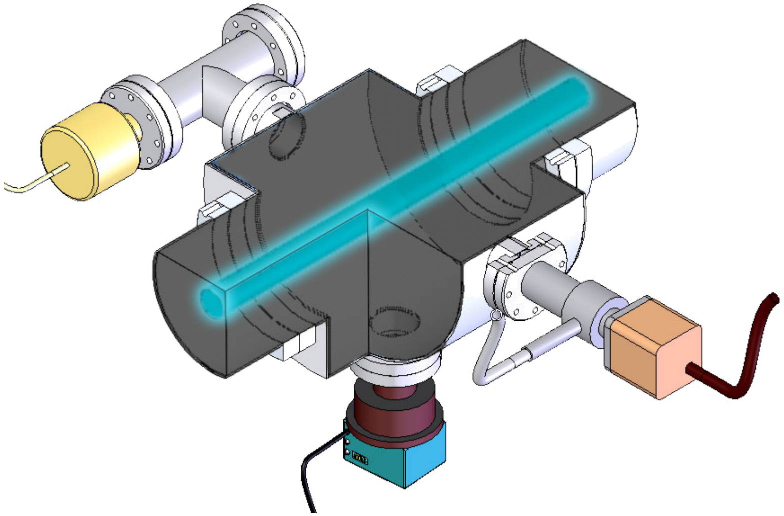
NON-INTERCEPTING BEAM PROFILE MONITORS BASED ON RESIDUAL GAS INTERACTION



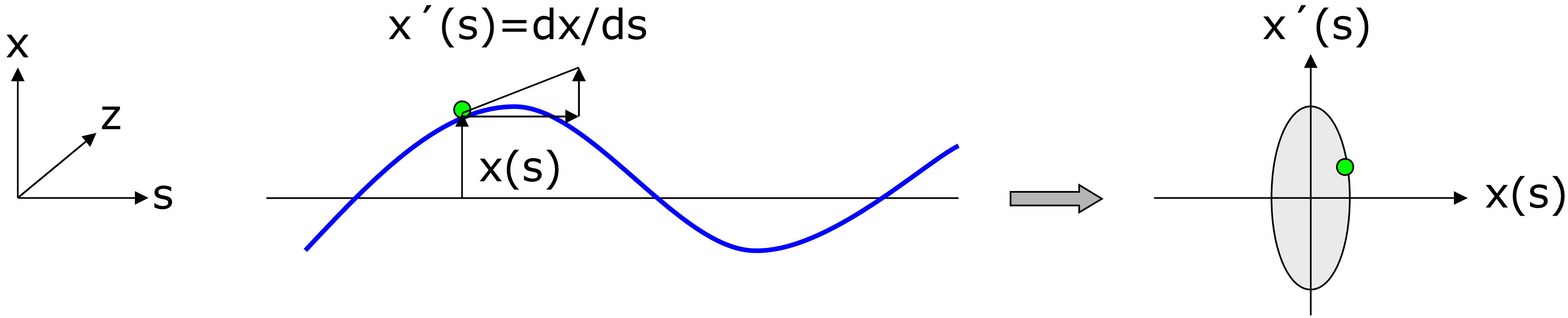
CERN BI-Seminar July 9th 2010

Frank Becker – GSI Beam Diagnostics

Outline

- Motivation for gas-based profile monitors
  - How a particle beam is characterized
  - Benefit of non-intercepting profile measurement
- Introduction: IPM & BIF-monitor
  - General idea and functionality
  - Construction and components
- Results of Research (BIF-monitor)
  - Estimation of the photon yield
  - Variation of gas-pressure and particle-energy
  - Radiation induced background & shielding concept
  - Investigation of alternative working gases
- Conclusion

How a Particle Beam is Characterized

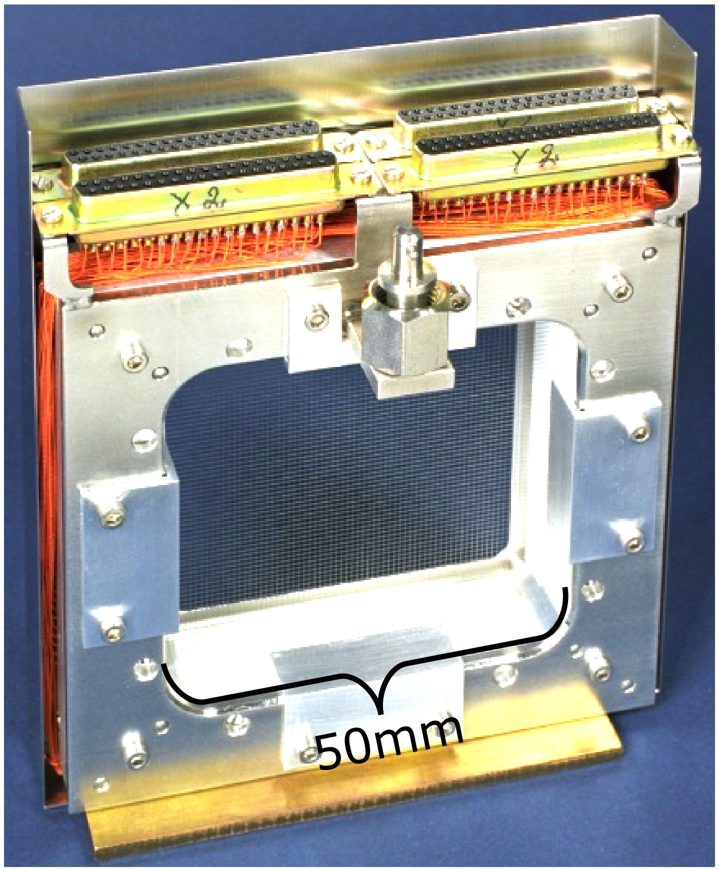


- Particle beam determined by its 6-dimensional phase space volume $X_n=(x,x'|z,z'|\tau,\Delta p/p)$
- Projecting phase space into spatial coordinate system determines beam profile
- Phase space ellipse can be reconstructed measuring several beam profiles – for known B-field pattern

High sensitivity less interaction required → Small impact on beam parameters

Small impact on the monitor

Conventional Wire-Based Systems

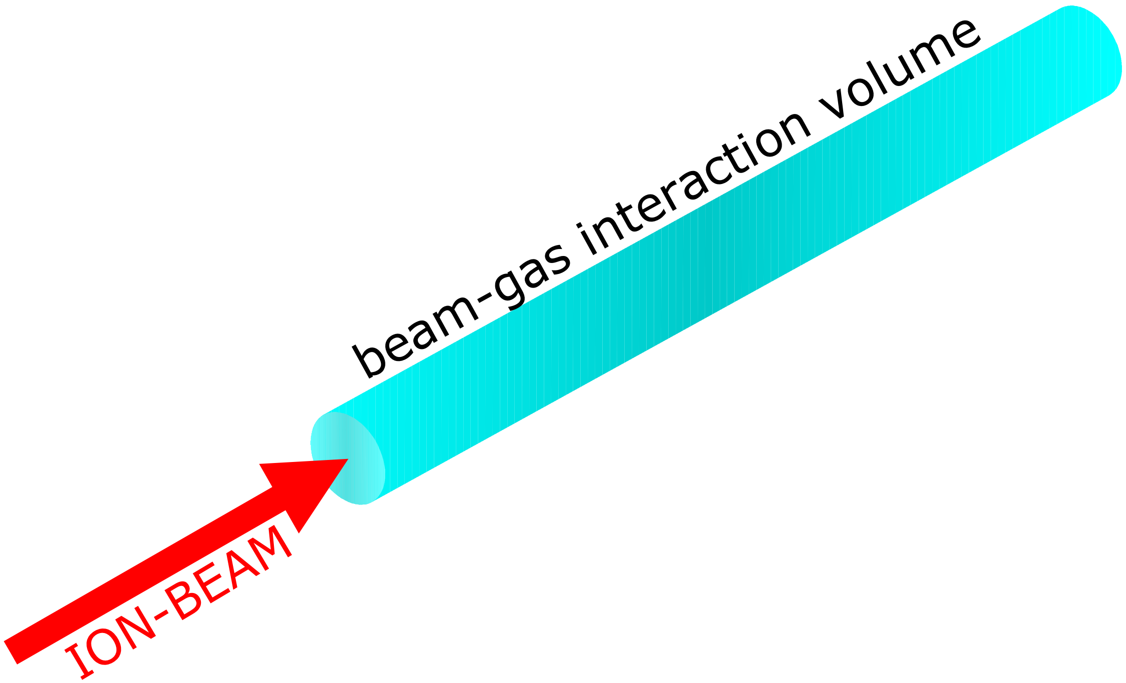


Secondary Electron Monitor (SEM)-Grid of 48 Tungsten wires Ø 100 µm in x-y-plane with 1 mm wire-spacing.

- Secondary Electron Monitor Grid
  - Sufficient signal strength
  - Limited spacial resolution (wire-spacing)
  - Accuracy is not well characterized!
- Impact on the beam
  - Energy-loss in the wire, scattering (x´) momentum distr. (Δp/p), e^--stripping…
  - Emittance „blow-up", beam-loss!
- Impact on the monitor
  - Wire heating → melting!

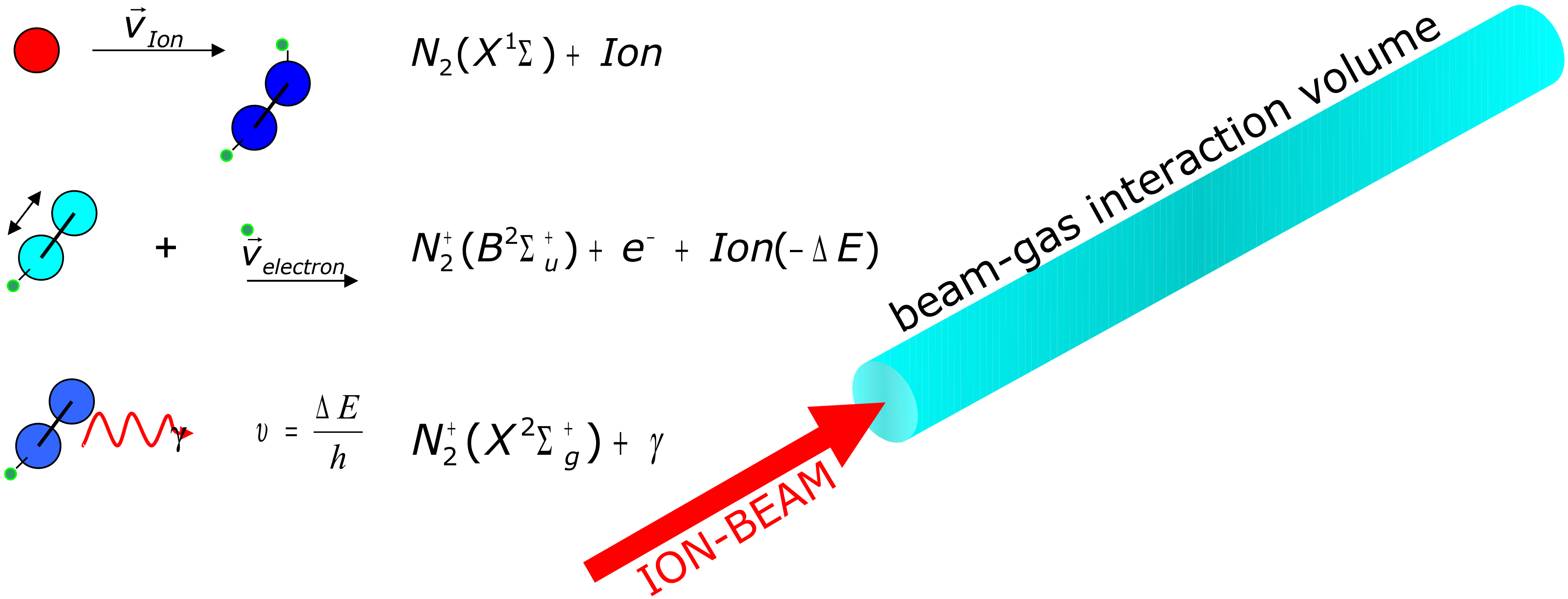
Non-intercepting beam diagnostics is mandatory!

Gas-Based Detectors



- For p ≥ 10^{-8} mbar residual gas N_2-dominated, UHV → H_2
- Atomic collisions drive -dE/dx → electronic stopping
- Processes to be observed: ionization and fluorescence…

Gas-Based Detectors



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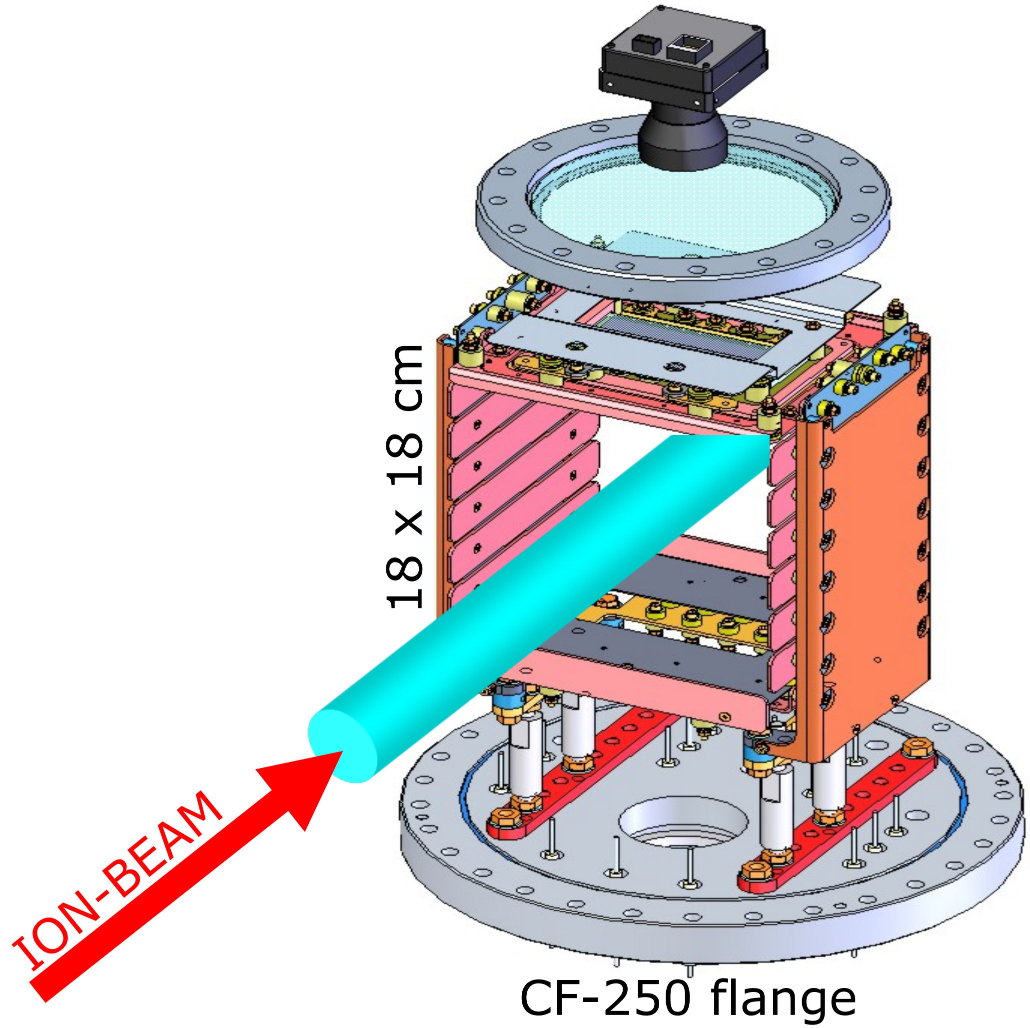
Ionization Profile Monitor



[T. Giacomini et al. (2009)]

