Beam Induced Fluorescence Monitor Developments at GSI heavy Ion Facility

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HB 2010, Morschach

Non-destructive transverse profile determination:

- No influence to the beam ⇒ time dependence evolution detectable
- No risk of material melting by beam power ⇒ save operation of the device

Outline of the talk:

- Technical realization for single photon detection generated by residual gas
- Spectroscopic investigations for rare gases and N_2
- Energy scaling of signal strength and background, $1.4\text{MeV/u} < E_{kin} < 750\text{MeV/u}$
- Conclusion

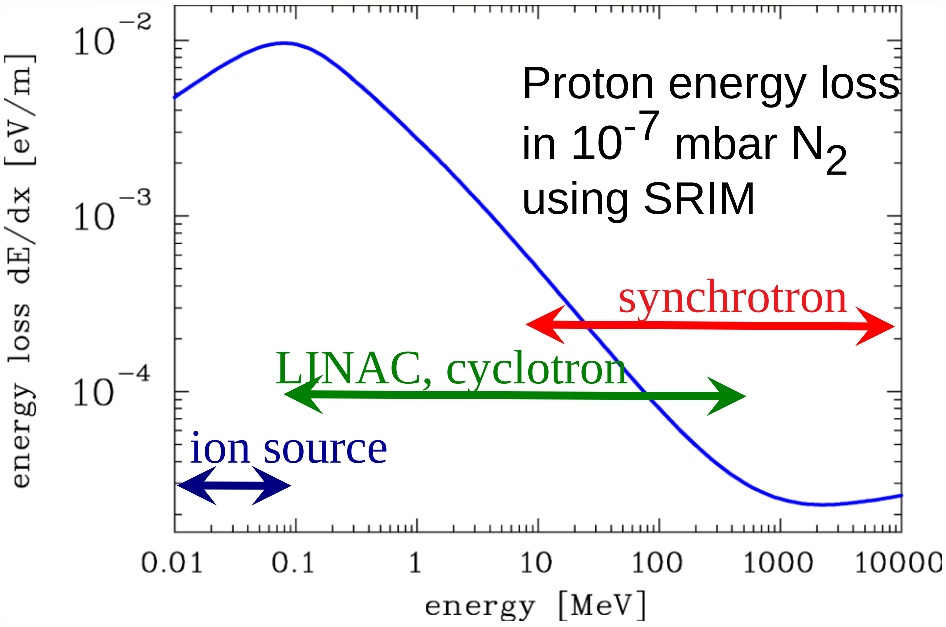
Expected Signal Strength for BIF-Monitor

***Physics*:**

Energy loss of hadrons in gas ***dE/dx***

⇒ Profile determination from residual gas

- **Ionization:** about 100 eV/ionization
- **Excitation + photon emission:** about 3 keV/photon



Ionization probability proportional to ***dE/dx*** by Bethe-Bloch formula:

$$-\frac{dE}{dx} = \text{const} \cdot \frac{Z_t \cdot \rho_t}{A_t} \cdot Z_p{}^2 \cdot \frac{1}{\beta^2} \cdot \left[\ln\left(\text{const} \cdot \frac{\gamma^2 \beta^2}{W_{max}} \right) - \beta^2 \right]$$

Target electron density:
Proportional to vacuum pressure
⇒ Adaptation of signal strength

$\propto 1/E_{kin}$ (for $E_{kin} > 1$GeV nearly constant)

Strong dependence on projectile charge for ions A^{Zp}

Beam Induced Fluorescence Monitor: Principle

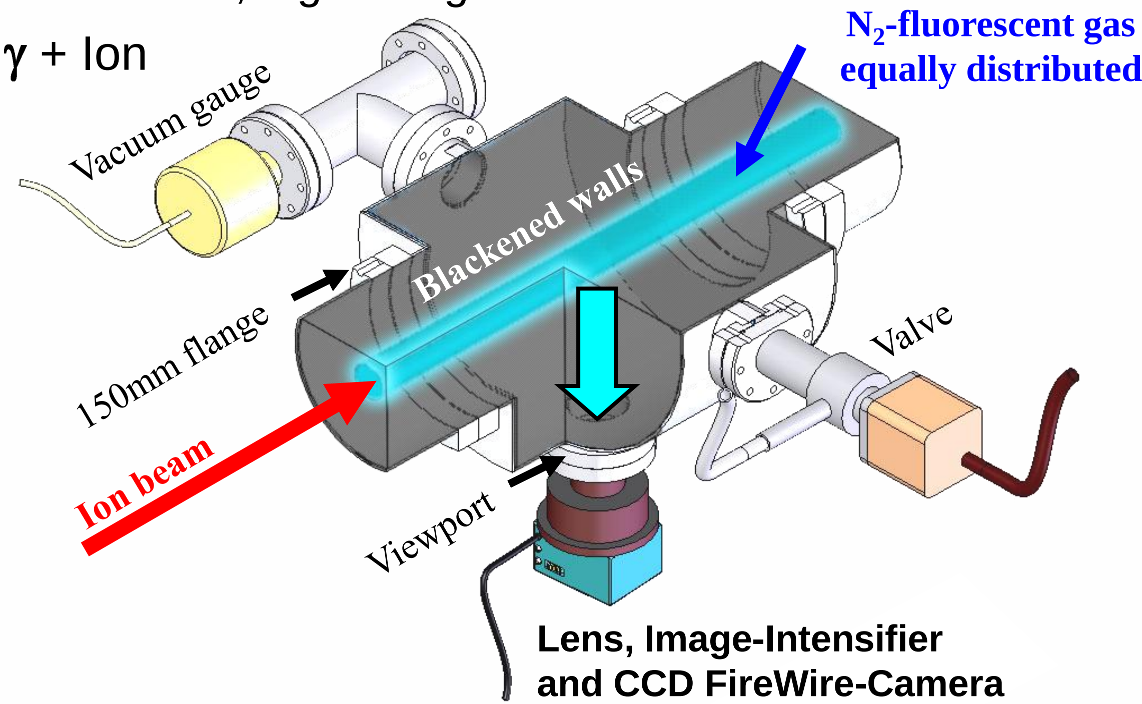
Detecting ***photons*** from residual gas molecules, e.g. Nitrogen

N_2 + Ion → $(N_2^+)^*$ + Ion → N_2^+ + γ + Ion

390 nm< λ< 470 nm

emitted into solid angle Ω to camera

single photon detection scheme



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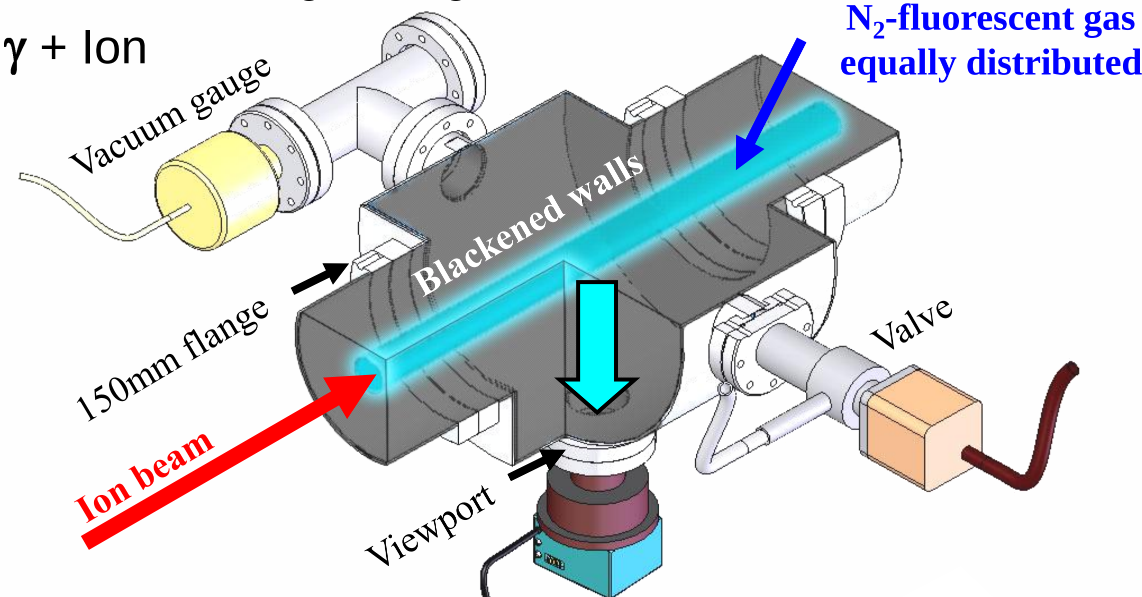
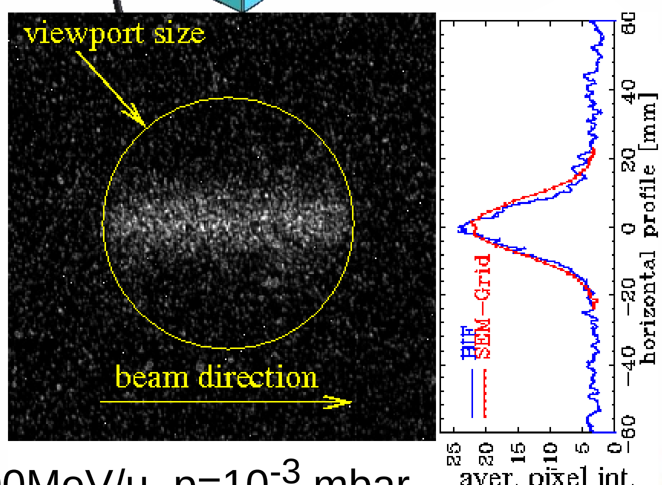


