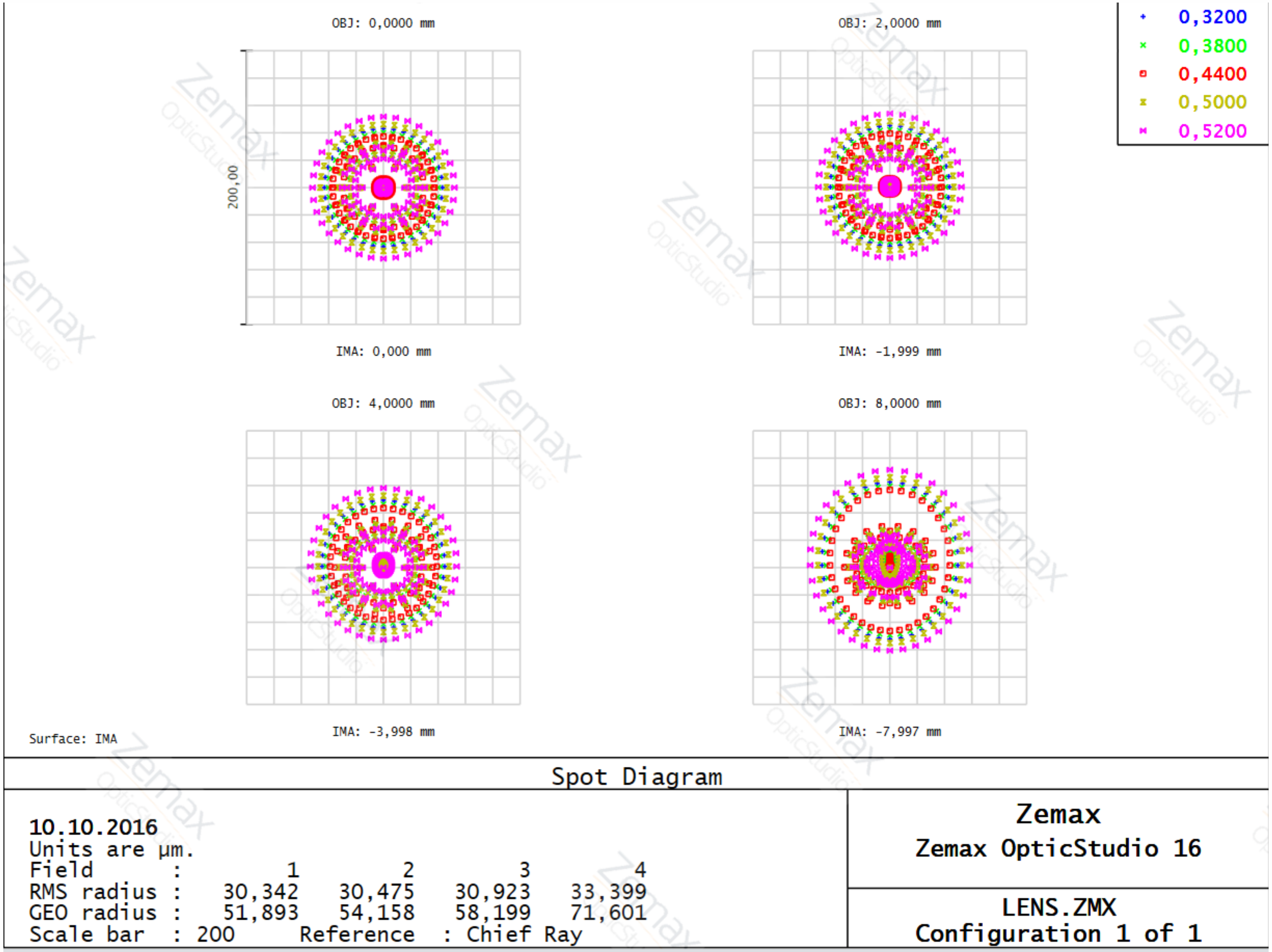
Optimized for low chromatic aberrations at short wavelengths and 1:-1 imaging
Transmission down to 310 nm
Geometric aberrations not yet corrected
Focal length (EFL): 210 mm
Maximum aperture: 22 mm
Lens diameter: 25 mm