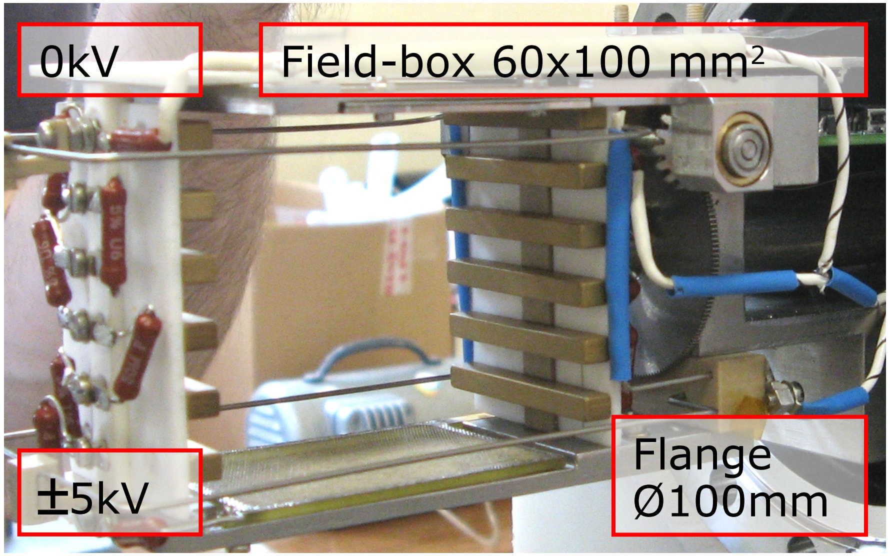
- Gas-ions accelerated in homogeneous E-field vs. spatially resolving sensor
- Either stripline or optical readout
- ±6 kV accelerating voltage → E = 70 kV/m
- TOF N_2^+ ions ~ 100 ns
- 4π-acceptance → all ions
- MCP-amplification ~10^6

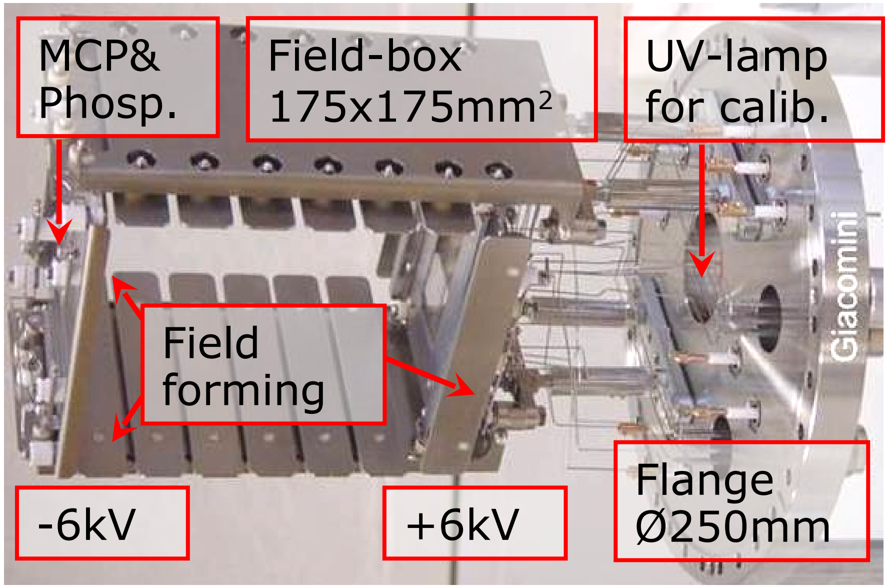
Sensitive profile monitor suitable for synchrotrons

Layout - Stripline vs. Intensified IPM

- Striplines lithographically etched to a ceramic waver
- Field-inhomogeneity < 4%

[J. Marroncle et al. (2010)]

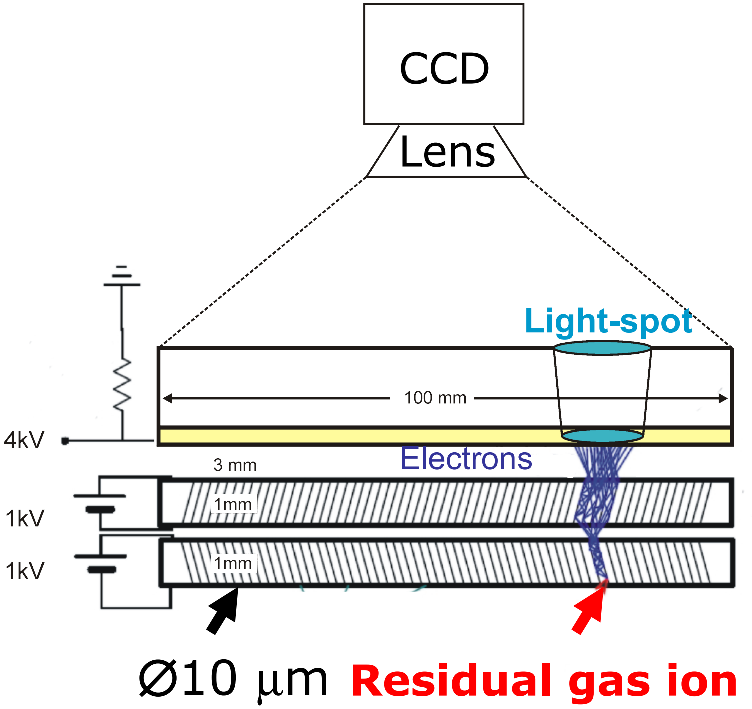




- Intensified by V-stack MCP
- Field-inhomogeneity < 1%
- Calibration with UV-light-source $\lambda < 190$nm

[T. Giacomini et al. (2009)]

Detection Principle – Intesified IPM



- 10^6-fold amplification ratio in a V-stack MCP & P47 (<100 ns)
- MCP were preselected and matched by electrical properties
- Intensifier-unit calibrated by homogeneous, diffuse UV-lamp
- Masking of MCP-edges to avoid field emission and sparking

Application – Cooling and Stacking

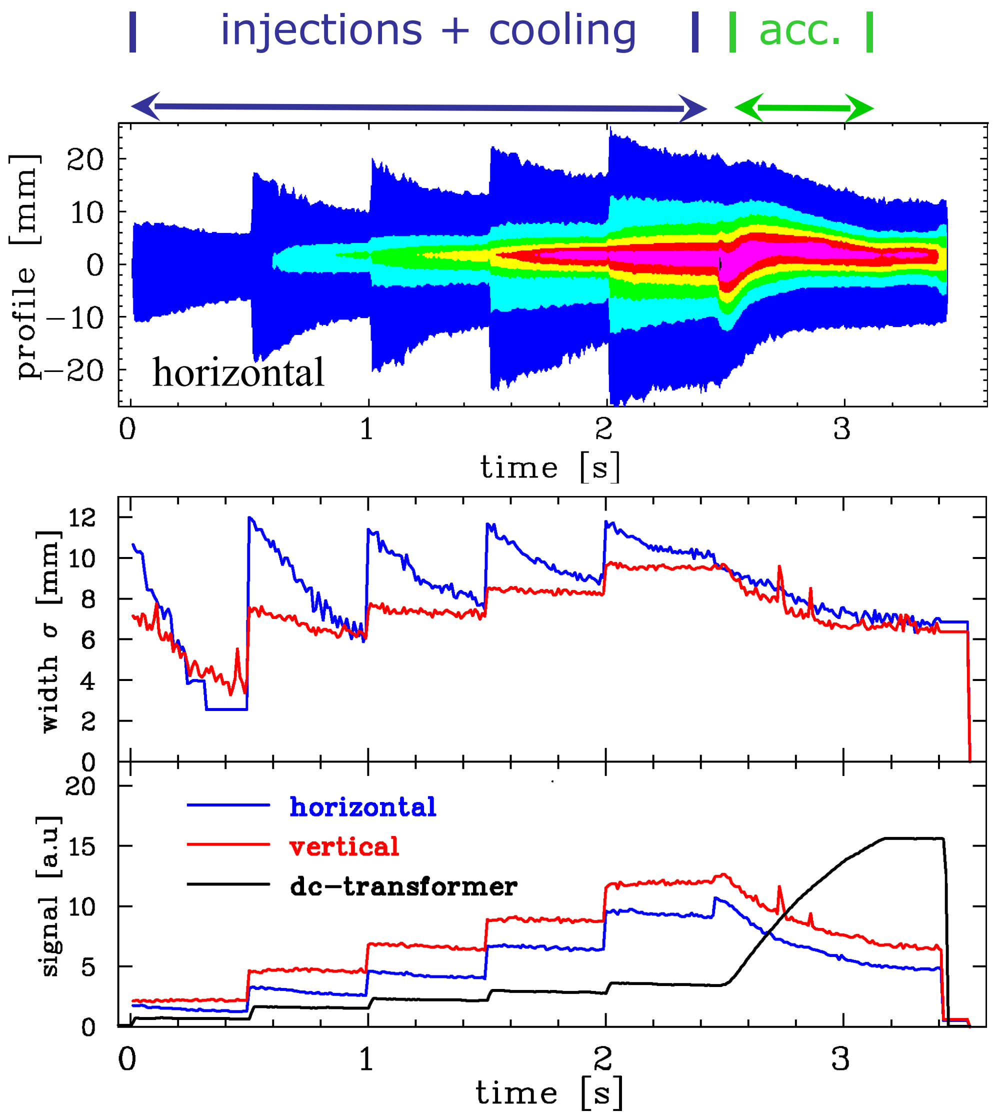
Example:

- U^{73+} beam at GSI
- For intensity increase stacking with electron cooling
- Multiple injections
- Acclereation 11.4 to 400 *A*MeV

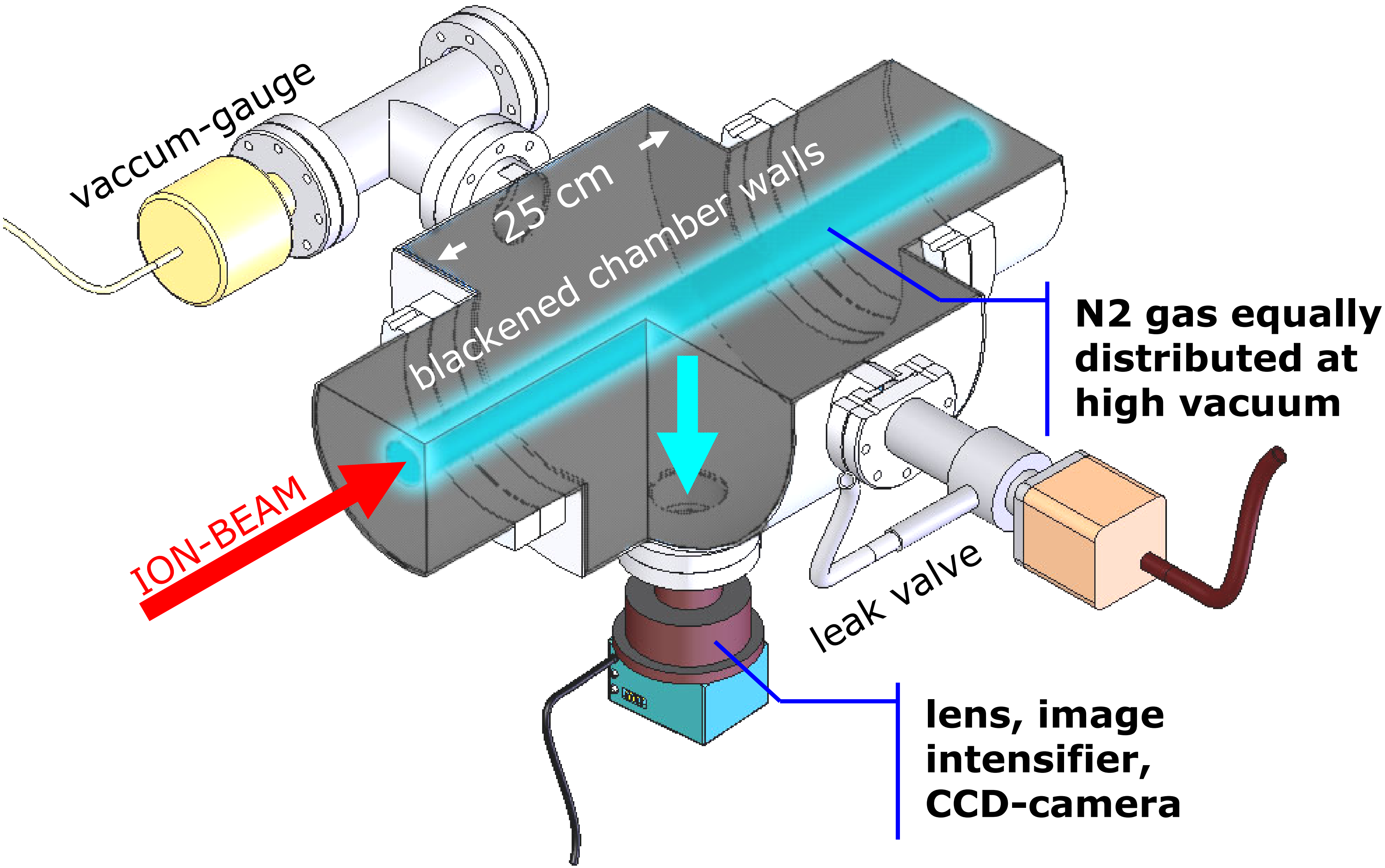
Task for IPM:

- Observation of cooling
- Emittance evalutation during cycle

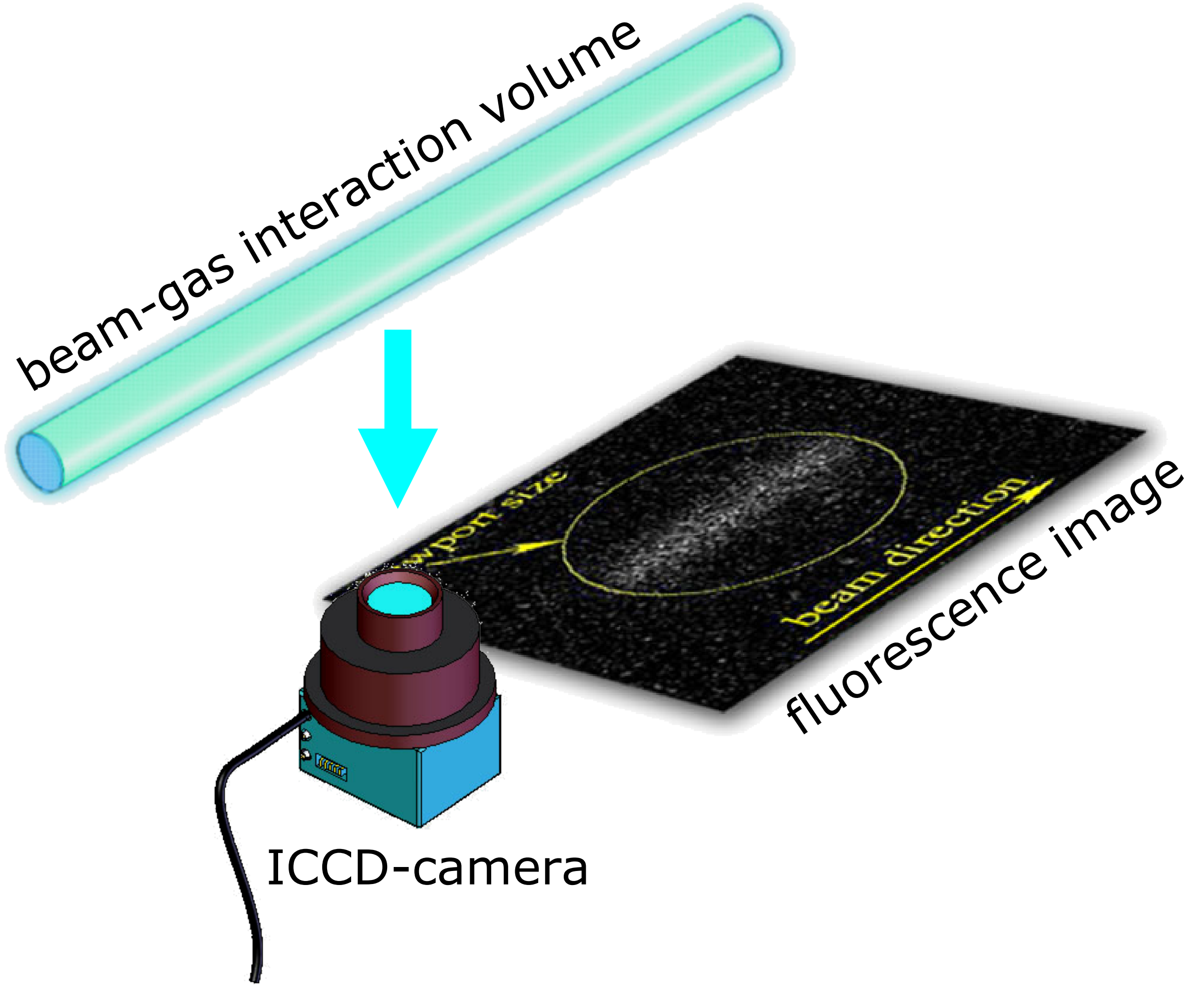
[T. Giacomini et al. (2009)]