Features:

- Single pulse observation possible down to ≈1 µs time resolution
- High resolution (here 0.2 mm/pixel) can be easily matched to application
- Commercial Image Intensifier
- Less installations inside vacuum as for IPM
  ⇒ compact installation e.g. 20 cm for both panes

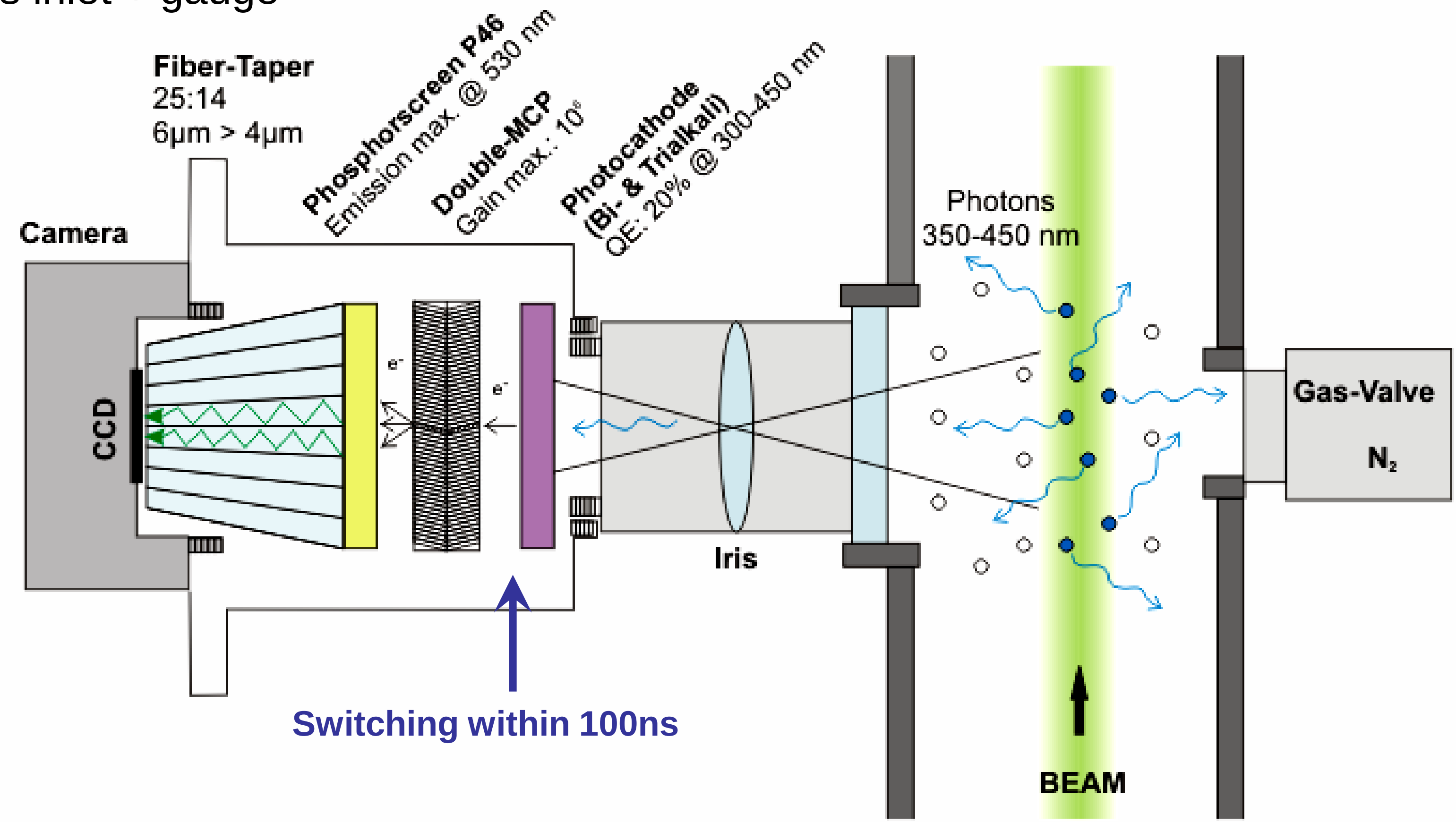


Beam: $4\mathrm{x}10^{10}$ $\boldsymbol{Xe^{48+}}$ at 200MeV/u, p=10^{-3} mbar

BIF-Monitor: Technical Realization

Example BIF station at GSI-LINAC:

- 2 x image intensified CCD cameras: photon → e^- → amplification of e^- → photons → CCD
- Optics with reproduction scale 0.2 mm/pixel
- Gas inlet + gauge

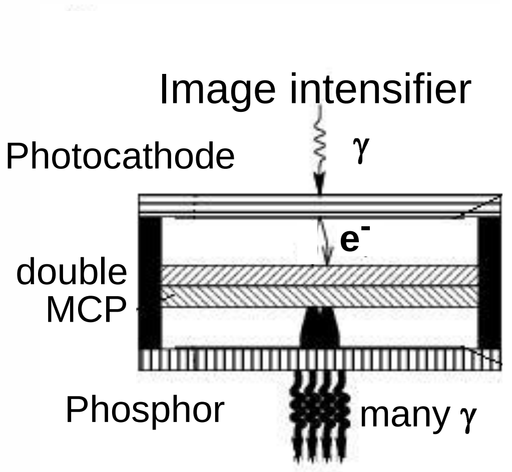


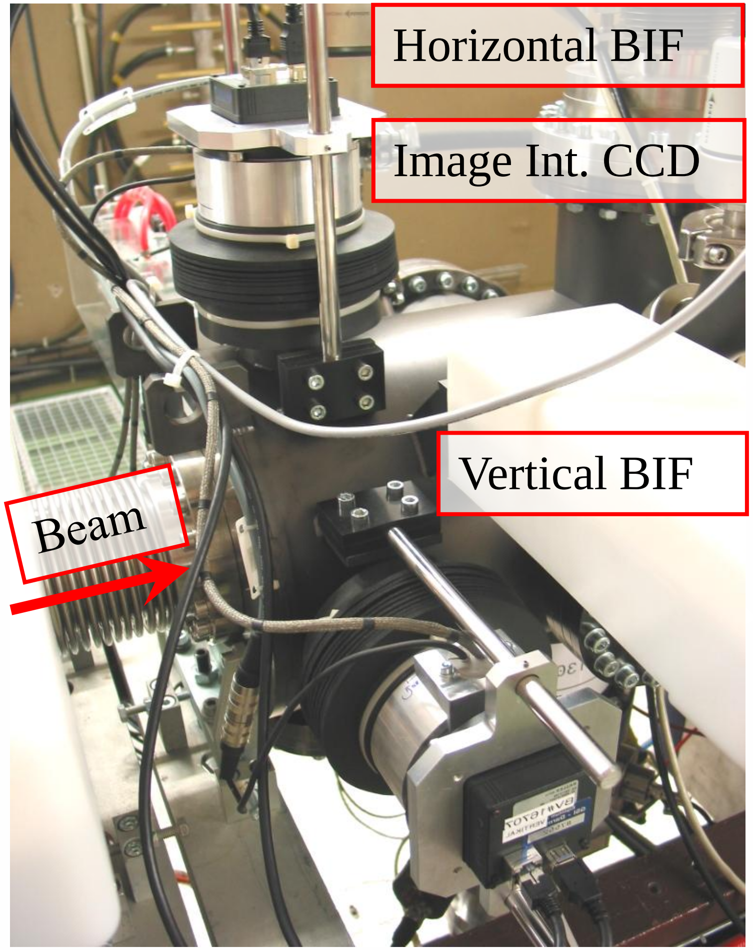
BIF-Monitor: Technical Realization

Example BIF station at GSI-LINAC:

- ➢ 2 x image intensified CCD cameras
- ➢ Optics with reproduction scale 0.2 mm/pixel
- ➢ Gas inlet + gauge
- ➢ Pneumatic feed-through for calibration
- ➢ Insertion length 25 cm for both directions only

Realization at other labs (e.g.BNL, CERN, FZJ):
Segmented photomultiplier, CID or emCCD





Examples from Ion LINAC at GSI

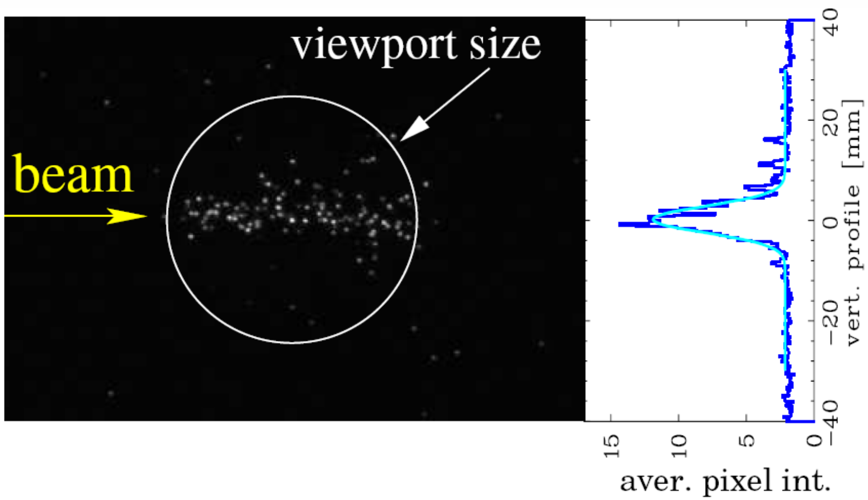
Single pulse observation

4.7 MeV/u Ar^{10+} beam

I=2.5 mA equals to 10^{11} particles

One single macro pulse of 200 μs

Vacuum pressure*:* p=10^{-5} mbar (N_2)



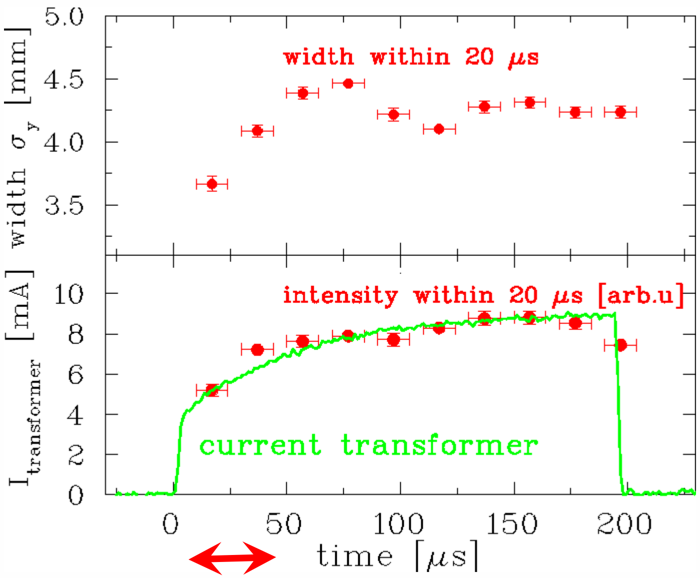
Installed at several location along UNILAC

Time resolved observation

Variation ***during*** the macro pulse detectable:

Switching of image intensifier (within 100 ns)