Aperture limited to 22 mm
$\Omega \approx 5\pi \cdot 10^{-4}$ sr

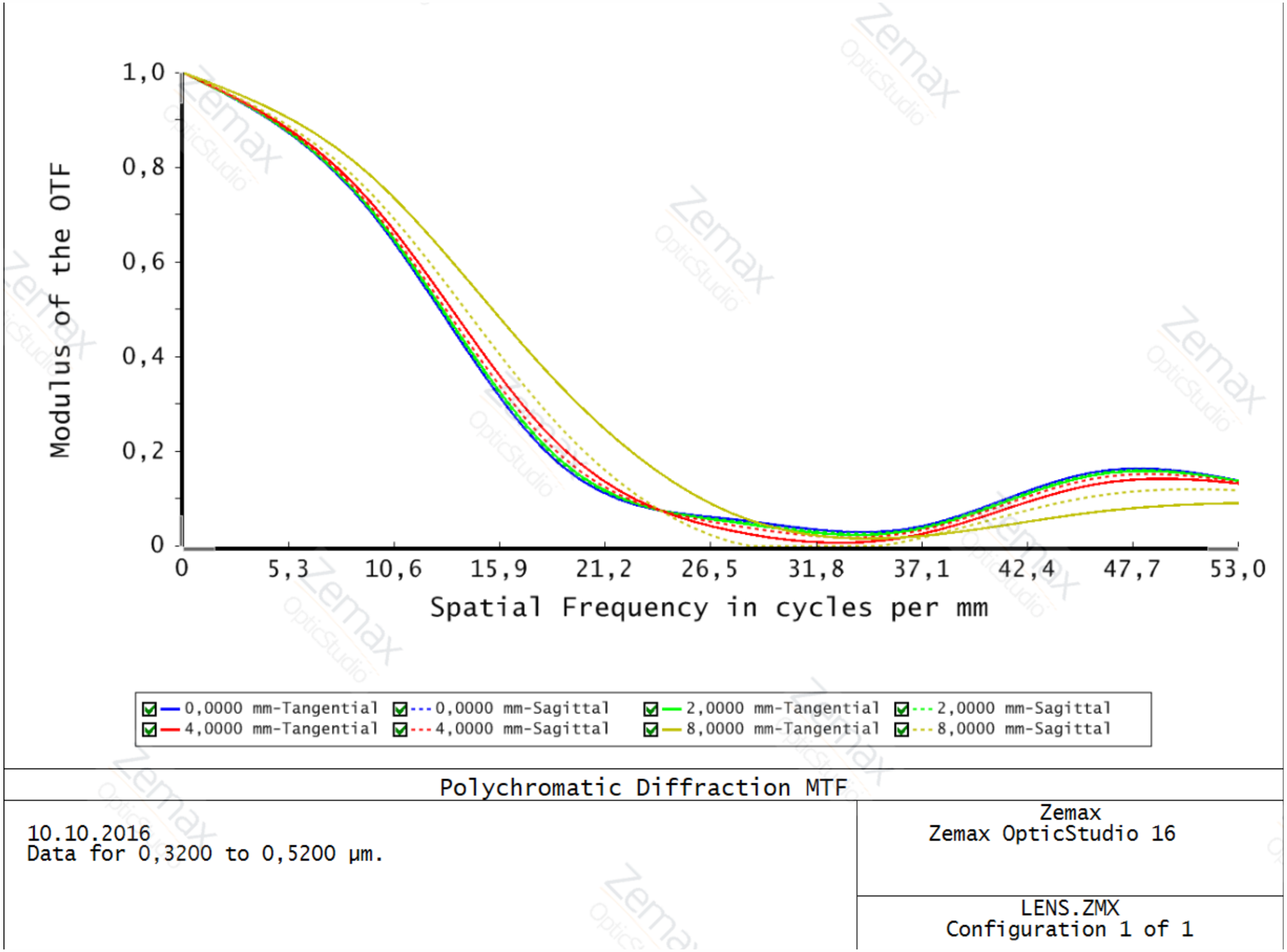
1 – Fused silica
2 – BaF_2
3 – LLF1HTi



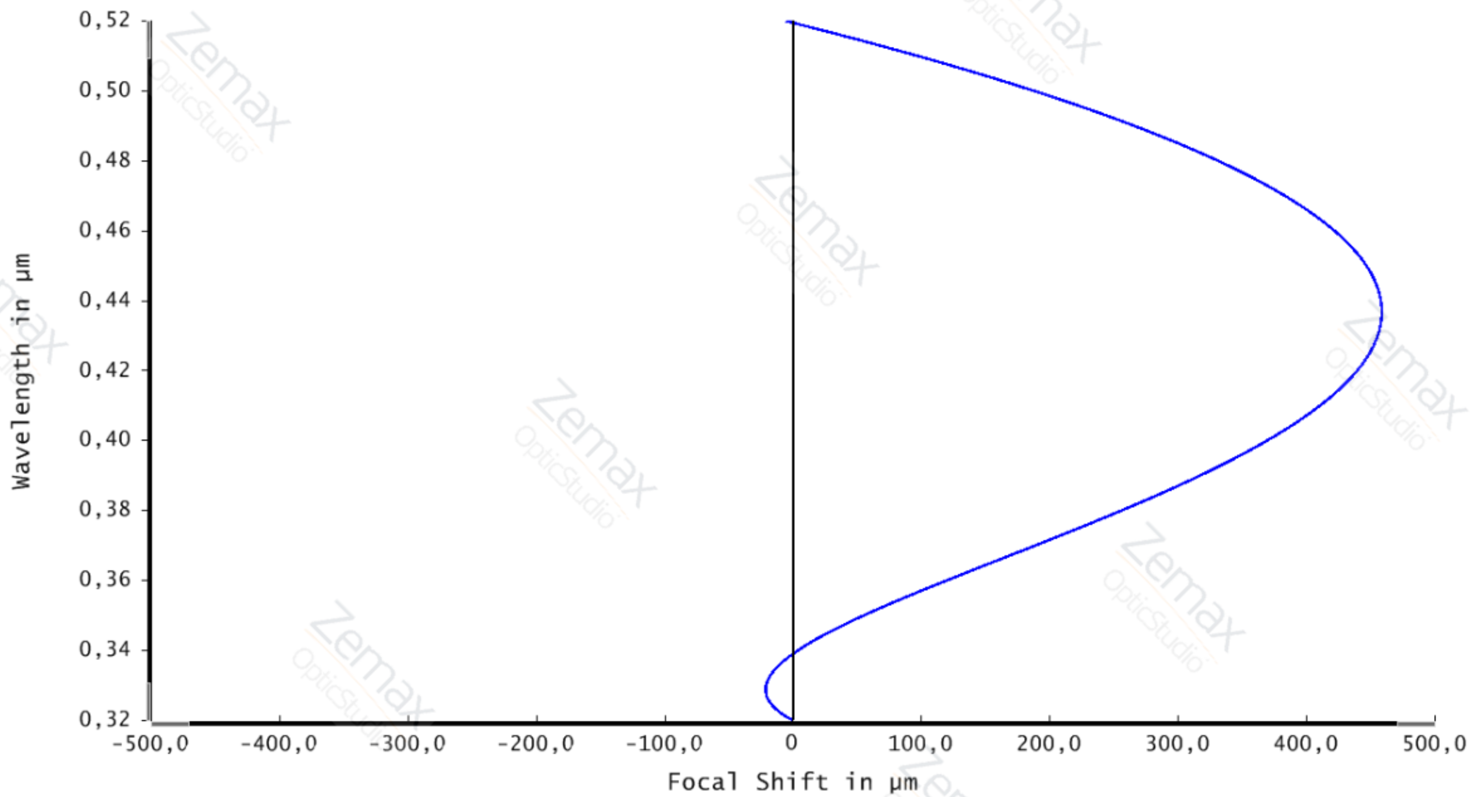
Optics: custom lens (part 2)



Optics: custom lens (part 3)



Optics: custom lens (part 4)



Chromatic Focal Shift

10.10.2016
Maximum Focal Shift Range: 480,0726 µm
Diffraction Limited Range: 455,082 µm
Pupil Zone: 0,0000

Zemax
Zemax OpticStudio 16

LENS.ZMX
Configuration 1 of 1

Open questions

- Role of secondary electrons
- Cleaning electrodes for secondary electrons
- Radiation hardness and scintillation of optical materials
- Move to an optical system made exclusively of mirrors
- How to best distinguish between electron and proton beam
- Reasons for low signal at the Cockcroft Institute; acquisition of a better electron gun
- Use of another detector system: emCCD
- What are the priorities

Conclusions

- MCP based detector system is a good option
- Commercially available optics identified
- Alternative custom lens with promising characteristics
- Integration times in case of N_2 got estimated and are short enough for detection at 391 nm
- Setup at Cockroft delivered first signal from background gas