Beam Induced Fluorescence

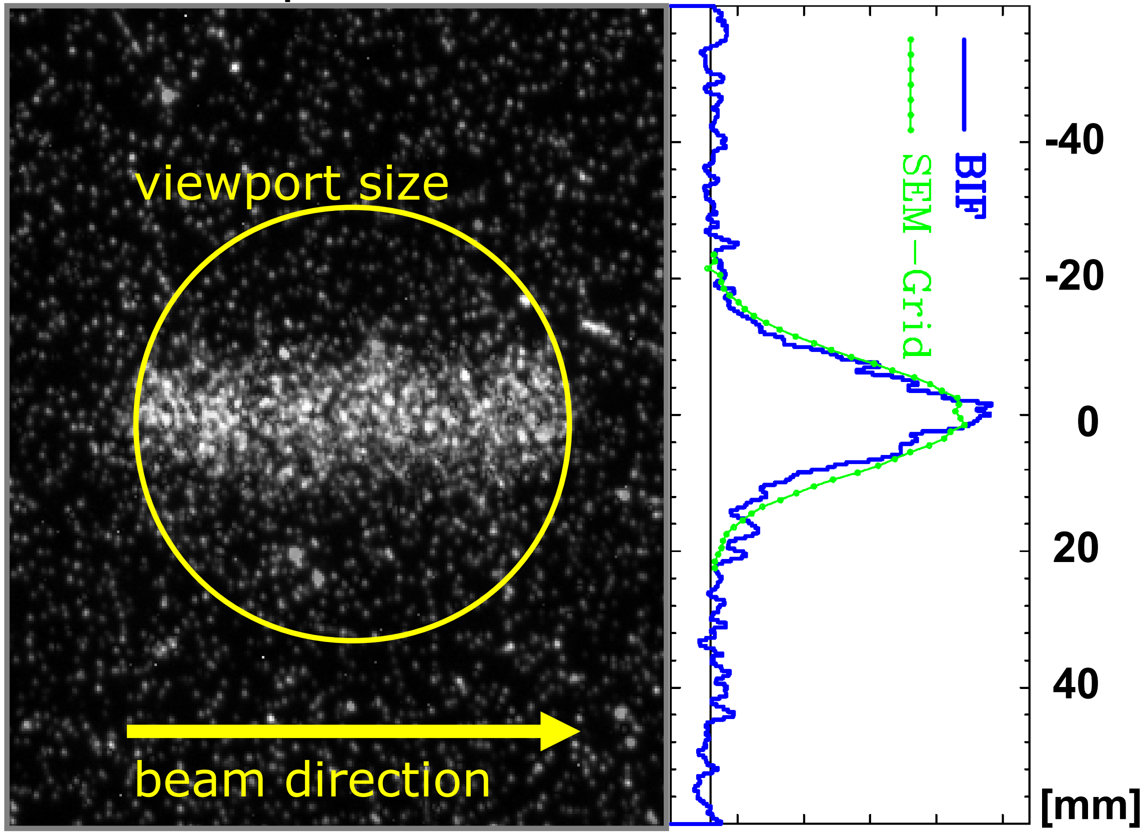


How a Beam Profile is Obtained



How a Beam Profile is Obtained

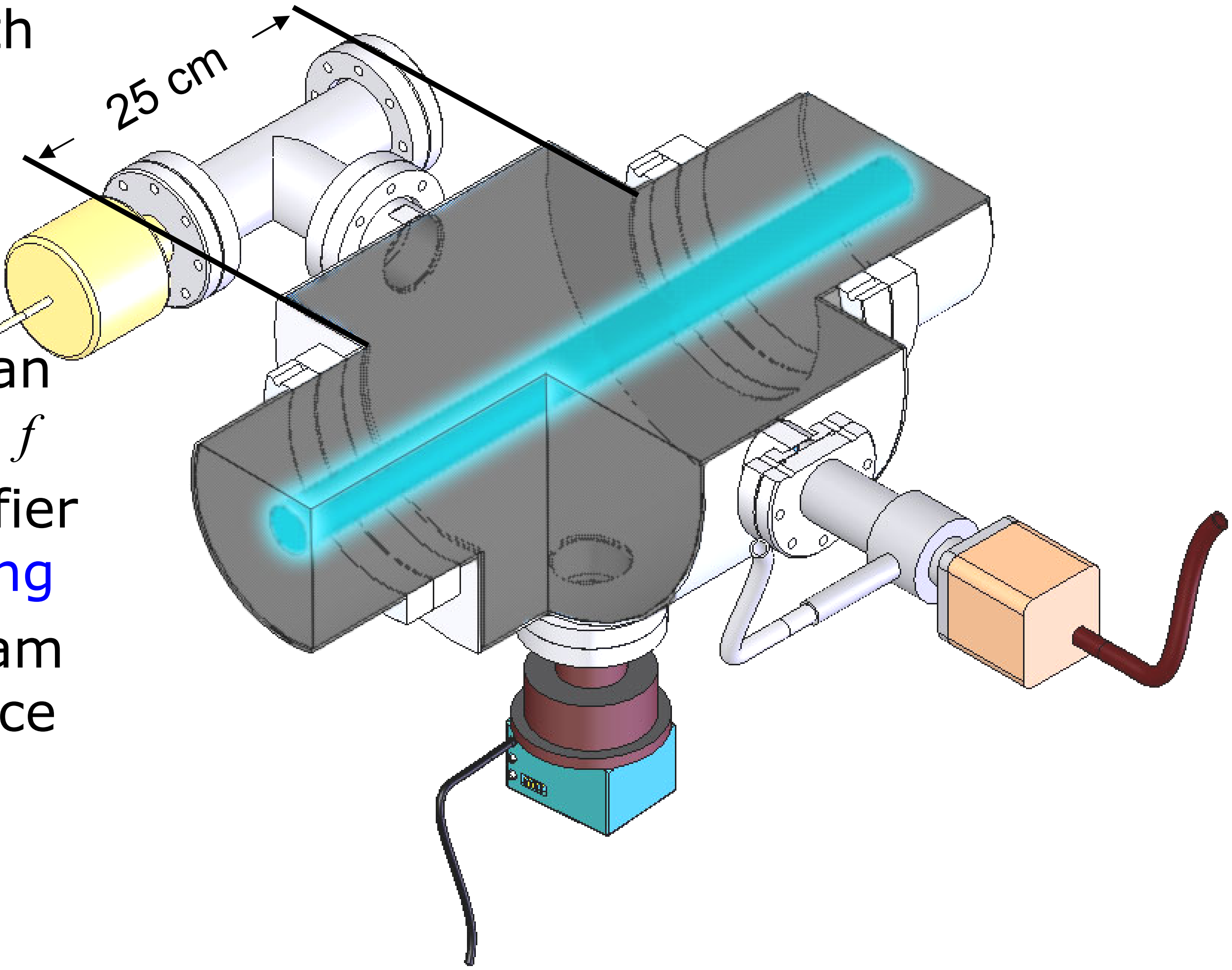
200 *A*MeV Xe^{48+} 20 pulses of 10^9 Ions in $5 \cdot 10^{-4}$ mbar N_2



BIF- and SEM-profiles in accordance with each other, $\Delta\sigma/\sigma \leq 10\%$

Benefit of the BIF-monitor

- Short insertion-length
- No mechanical parts inside the vacuum
- Magnification ratio can be adapted choosing f
- V-stack image intesifier single photon counting
- Digital 12-bit VGA-cam with FireWire-interface



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- Short insertion-length
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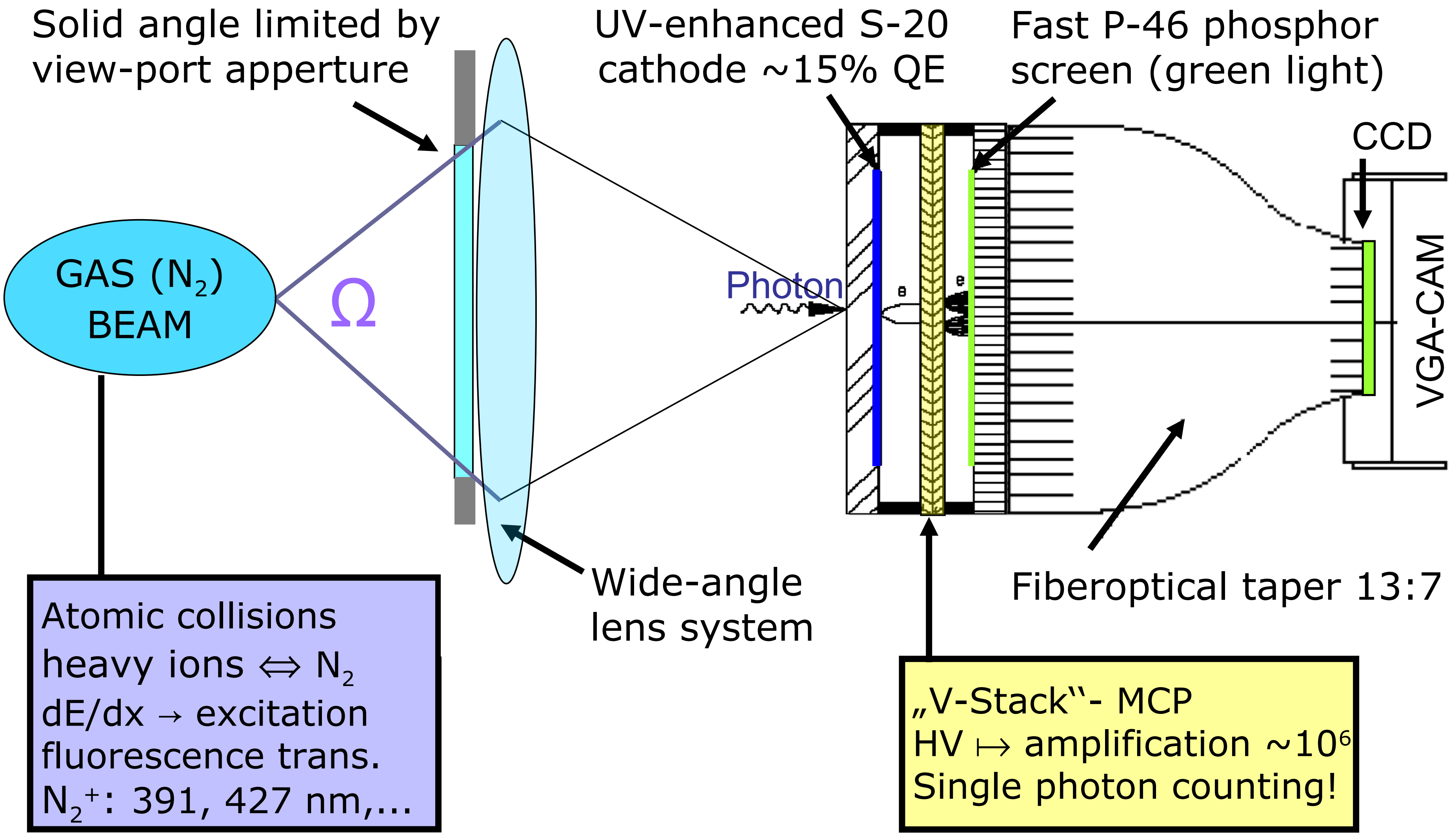
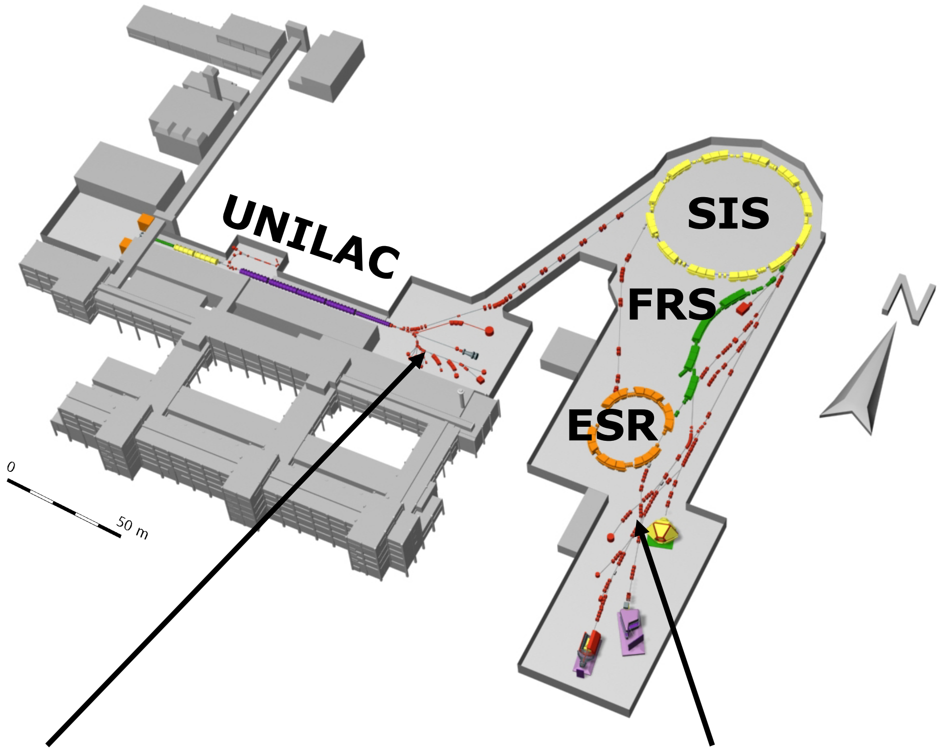
- Components of the shelf

Detection Principle



Non-intercepting Profile Monitors @ GSI



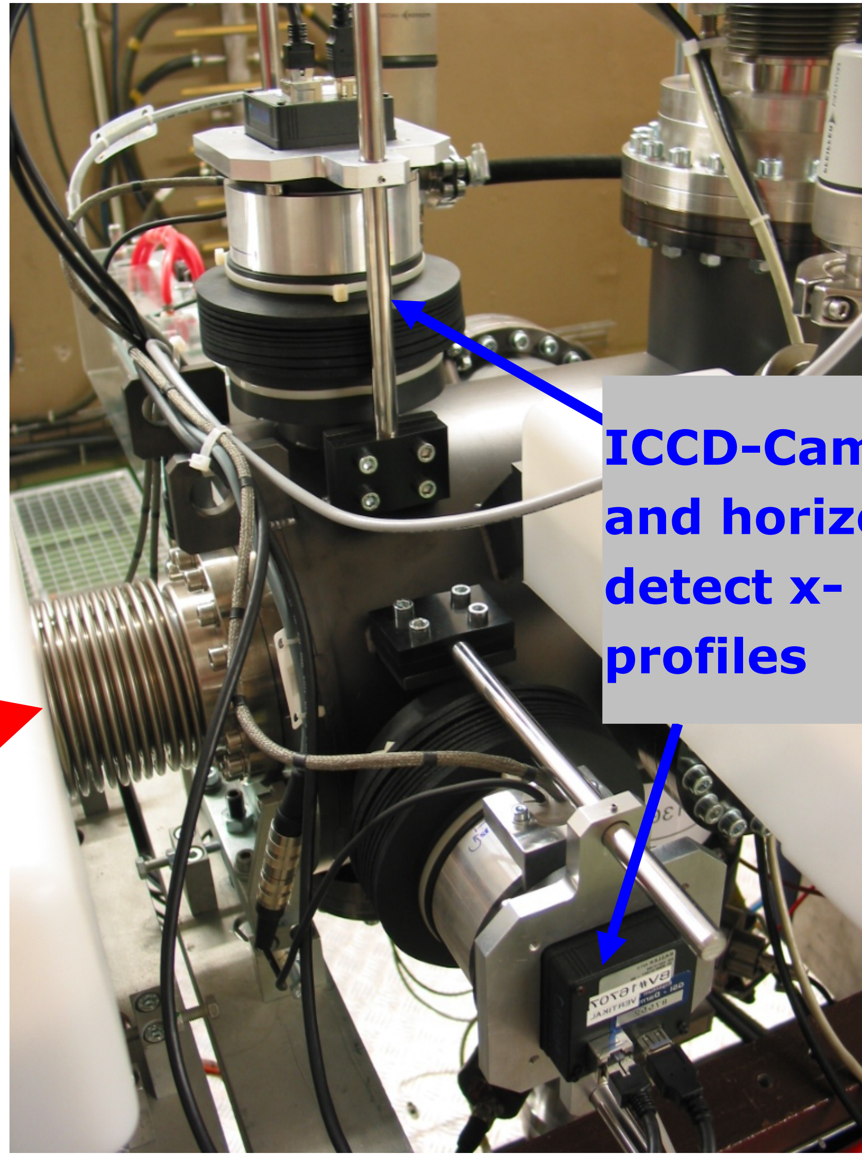
X2 experimental area (UNILAC) addressing beam energies (3,5 – 12 *A*MeV) and HTP Experimental area (SIS) with energies (50 – 750 *A*MeV).