→ 20 μs exposure window during macro-pulse



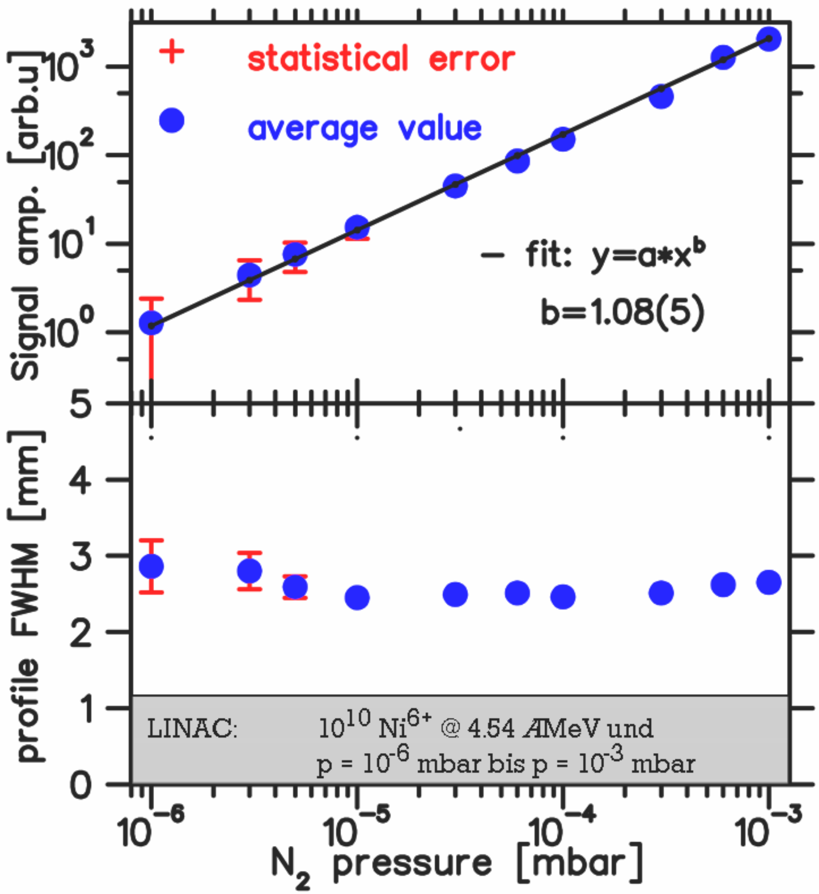
8 mA Ar^{10+}

at 11 MeV/u

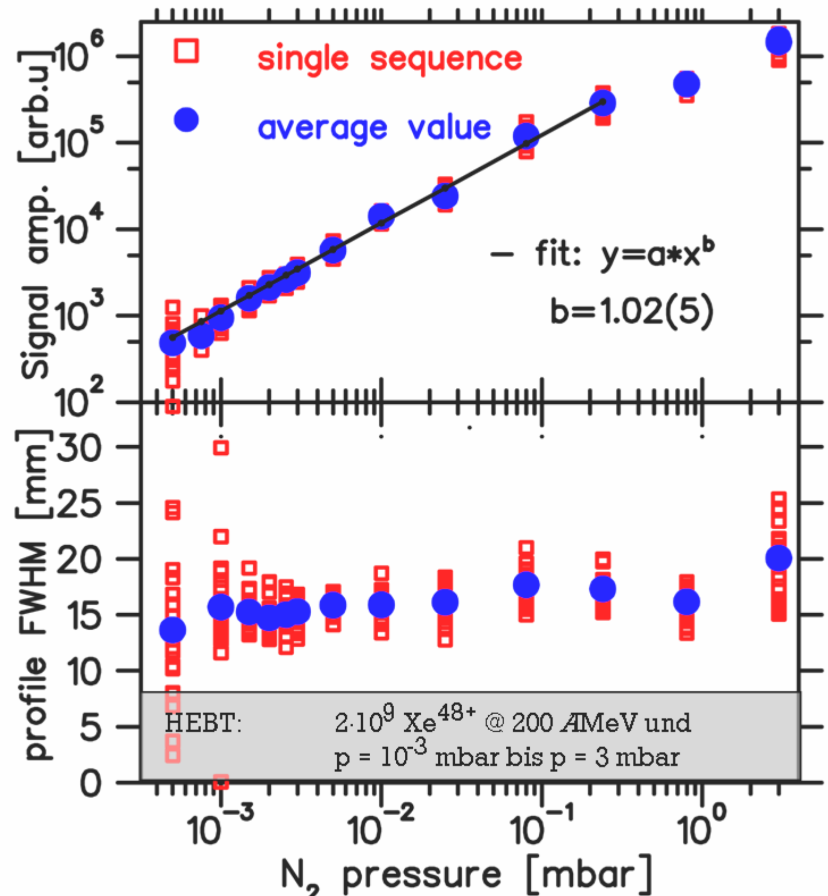
Further application: Background suppression by matching the exposure to beam delivery

Variation of N_2 Pressure over 6 Orders of Magnitude

UNILAC: Ni^{6+} at 4,5 MeV/u



Behind SIS-18: Xe^{48+} at 200 MeV/u



Results: signal amplitude ∝ p and σ = constant

⇒ gas pressure up to 1 mbar is a free parameter

Energy Scaling behind SIS18 at GSI

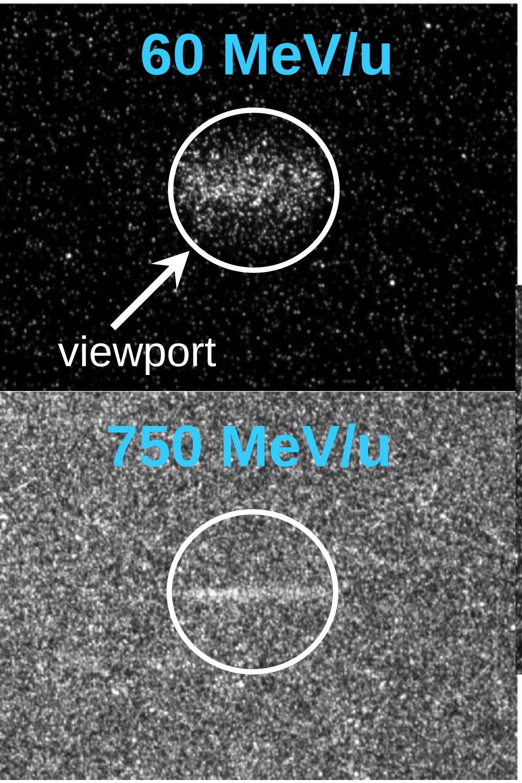
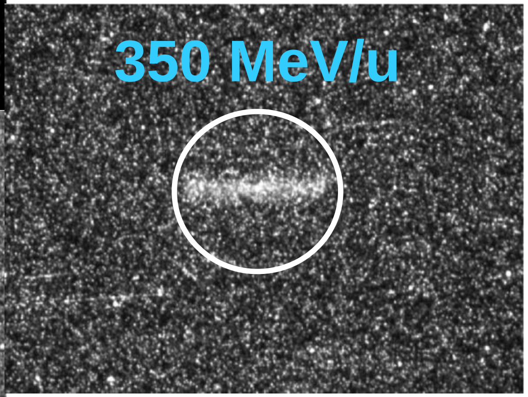
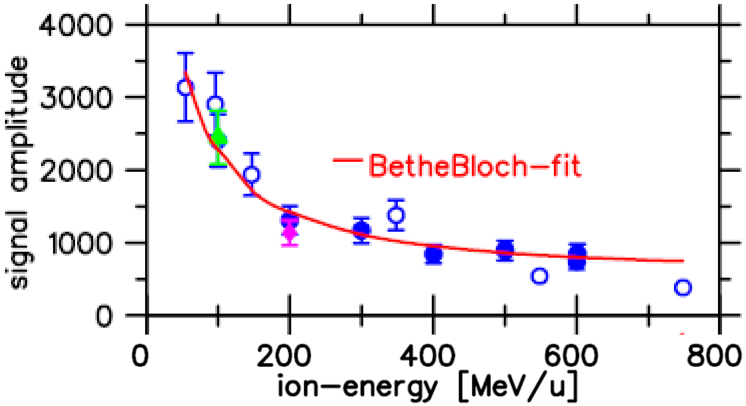


Image from $1{\cdot}10^9$ U
p= $2{\cdot}10^{-3}$ mbar,
mounted ≈ 2 m
before beam-dump:



E_{kin} dependence for signal
& background close to beam-dump:



- Signal proportional to energy loss
- Suited for FAIR-HEBT with ≥ 10^{10} ions/pulse

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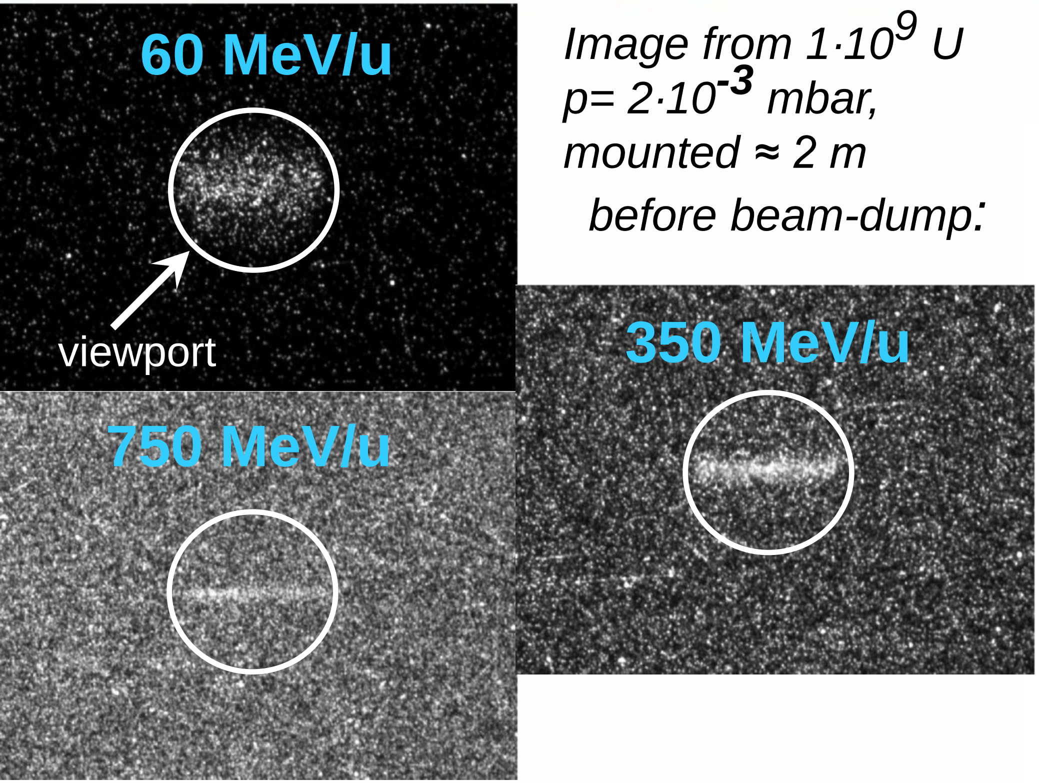

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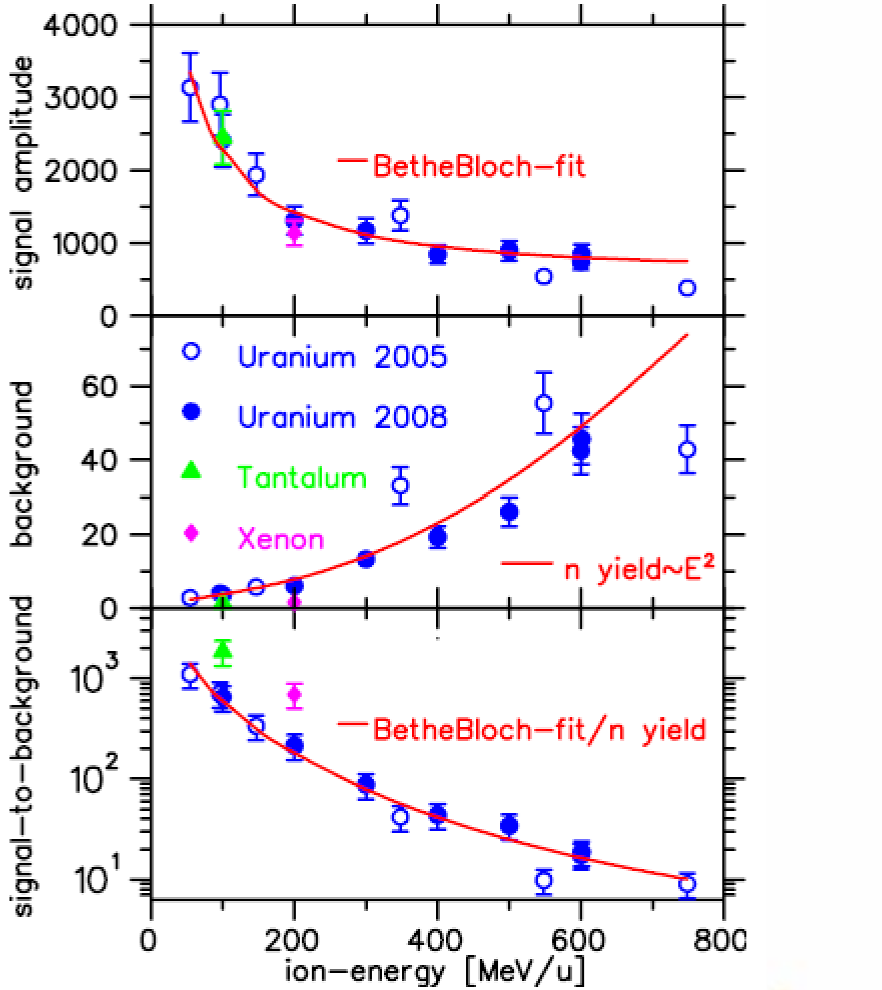
E_{kin} dependence for signal & background close to beam-dump:



- Signal proportional to energy loss
- Suited for FAIR-HEBT with ≥ 10^{10} ions/pulse
- Background prop. E_{kin}^2 ⇒ shielding required
- Background suppression by 1 m fiber bundle

Shielding Concept for Background Reduction

FLUKA simulation:
Shielding of 1x1x1 m^3 concrete block:
900 MeV/u BIF monitor 2m to beam dump
⇒ γ & n reduction 95 %

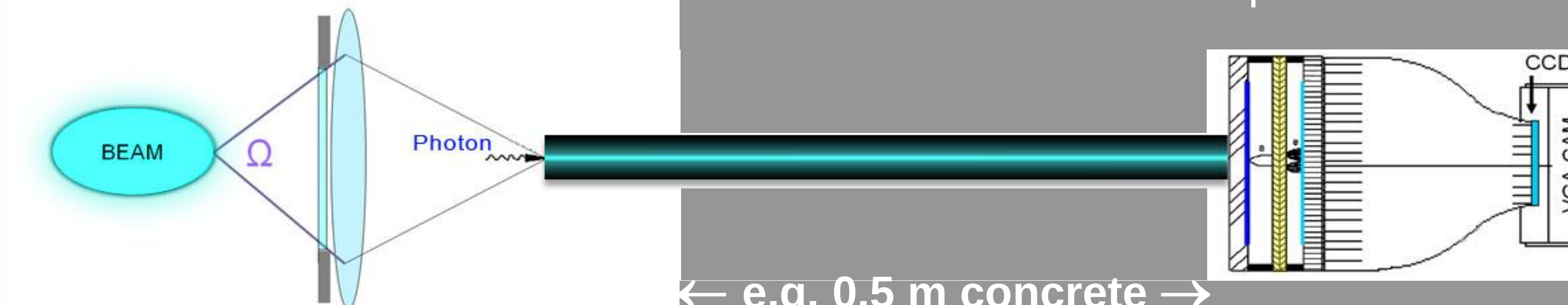
Fiber-optic bundle with ≈1 million fibers:
- Commercial device for reduction of background and CCD destruction
- Image Intensifier and CCD in shielded area
- larger distance but same solid angl

Experimental results:
- No significant image distortion
- Low scintillation by n & γ inside bundle

  un-shielded: ≈30 % increase of background

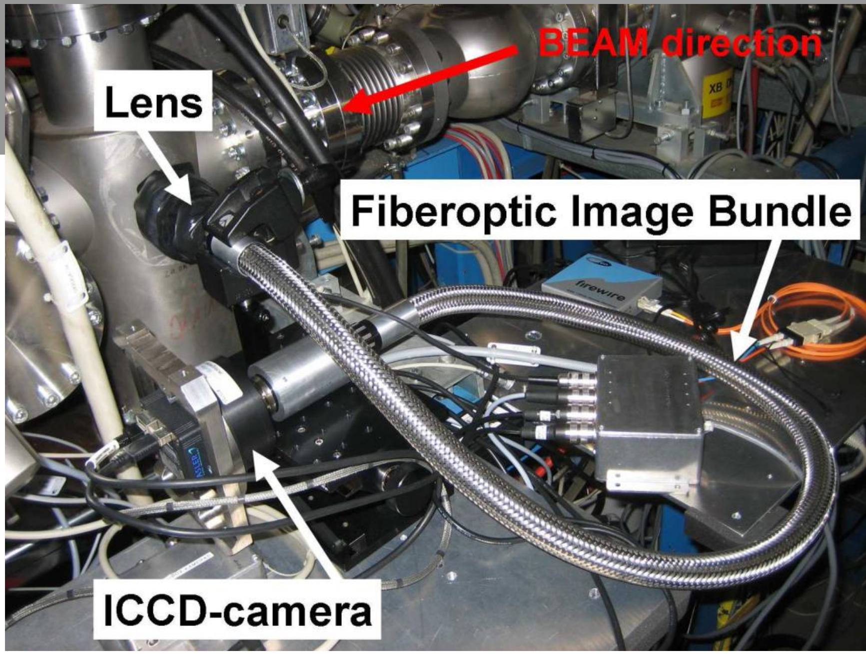
Shielding Concept for Background Reduction

Effective neutron shielding:
moderation and absorption



← e.g. 0.5 m concrete →

FLUKA simulation:
Shielding of 1x1x1 m^3 concrete block:
900 MeV/u BIF monitor 2m to beam dump
$\Rightarrow$ γ & n reduction 95 %