NDCX injector Berkeley (7,5 *A*keV)

- IPM's at SIS-18 and currently setup for ESR
- BIF-monitors along the UNILAC at 7 locations
- FAIR requires 2 IPM's and 14 additional BIF-stations
- 3 experimental areas for different beam energies 7,5 *A*keV – 750 *A*MeV

Non-intercepting profile diagnostics is mandatory!

BIF Setup at GSI-UNILAC



BEAM

ICCD-Cameras in vertical and horizontal plane to detect x- and y- beam profiles

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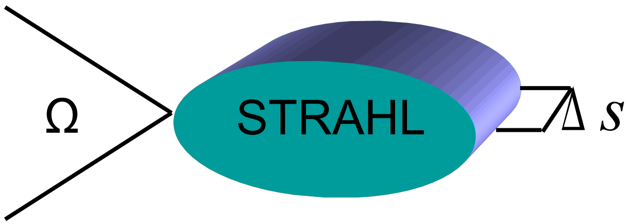
Expected Photon Yield



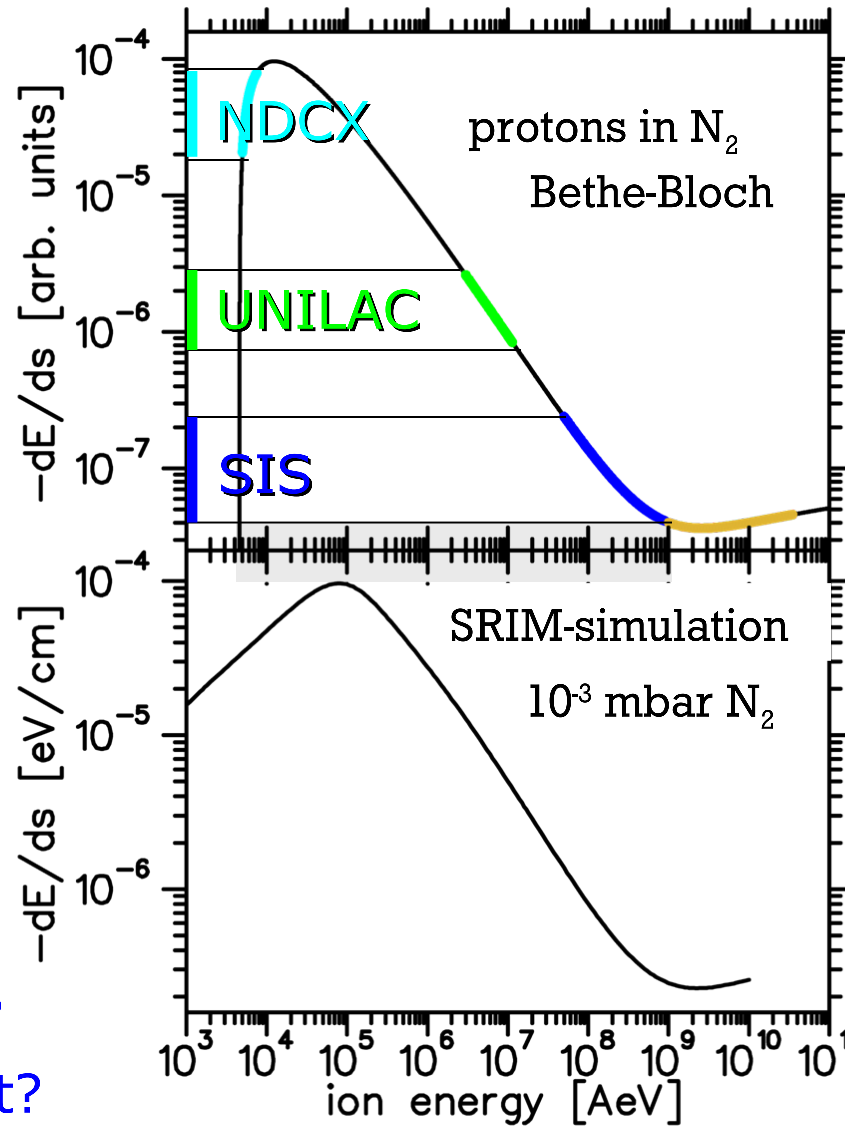
$$n_{photon} = p \, \frac{dE(\bar{q}^2_{Ion}, E)}{ds} \, \Delta s \, \frac{f}{h\nu} \, \Omega \, \varepsilon_{Detect.} \, n_{Ion}$$

$$f \equiv \frac{E_{photon}}{\Delta E_{Ion}} \approx 1\% \, ; \quad \sigma_{photon,p,11AMeV} \approx 10^{-19} cm^2$$

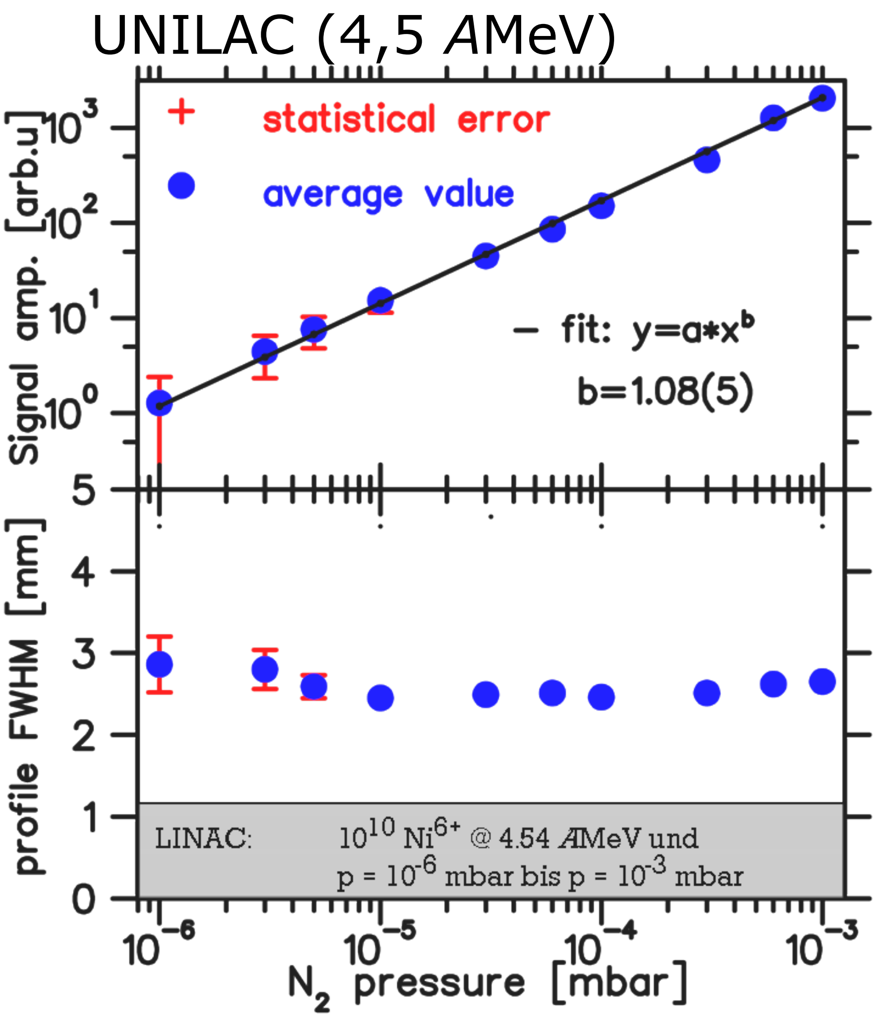
- Yield determined by geometry and beam parameters (I,E,q)
- Energyloss scales like: NDCX/UNILAC/SIS → 500/10/1

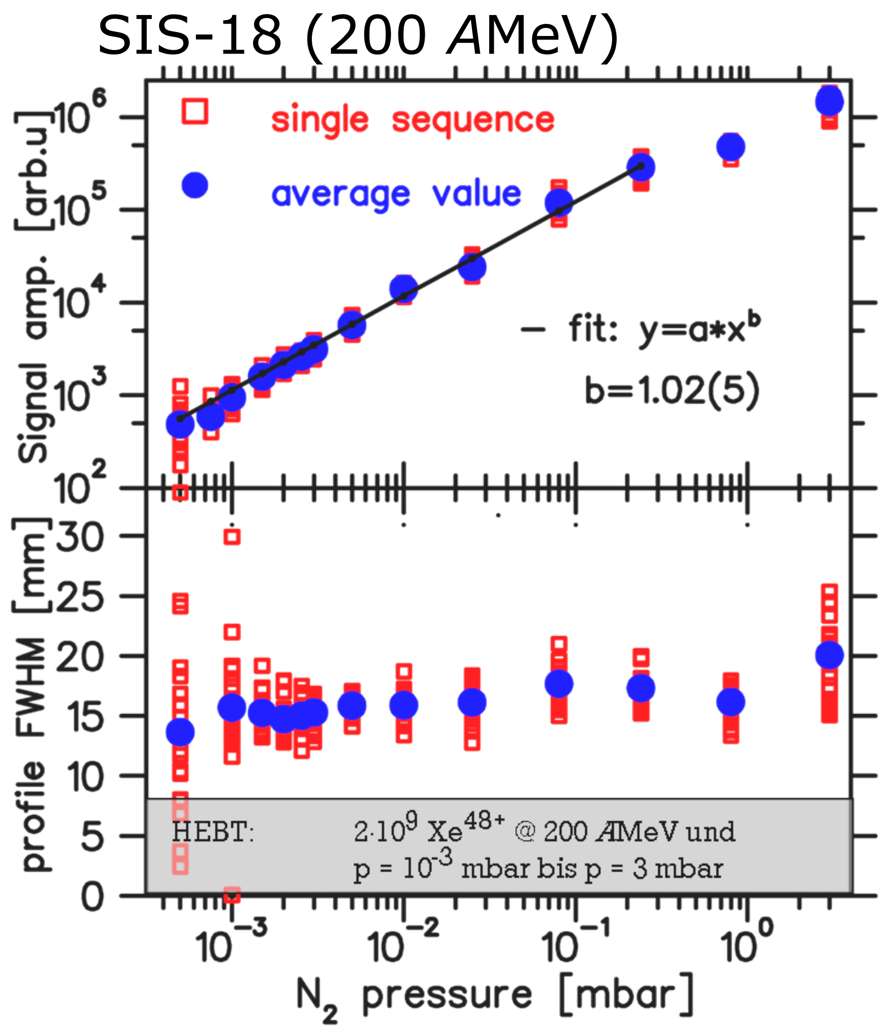
Is p free parameter to compensate?

Remains conversionfactor f constant?



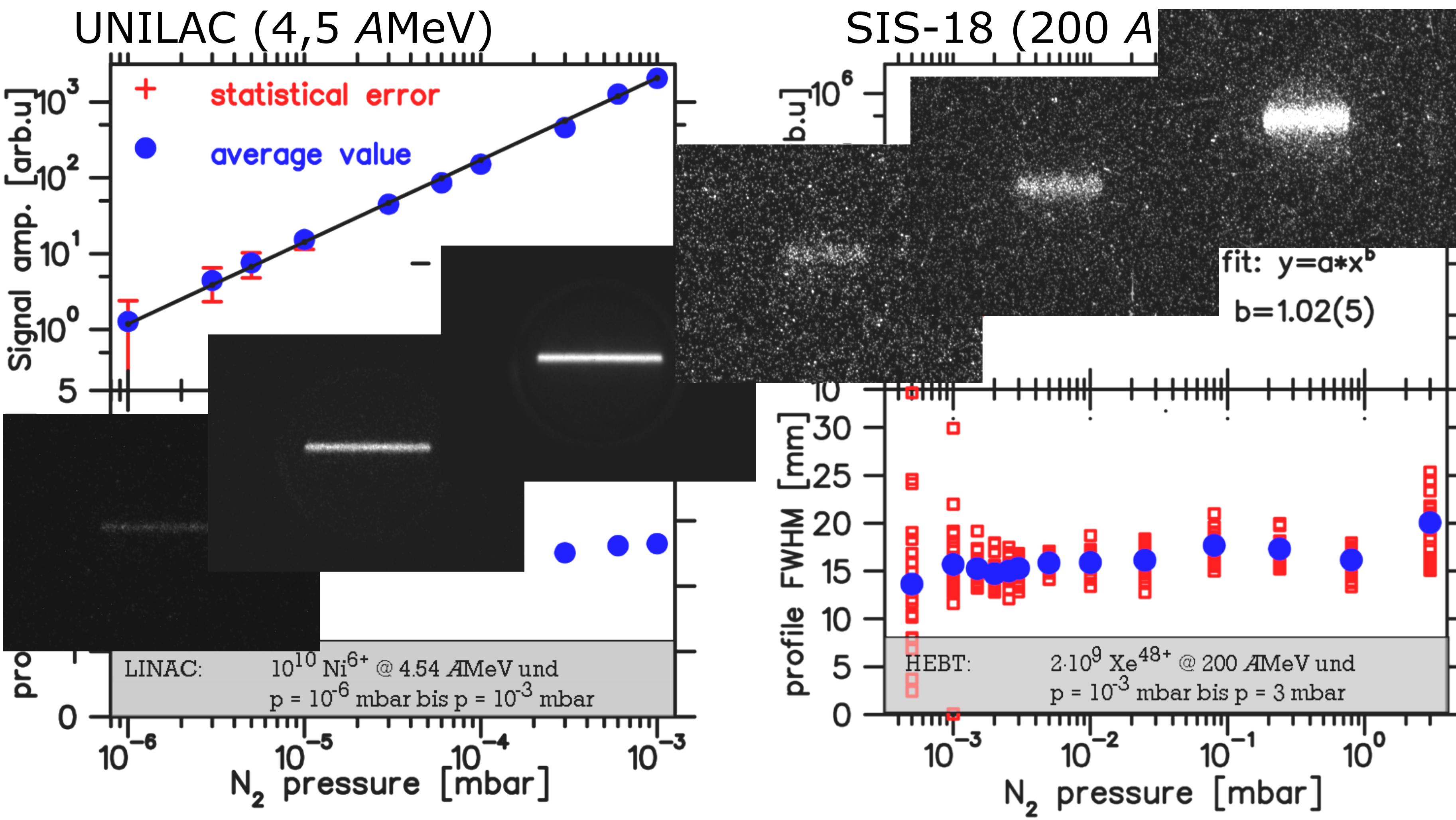
Pressure-Variation by 6 OM





Amplitude ~ p and σ = constant → p is a free parameter

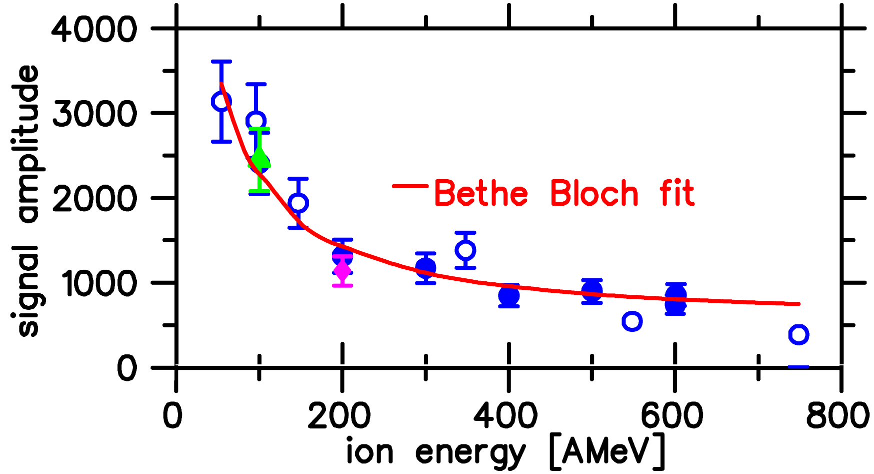
Pressure-Variation by 6 OM



Amplitude ~ p and σ = constant → p is a free parameter

Energy-Variation from 50 to 750 *A*MeV

- Integral signal-amplitude scales according to Bethe-Bloch formula
- Consistent results for Tantalum and Krypton ions, when normalized with respect to m and q of $^{238}U^{73+}$



Conversionfactor f does not depend on energy or ion-species → constant

Energy-Variation from 50 to 750 *A*MeV

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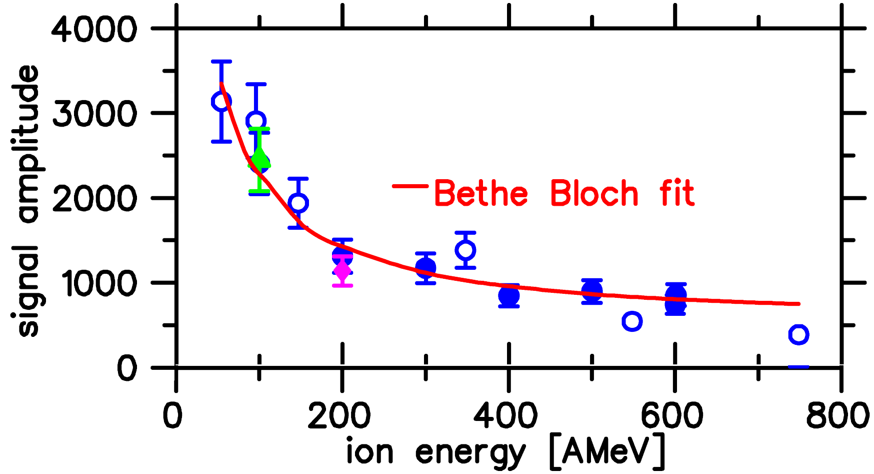
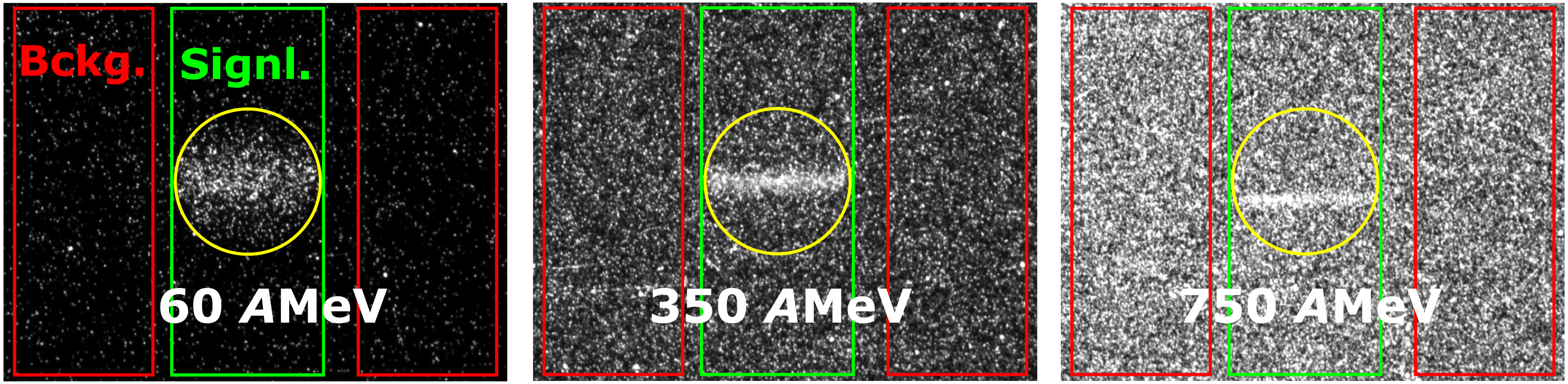


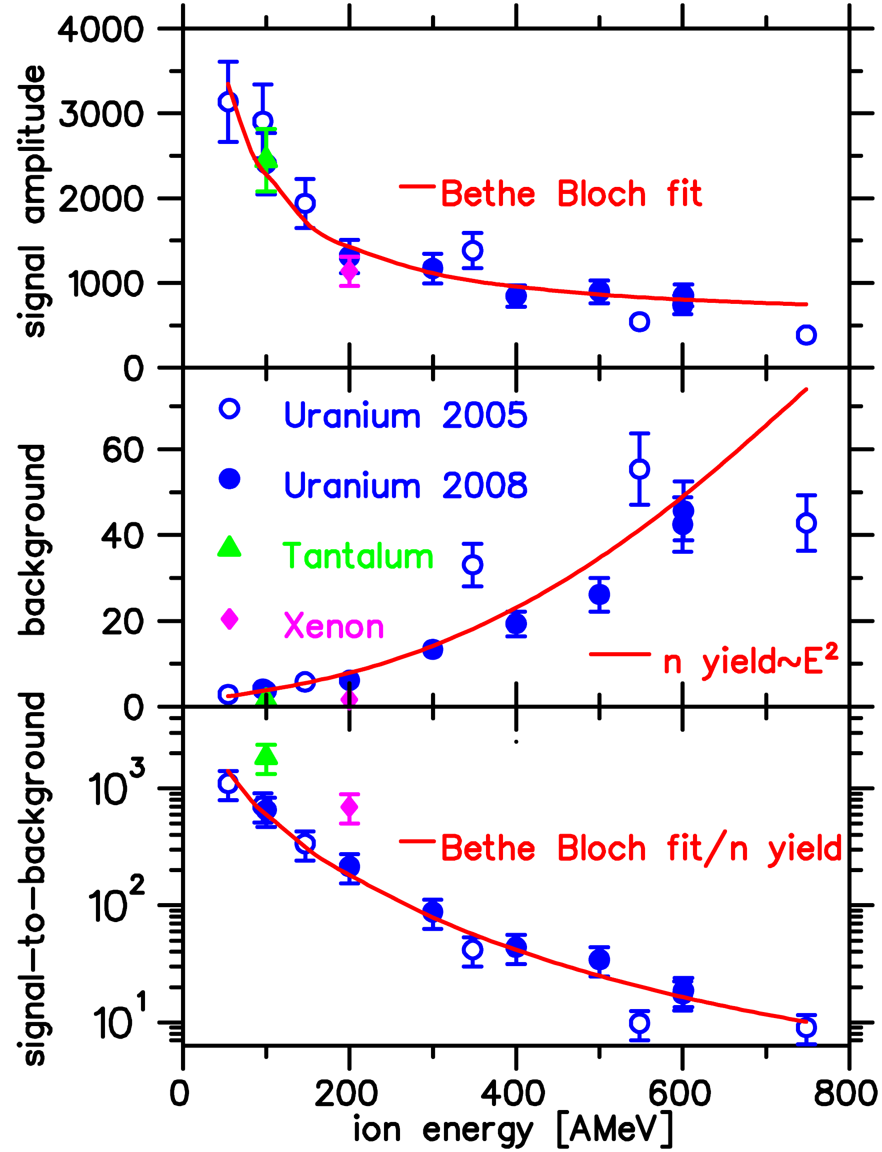


For increasing ion energy → Background increases and signal decreases!

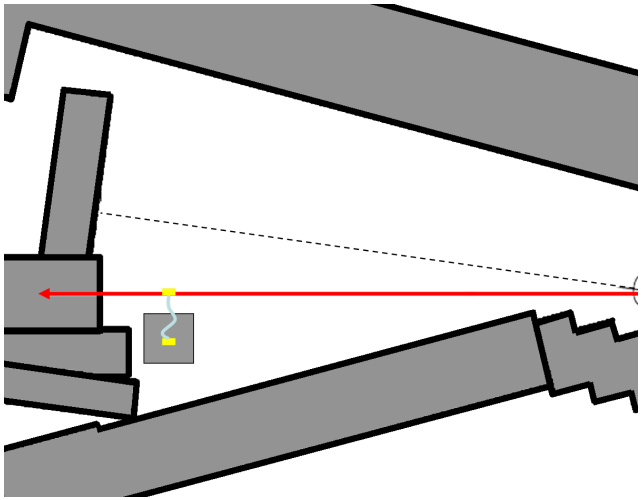
Energy-Variation from 50 to 750 *A*MeV

- Integral signal-amplitude scales according to Bethe-Bloch formula
- Consistent results for Tantalum and Krypton ions, when normalized with respect to m and q of $^{238}U^{73+}$
- Background is generated by neutron impact on the photocathode
- Neutron production yield scales ~ E^2
- Signal-background-ratio decreases by 2 orders of magnitude
- 1 µs integration time during fast extraction improves SBR of Ta, Xe by a factor of four

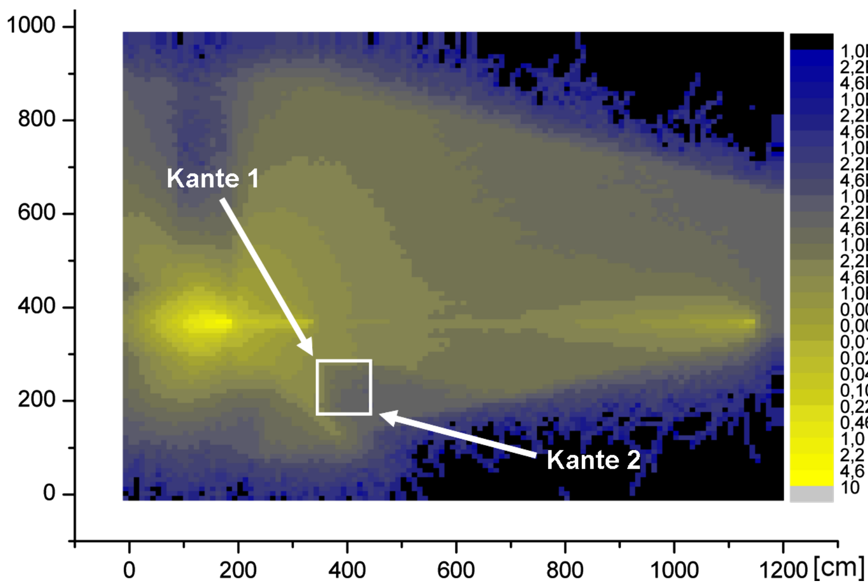
Background has to be reduced!



Simulation of the Neutron Flux



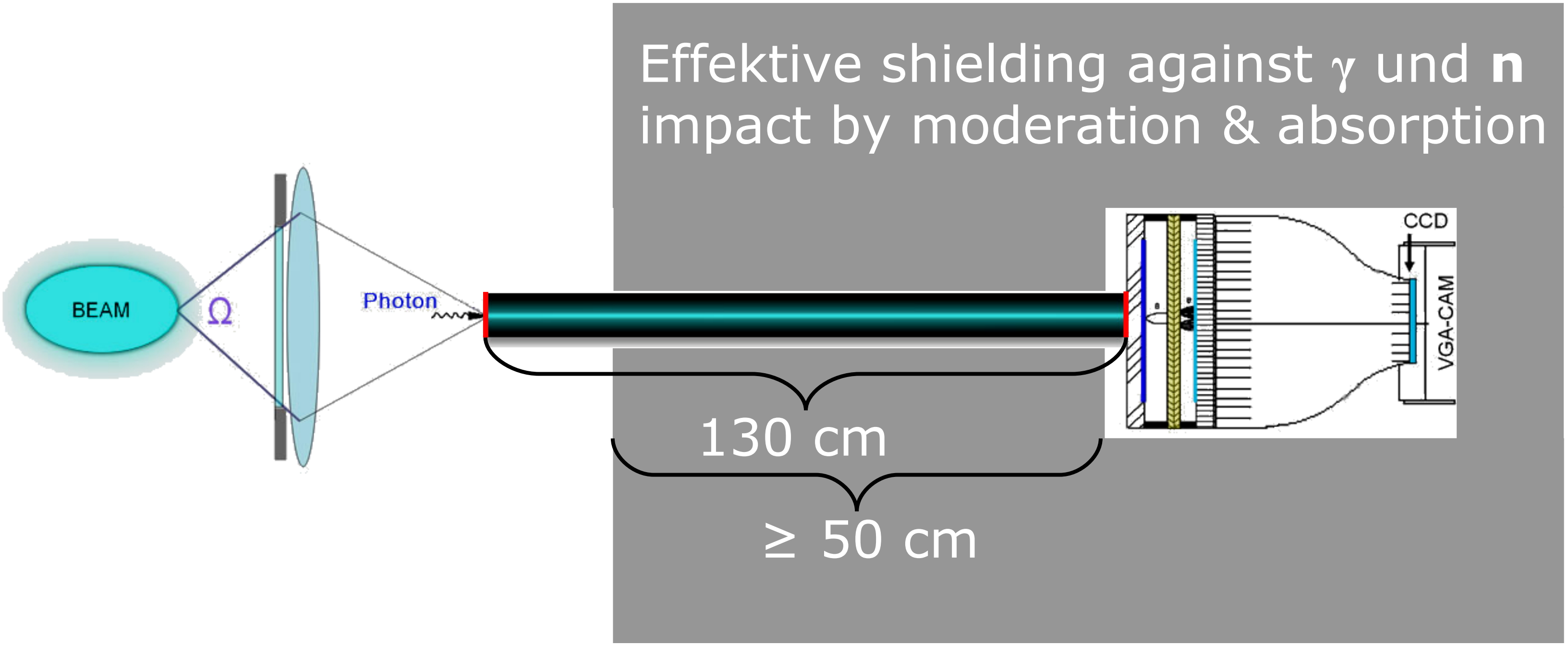
- HTP-caves topview with walls (grey), beamline (red) and 1 m^3 concrete shielding
- ICCD-camera (yellow) is placed in the center of the block ~50 cm wall-thickness



- FLUKA-simulation n-flux for 900 *A*MeV $^{40}Ar^{18+}$ ions
- n-flux suppressed by 94 % and γ-flux by 96%!

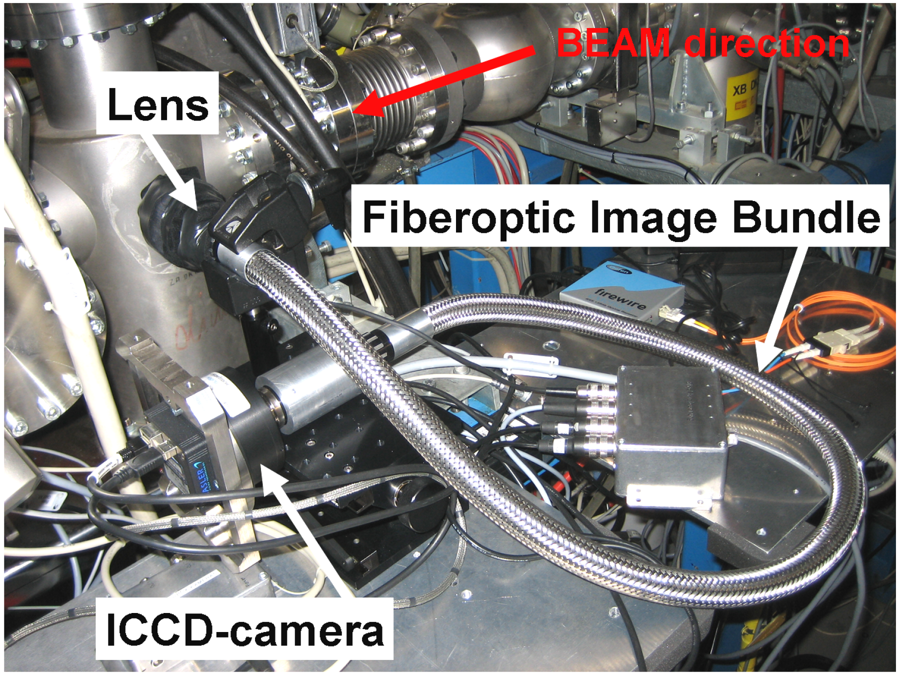
How can fluorescence images be transported into the shielded volume?