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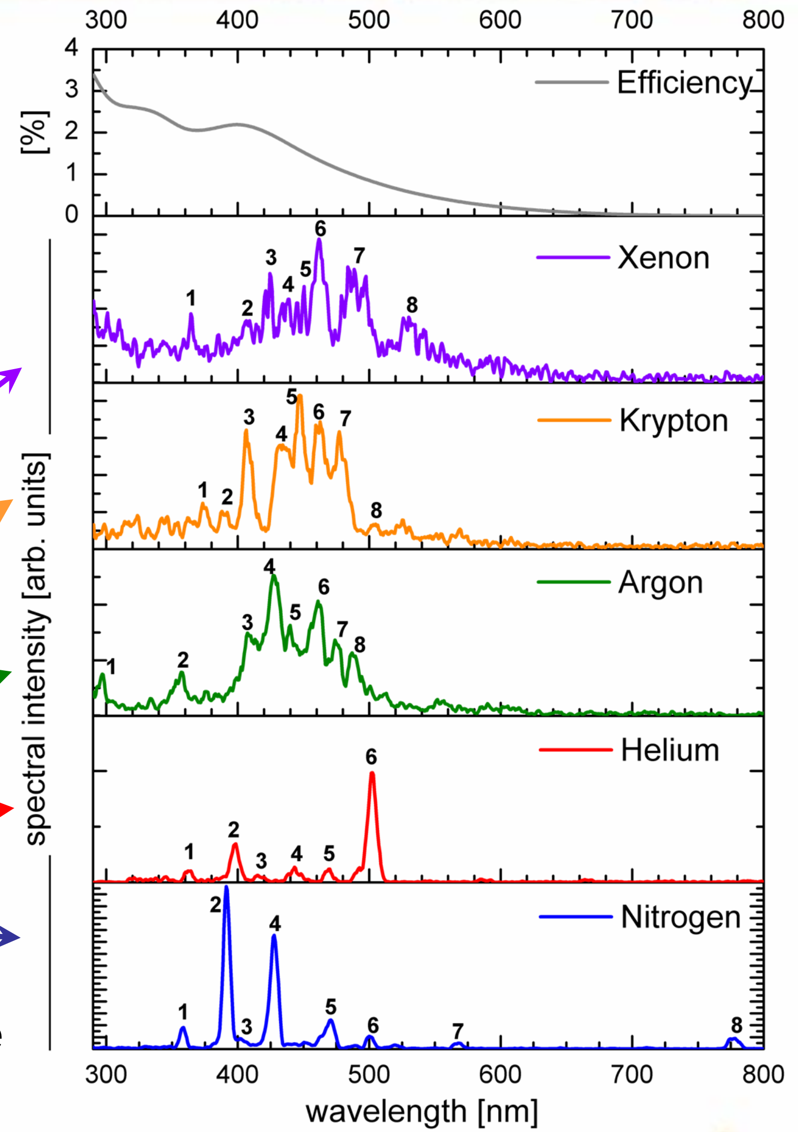
Spectroscopy – Color and Fluorescence Yield

Beam: S^{6+} at 5.16 MeV/u, $p_{N2} = 10^{-3}$ mbar



Results of detailed investigations:

- Rare gases and $\mathbf{N_2}$: green to near-UV
- Compact wavelength interval for $\mathbf{N_2}$
- Fluorescence yield: $\mathbf{N_2}$ ≈4x higher as rare gases

⇒ N_2 and Xe are well suited !

Relative fluorescence yield ***Y*** (all wavelength):

gas	*Y* for *p*	*Y* for p/n_e
Xe	86 %	22 %
Kr	63 %	25 %
Ar	38 %	30 %
He	4 %	26 %
N_2	100 %	100 %

n_e: gas electron density ∝ energy loss ⇔ beam influence

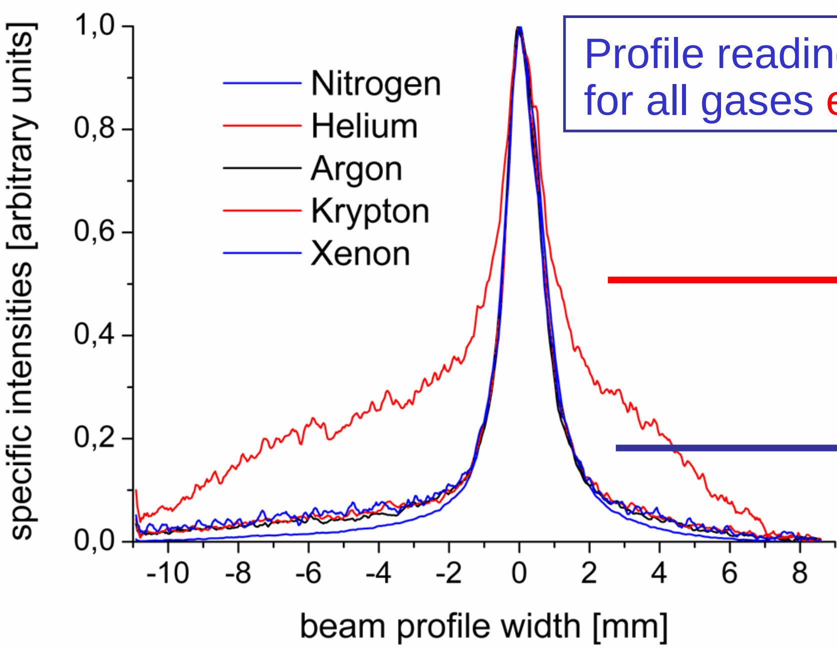
Spectroscopy – Profile Reading

Results of detailed investigations:

- Rare gases and **N_2**: green to near-UV
- Compact wavelength interval for **N_2**
- Fluorescence yield: **N_2** ≈4x higher as rare gases
- Same profile image for **all** gas, **except He**

⇒ ***N_2 and Xe are well suited !***

Normalized profile reading for all λ:



Profile reading equal for all gases except He

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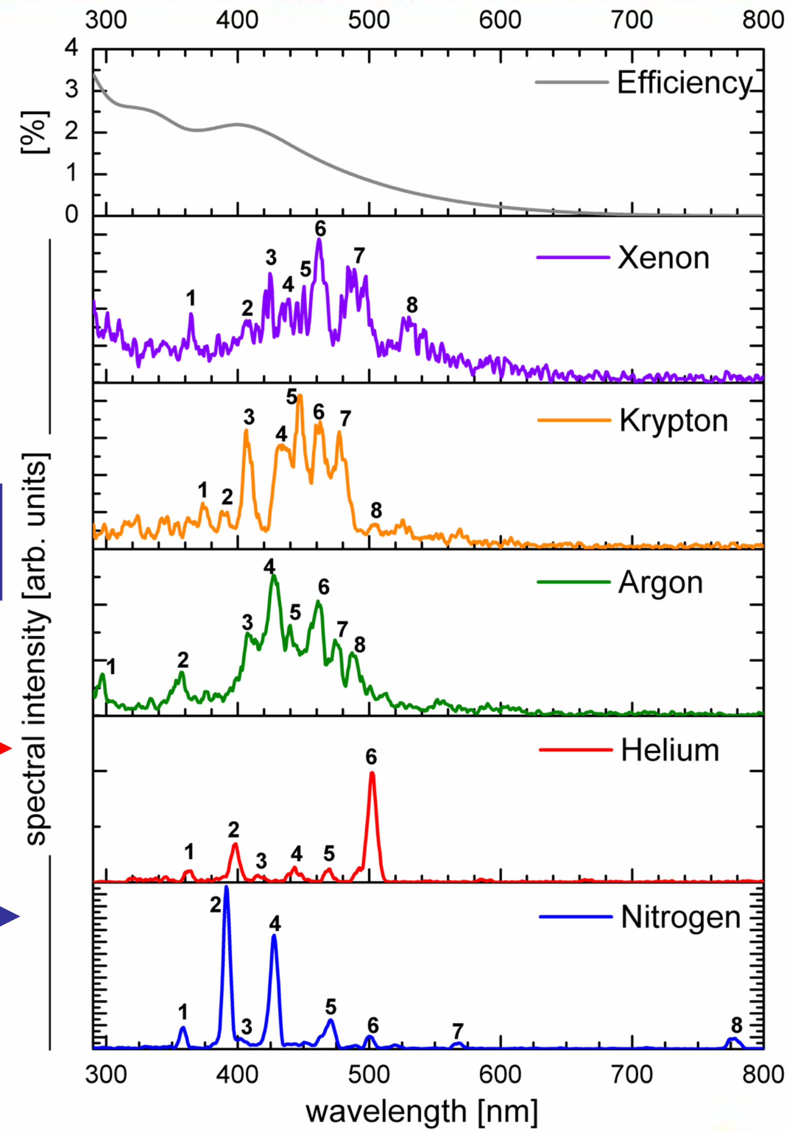