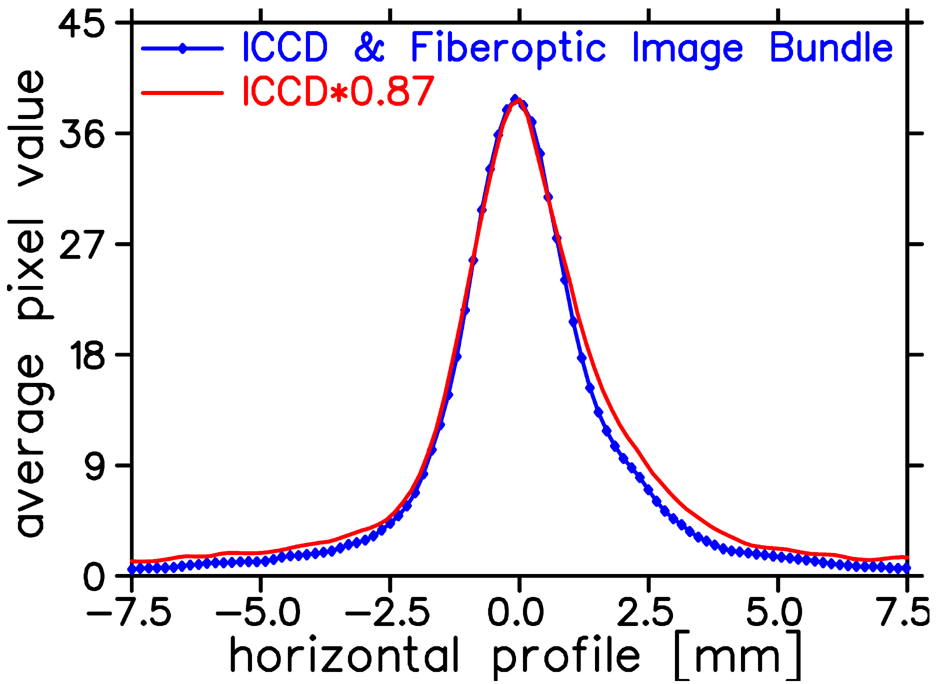
Shielding-Concept with Image-Guide



- Fiberoptic image guide with ~10^6 sorted optical fibers and $(15mm)^2$ transported active image area
- 65 % total optical losses (coupl. & transm.) 1,3 m length

Shielding-Concept with Image-Guide

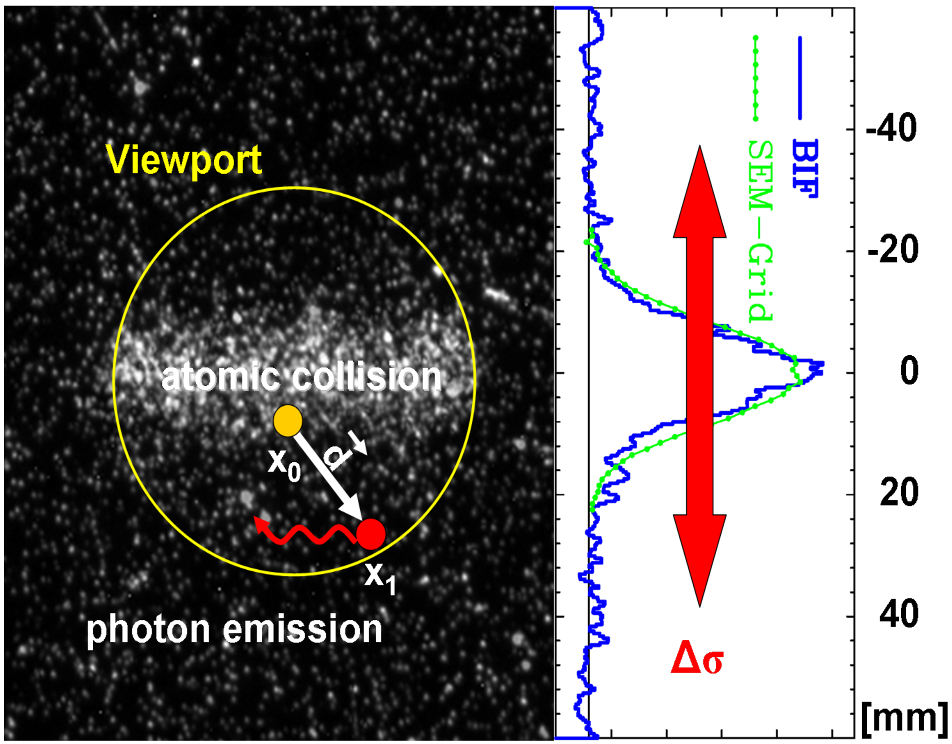




- Fiberoptic image guide with ~10^6 sorted optical fibers and $(15mm)^2$ transported active image area
- 65 % total optical losses (coupl. & transm.) 1,3 m length

Image guide and ICCD-camera resoulution have been matched
→ Imaging properties preserved, comparison profiles agree well

Systematic Errors – Alternative Gases



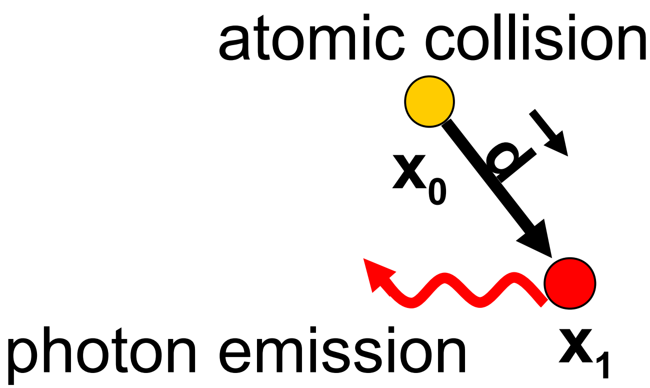
- BIF-profiles represent x_1 the location of photon-emission
- Gas-dynamics and lifetime of excited fluoresecence states influence profile errors
- Gas-dynamics defined by:
  - Temperature
  - Dissociation-kinetics
  - For ions E-field of the beam
  - Mass, charge…

Searching for alternative gases with larger mass and shorter optical lifetimes with respect to N_2 → Spectroscopy needed!

Systematic Errors – Alternative Gases

$$\bar{d}(\tau) = \sqrt{\tau\left(\bar{v}^2_{thermal} + \bar{v}^2_{collision} + \bar{v}^2_{diss.}\right) + \left(\min(\tau,t)\int_0^{\tau,t}\left(v_{E-field}(t)\right)dt\right)^2} + \ldots$$

$$\bar{v}_{thermal} = \sqrt{\frac{8k_BT}{\pi M}} \quad \bar{v}_{collision} \leq 2\,\bar{v}_{collision} \quad \bar{v}_{diss.} = \sqrt{\frac{E_{diss.}}{M}} \quad v_{E-field} = \frac{Eq\tau}{M}$$



parameters to choose: τ, ***M***, ***q***

$$\bar{d}(\tau, M, q) \leq \frac{\tau}{\sqrt{M}}\sqrt{5\frac{8k_BT}{\pi} + \frac{E_{diss.}}{2}} + \frac{\tau^2}{M}\sqrt{\frac{Eq}{2M}} + \ldots$$

Systematic Errors – Alternative Gases

$$\bar{d}(\tau) = \sqrt{\tau\left(\bar{v}_{thermal}^2 + \bar{v}_{collision}^2 + \bar{v}_{diss.}^2\right) + \left(\min(\tau,t)\int_0^{\tau,t}\left(v_{E-field}(t)\right)dt\right)^2 + \ldots}$$

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Parameters for N_2^+:

τ	=	60 ns
$M_{Nitrogen}$	=	28 amu
q	=	+1
$E_{diss.}$	≤	10 eV
E_{max} NDCX	>	$2\cdot10^5$ V/m

[M.A. Plum, NIM A (2002)]
[W.H. DeLuca, NuSc. (1969)]

parameters to choose: τ, *M*, *q*

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Parameters for N_2^+:

τ = 60 ns

$M_{Nitrogen}$ = 28 amu

q = +1

$E_{diss.}$ < 1 eV

E_{max} NDCX> $2 \cdot 10^5$ V/m

N_2^+ →

Velocities + drifts (60ns):

$v_{thermal}$ = $4{,}7 \cdot 10^{-4}$ mm/ns

$d_{thermal}$ = 28 µm

$v_{diss.}$ ≤ $5{,}8 \cdot 10^{-4}$ mm/ns

$D_{diss.}$ ≤ 35 µm

$V_{E\text{-field,max.}}$ = $4{,}1 \cdot 10^{-1}$ mm/ns

$d_{E\text{-field}}$ = 1240 µm

$$\bar{d}(\tau, M, q) \leq \frac{\tau}{\sqrt{M}}\sqrt{5\frac{8k_BT}{\pi} + \frac{E_{diss.}}{2}} + \frac{\tau^2}{M}\sqrt{\frac{Eq}{2M}} + \ldots$$

Systematic Errors – Alternative Gases

$$\bar{d}(\tau) = \sqrt{\tau\left(\bar{v}^2_{thermal} + \bar{v}^2_{collision} + \bar{v}^2_{diss.}\right) + \left(\min(\tau,t)\int_0^{\tau,t}\left(v_{E-field}(t)\right)dt\right)^2} + \dots$$

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Parameters for Xe^+:

τ = 5 ns
M_{Xe} = 133 amu
q = +1

E_{max} NDCX> $2 \cdot 10^5$ V/m

Xe^+ →

Velocities + drifts (5ns):

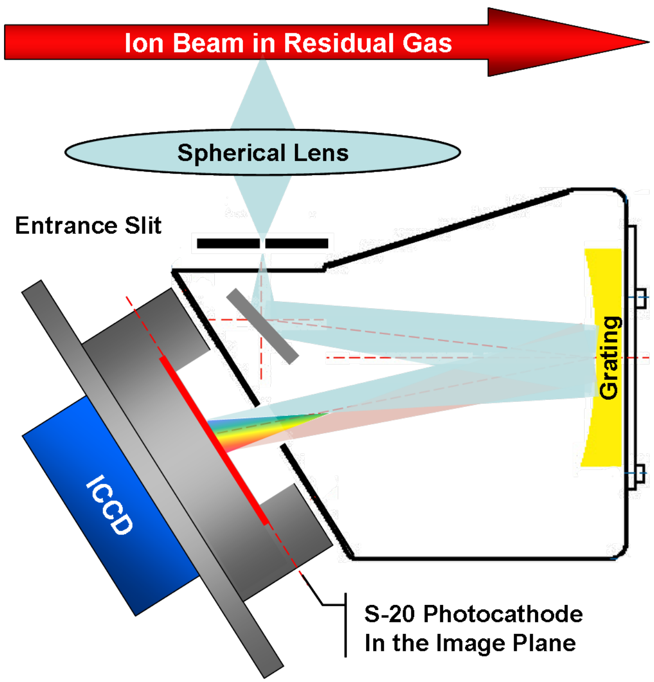
$v_{thermal}$ = $2{,}2 \cdot 10^{-4}$ mm/ns
$d_{thermal}$ = 1,1 µm

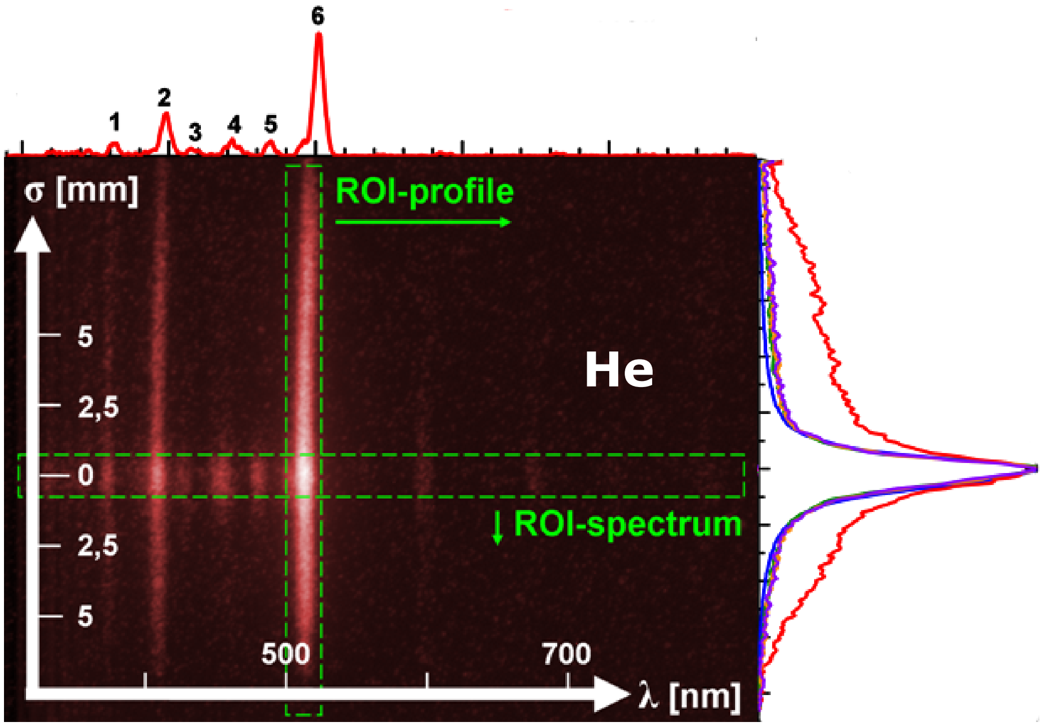
Factor 24, $(24)^2$ smaller error

$V_{E\text{-}field,max.}$ = $7{,}3 \cdot 10^{-1}$ mm/ns
$d_{E\text{-}field}$ = 1,8 µm

$$\bar{d}(\tau, M, q) \le \frac{\tau}{\sqrt{M}}\sqrt{5\frac{8k_BT}{\pi} + \frac{E_{diss.}}{2}} + \frac{\tau^2}{M}\sqrt{\frac{Eq}{2M}} + \dots$$

Imaging Spectrograph with ICCD

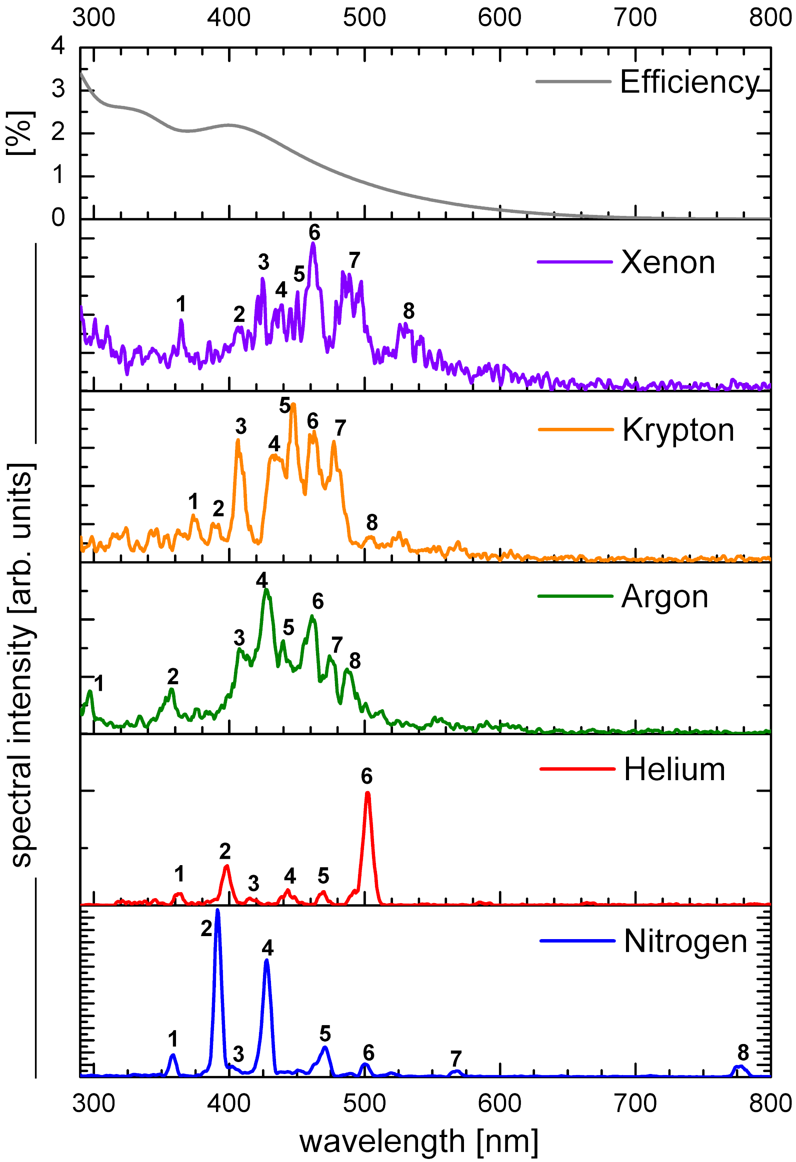




- Technique allows to record fluorescence-images with spectral and spatial information → spectra & beam-profiles
- Chromatically corrected quartz-optics → 300 – 800 nm

Intensity & spectral position of transitions → profile-width

Results - Spectroscopy



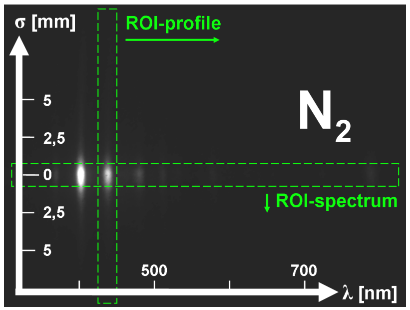
S^{6+} Ions @ 5 *A*MeV in 10^{-3} mbar gas:

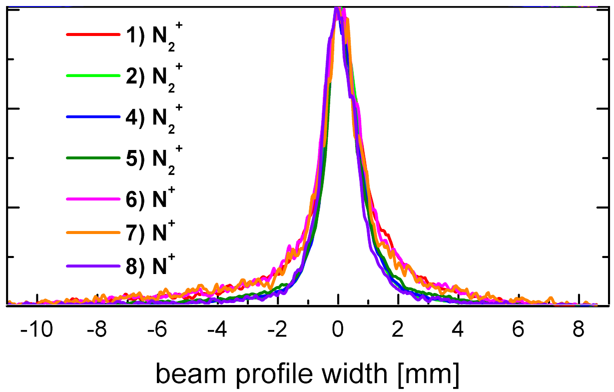
- Efficiency → S-20 cathode (blue)
- All investigated gases show fluorescence-transitions in the visible range → blue-dominated
- Light gases N_2/He show less lines than heavy species

  → Possibility of monochromatic profile analysis!

- He shows neutral lines (He-I) in sensitive spectral range, all other gases show ionic lines (X-II)

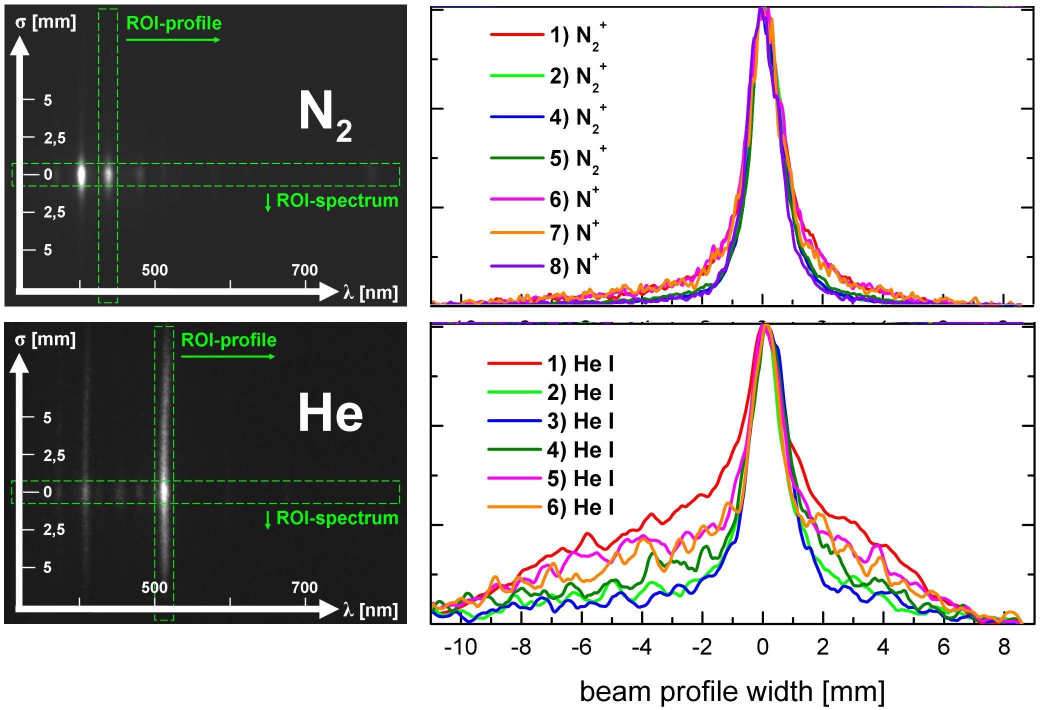
Results Profile Analysis





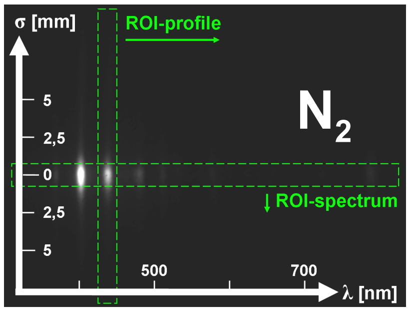
- Transition-selective profile-projections of all nitrogen lines N_2^+ und N^+ with similar shapes

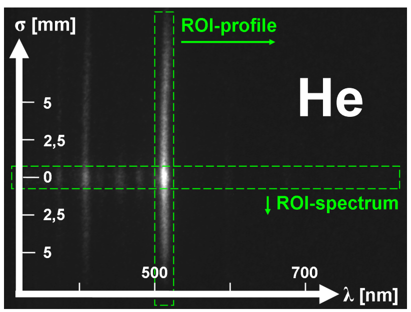
Results Profile Analysis



- Transition-selective profile-projections of all nitrogen lines N_2^+ und N^+ with similar shapes
- Beam-profiles by He-I transitions variably broadened, lifetime-independent

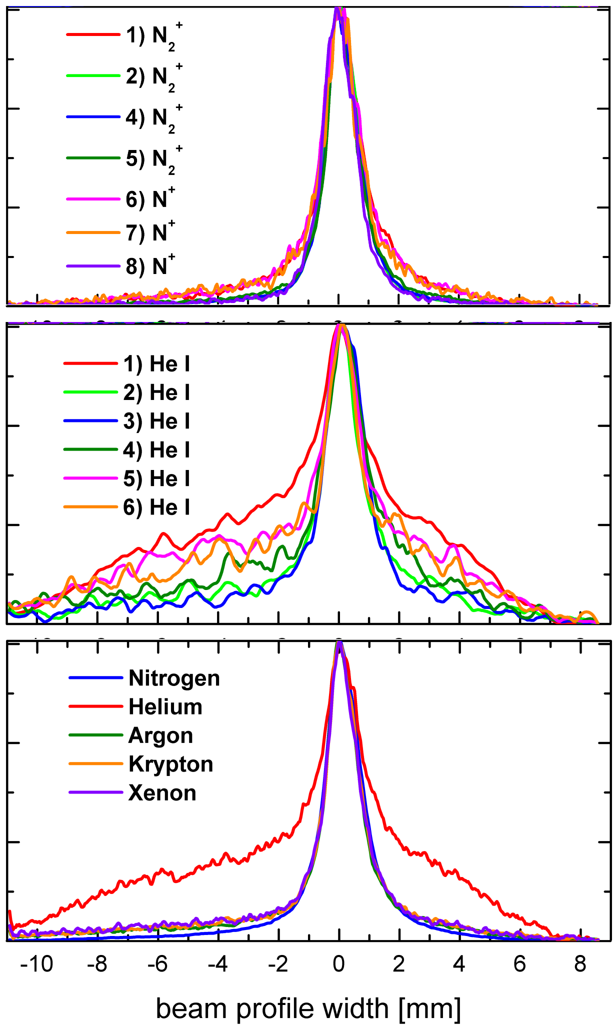
Results Profile Analysis





Comparison:

N_2, He, Ar, Kr, Xe



- Transition-selective profile-projections of all nitrogen lines N_2^+ und N^+ with similar shapes
- Beam-profiles by He-I transitions variably broadened, lifetime-independent
- Integral profiles of heavy rare gases and N_2 agree very well
- He profile ist broadened and of different shape

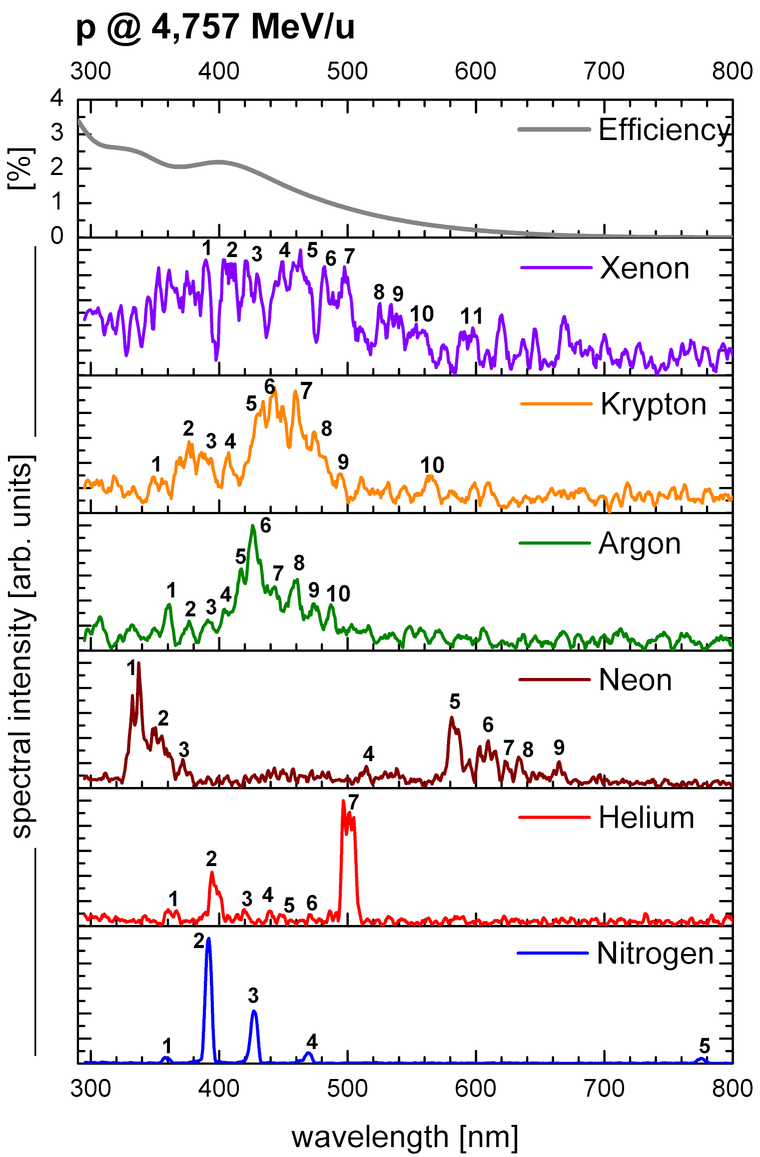
Which Gas Works Best?

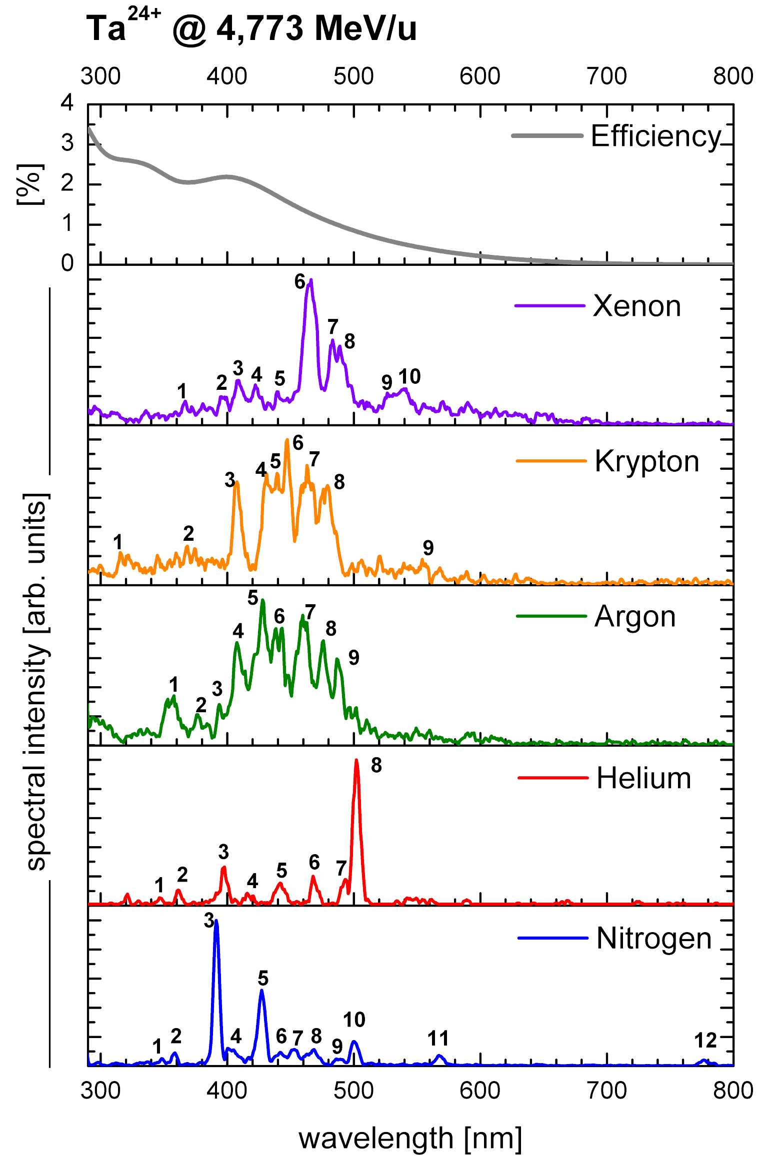
- Profiles in all rare gases but Helium agree with profiles in N_2
- Thermal drift $d_{thermal}$ for heavy gases (A_{Kr}=84, A_{Xe}=131, τ<10ns) vs. N_2 ($2A_N$=28, τ=60ns) → drops like 1 µm vs. 30 µm
- Rare gases occur as atoms → no dissociation-dynamics
- Chart compares light yields $\mathbf{I_{mess}}$ and $\mathbf{I_{eff}} = I_{mess}/Z_{gas}$ normalized with respect to -dE/dx ~ Z_{gas}:

Gas	N_2	He	Ar	Kr	Xe
$\mathbf{I_{mess}}$	258	9	98	163	222
$\mathbf{I_{eff}}$	**100**	26	30	25	22