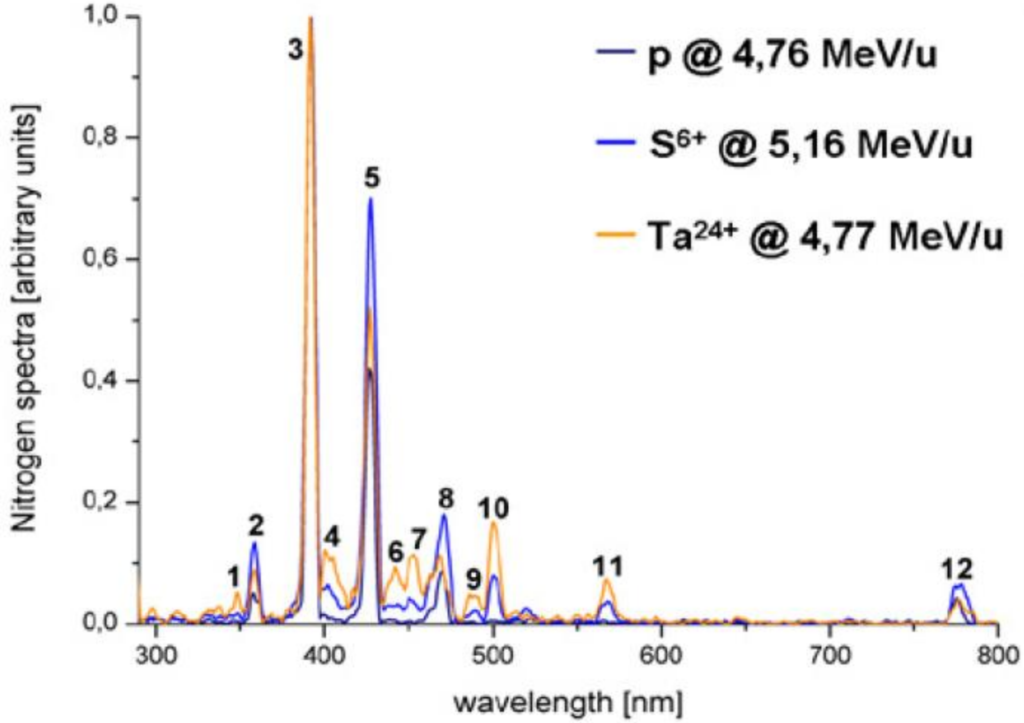
Spectroscopy – Excitation by different Ions

For N_2 working gas the spectra for different ion impact is measured:

Results:

- Comparable spectra for all ions
- Small modification due to $\boldsymbol{N_2^+}$ dissociation by heavy ion impact
- Results fits to measurements for proton up to 100 GeV at CERN

$\Rightarrow$ Stable operation possible for $\boldsymbol{N_2}$

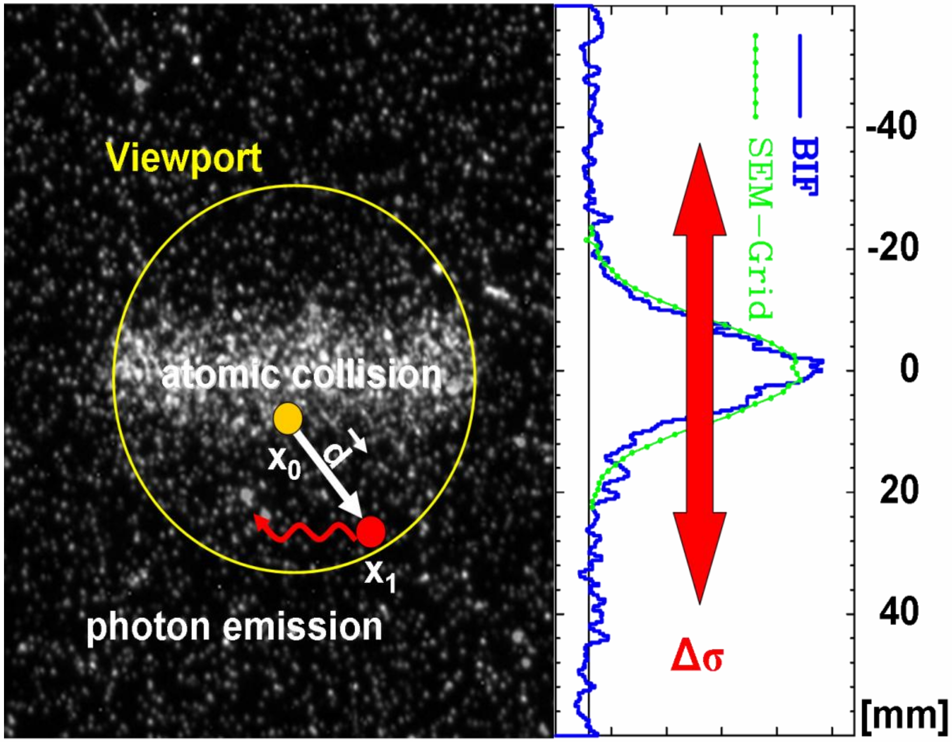


Care: Different physics for $E_{kin} < 100$ keV/u $\Leftrightarrow v_{coll} < v_{Bohr}$

$\rightarrow$ Different spectra measured

M. Plum et al., NIM A (2002), A. Variola, R. Jung, G. Ferioli, *Phys. Rev. Acc. Beams* (2007),

Systematic Errors → Movement in Beam's E-Field



BIF-profiles represent x_1 the location of photon-emission

- Gas-dynamics and lifetime of excited fluorescence states influence profile errors

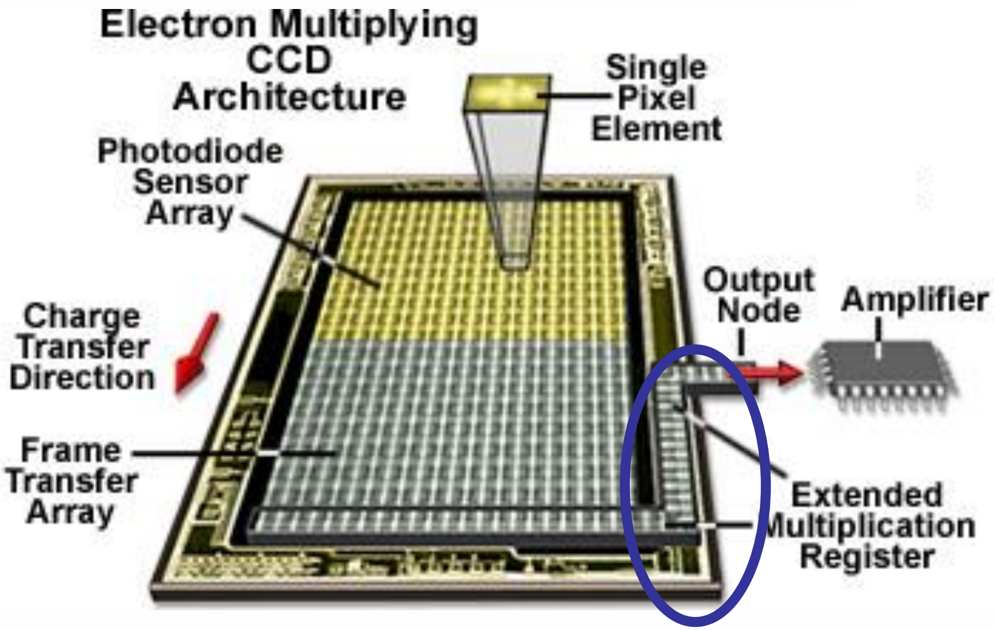
  (not important present GSI beam parameter but for FAIR)