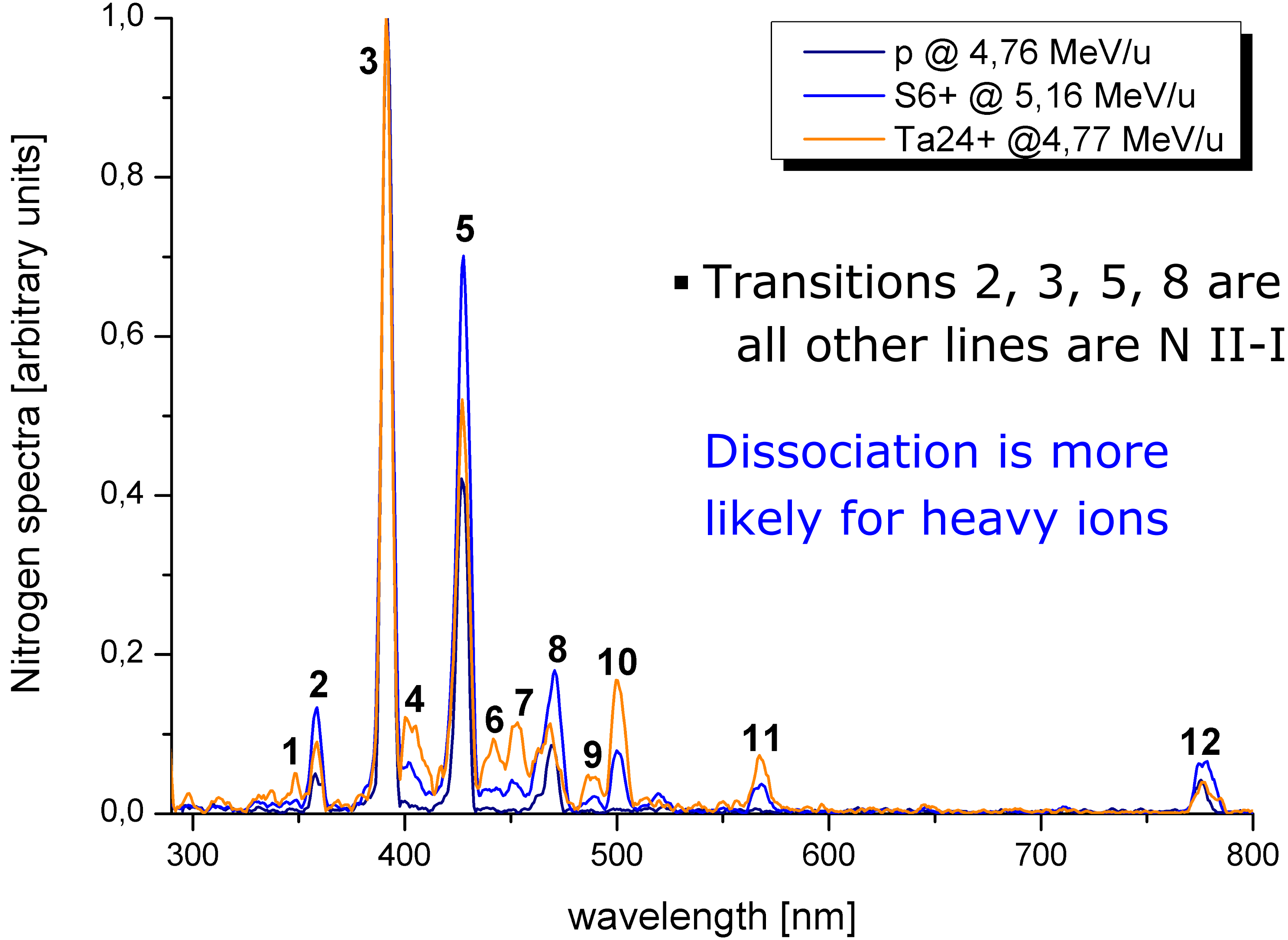
For most applications N_2 is the best compromise,
due to its four times higher fluorescence-efficiency per -dE/ds

How the Ion Species influences Spectra





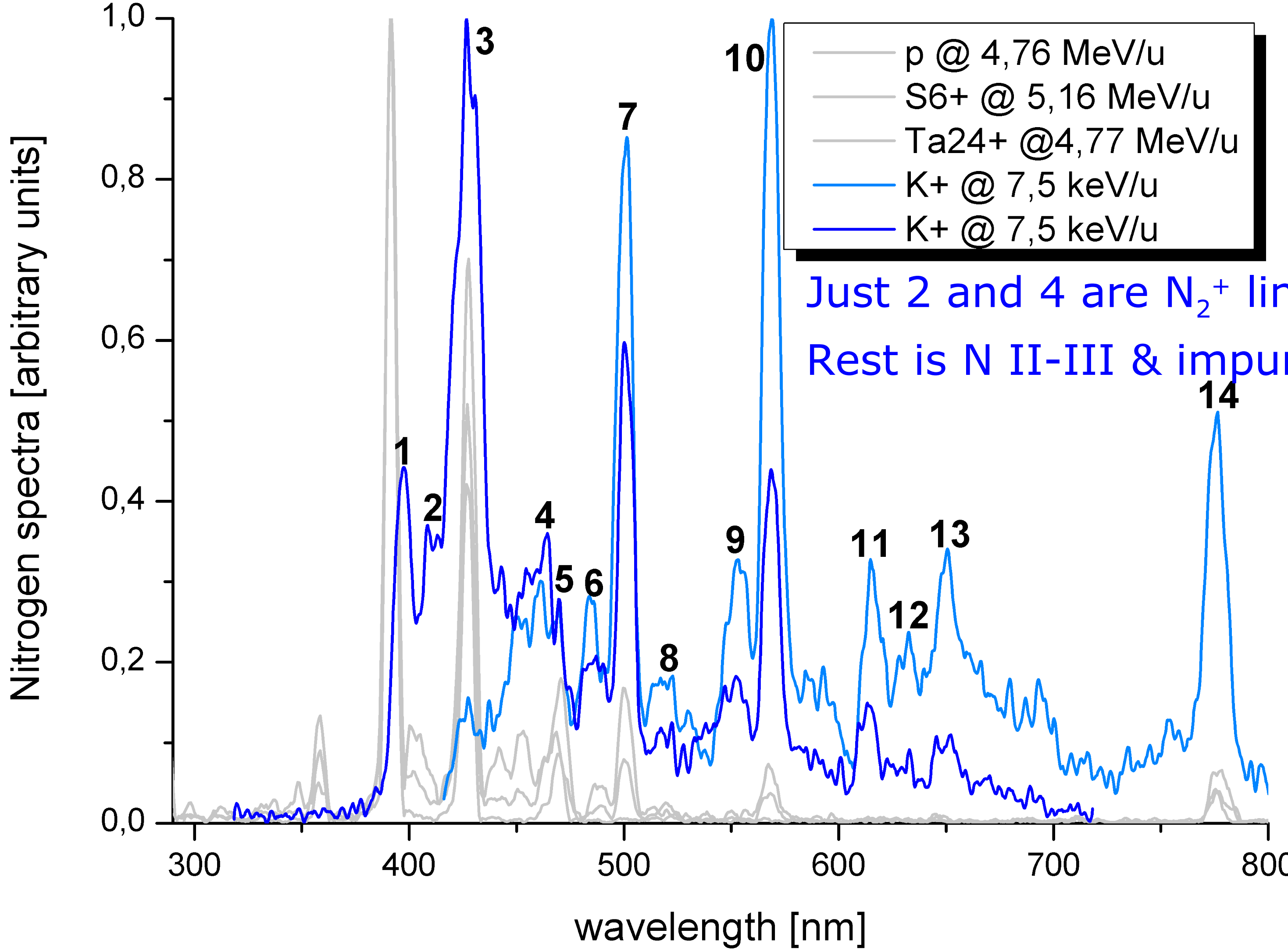
How the Ion Species influences Spectra



- Transitions 2, 3, 5, 8 are N_2^+ all other lines are N II-IV

Dissociation is more likely for heavy ions

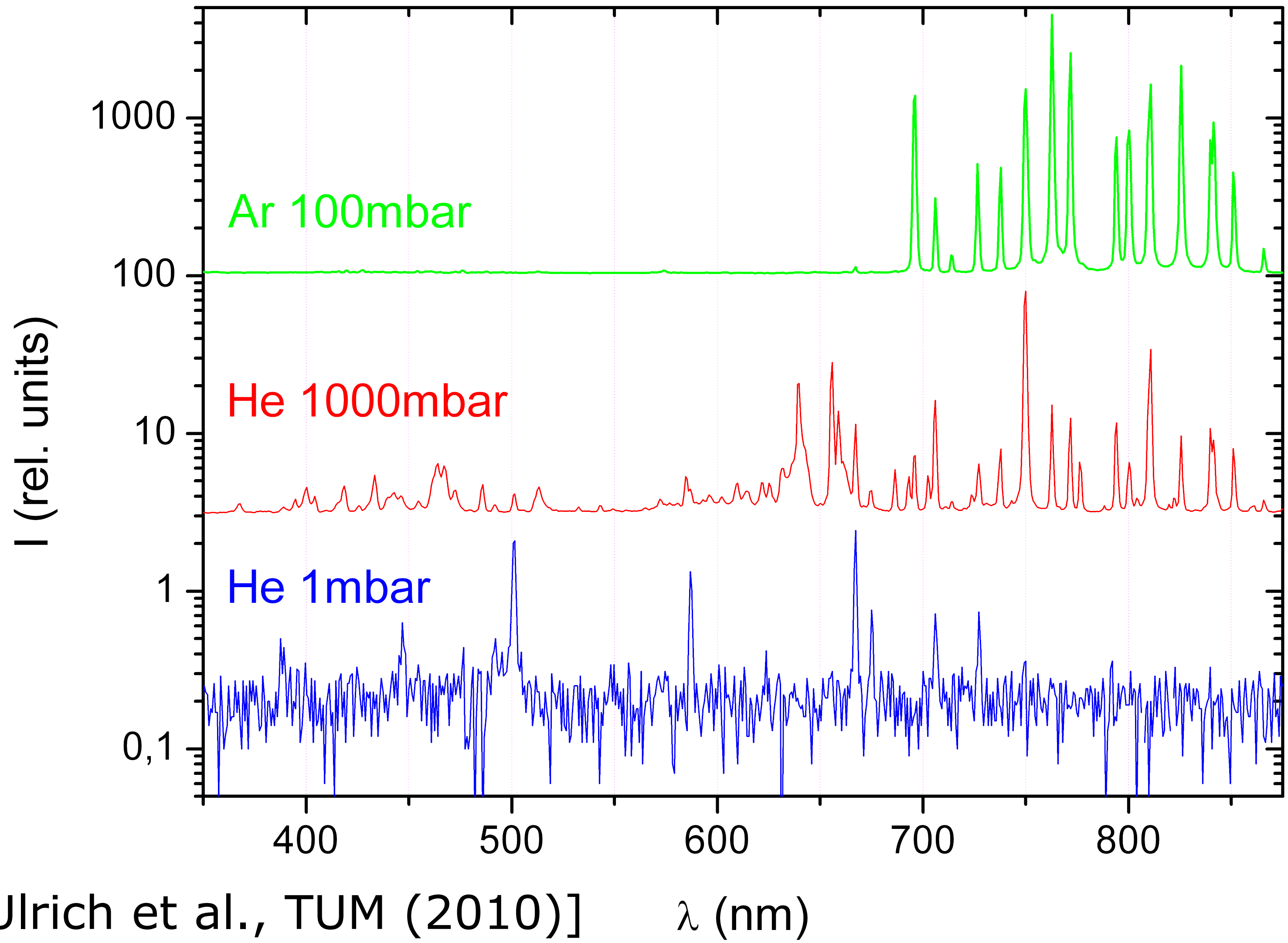
How the Energy influences Spectra



Just 2 and 4 are N_2^+ lines

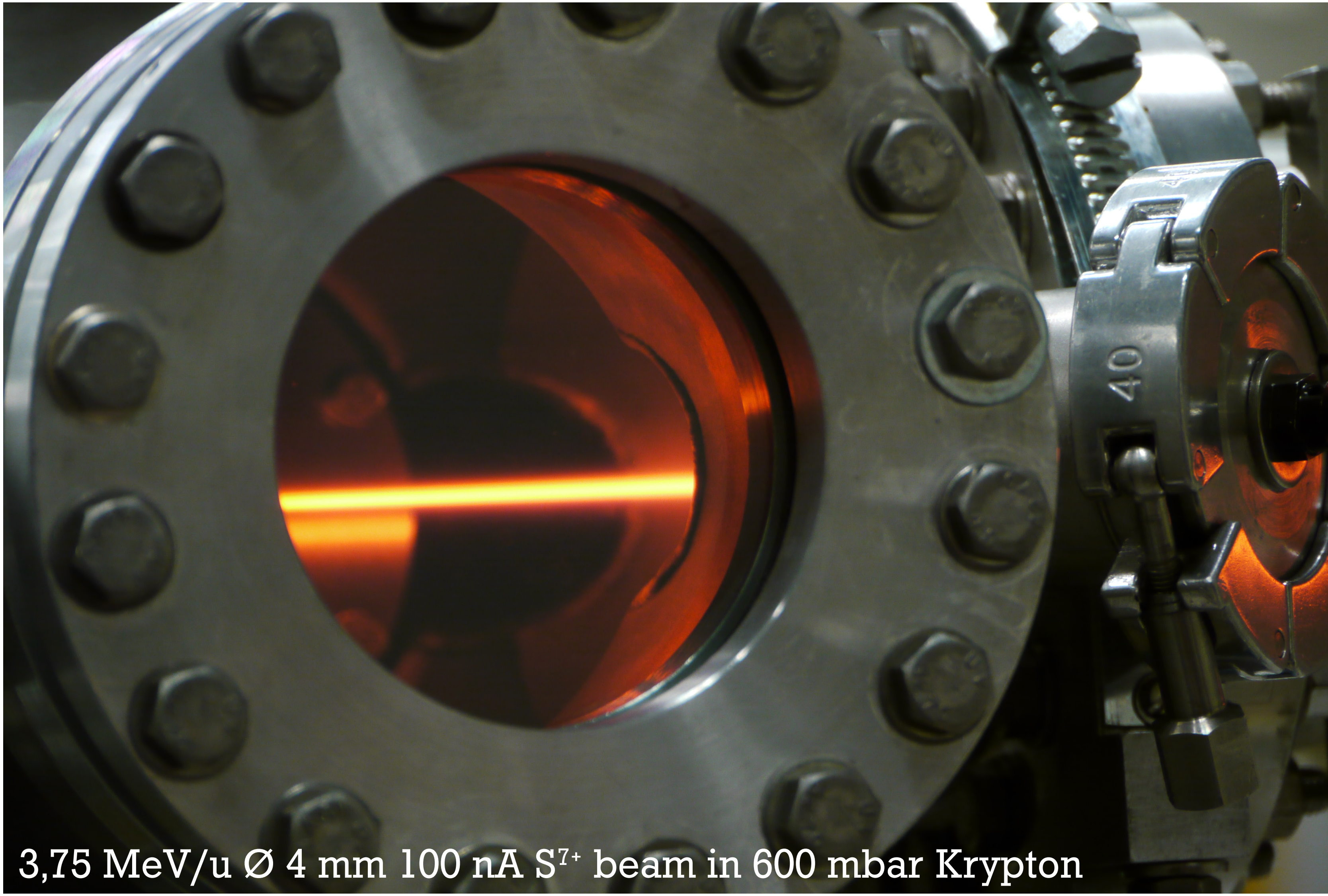
Rest is N II-III & impurities

How the Gas-Pressure influences Spectra



[A. Ulrich et al., TUM (2010)]

Easy Diagnostics :-)



Decreasing Kr-Pressure 1000 – 1 mbar

3,75 MeV/u Ø 4 mm 100 nA S^{7+} beam in 1000 - 1 mbar Krypton

Conclusion

- Gas-based profile measurement is important for:
  - Synchrotrons & transport to characterize intensive ion beams
  - Best focusing upon experimental targets (WDM, FRS, ...)
- Successful application of IPM and BIF was shown:
  - In the energy-range of 7,5 *A*keV – 750 *A*MeV
- Results of research:
  - Signal-amplitude $\rightarrow$ linear with p, dE/ds with E $\rightarrow$ f = const.
  - Profile-width $\rightarrow$ does not depend on p $\rightarrow$ p free parameter
  - Radiation-background $\rightarrow$ $\sim E^2$ $\rightarrow$ Shielding is mandatory
  - Rare gases (Kr, Xe) can replace N_2 $\rightarrow$ reduced profile-errors
  - N_2 has highest fluorescence-efficiency per energy-loss
- Outlook – Technical improvement
  - Construction of a shielded BIF-monitor with an image-guide
  - Pulsed piezo-driven gas-valves for lower average gas load
  - Careful comparison between IPM‘s and BIF-monitors

Thank`s to...

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Thank you for your attention :-)