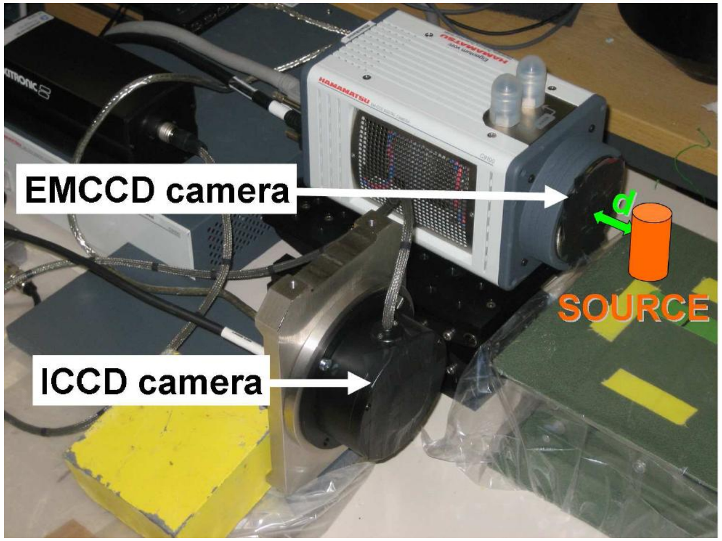
- Gas-dynamics defined by:
  - Lifetime e.g. ***N*$_2$**: 58 ns ***Xe***: 6 ns
  - Mass and ionic charge
  - Dissociation-kinetics
  - **For ions E-field of the beam**

Xe as an alternative gases with 5-fold higher mass and 10-fold shorter optical lifetimes as ***N*$_2$**

Alternative Single Photon Camera: emCCD

Principle of electron multiplication CCD:





Multiplication by avalanche diodes:

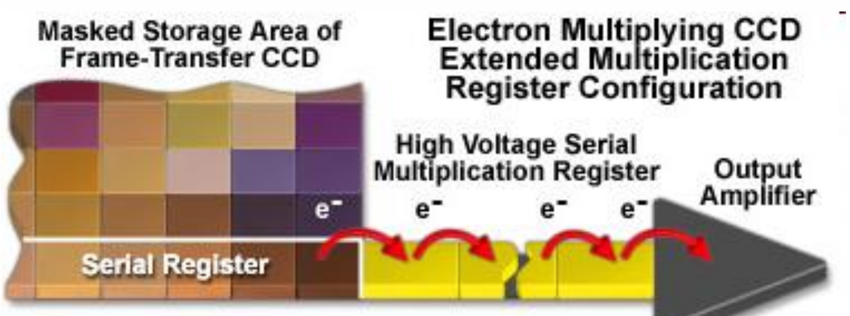


Figure 3

Parameter of Hamamatsu C9100-13

Pixel: 512x512, size16x16μm^2

Maximum amplification: x1200

Temperature of emCCD sensor: -80 ^{O}C

Readout noise: about 1 e$^-$ per pixel

Alternative Single Photon Camera: emCCD

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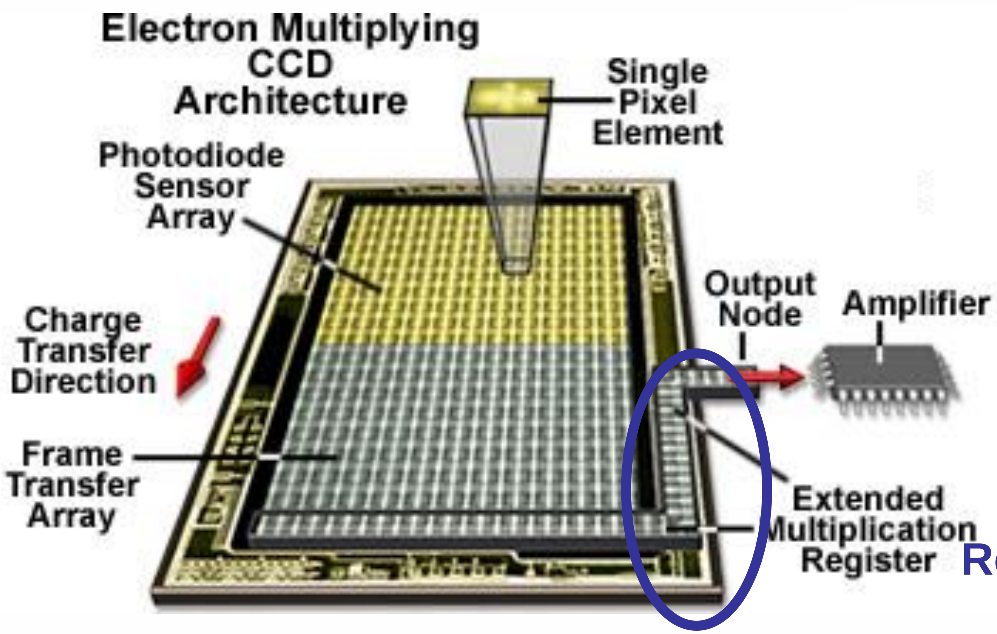

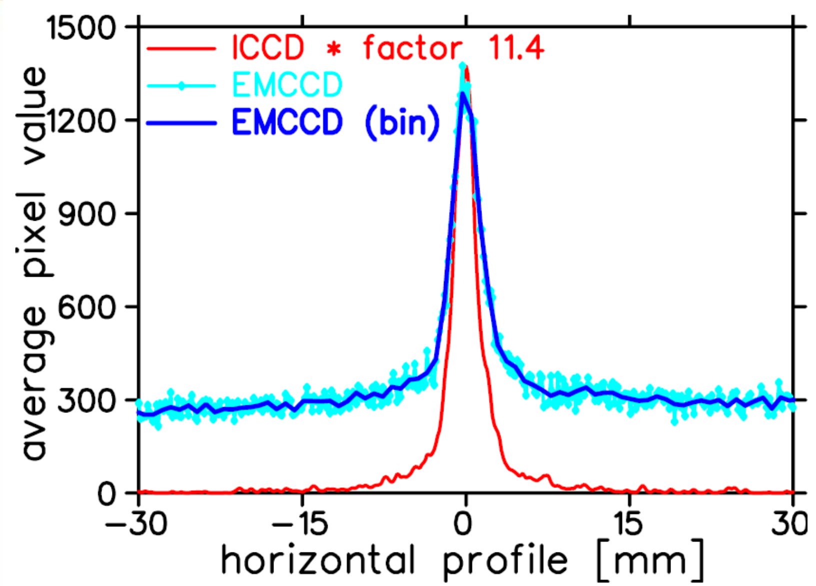

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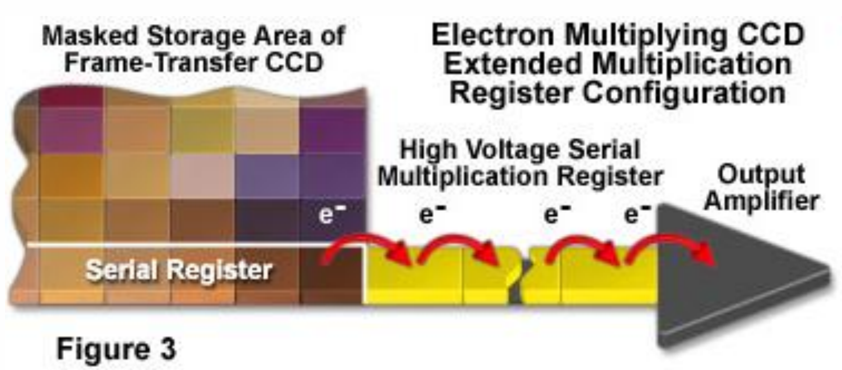

Results: Suited for single photon detection

x5 higher spatial resolution as ICCD

more noise due to electrical amplification

$\Rightarrow$ Acts as an alternative

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Temperature of emCCD sensor: -80 ^{o}C

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Summary Beam Induced Fluorescence Monitor

- Non-destructive profile method demonstrated (single photon detection possible)
- Independence of profile reading for pressures up to 10^{-1} mbar for ***N_2*, *Xe*, *Kr*, *Ar***
- Operational usage at UNILAC started, pressure typ. $p < 10^{-5}$ mbar
- Shielding concept partly demonstrated
- Modern emCCD might be an alternative
- ***N_2*** is well suited: blue wavelength, good vacuum properties, high light yield
- ***Xe*** is an alternative due to 10-fold shorter lifetime: less influence in beam's E-field
- ***He*** is **excluded** as working gas due to wrong profile reproduction
- **Future:** Working gas pressure up 1 bar (i.e. mean free path << beam diameter)
- **Future:** Investigation of shielding and radiation hardness of components
- **Future:** Investigation as target diagnostics for RIB, neutrons or antiprotons

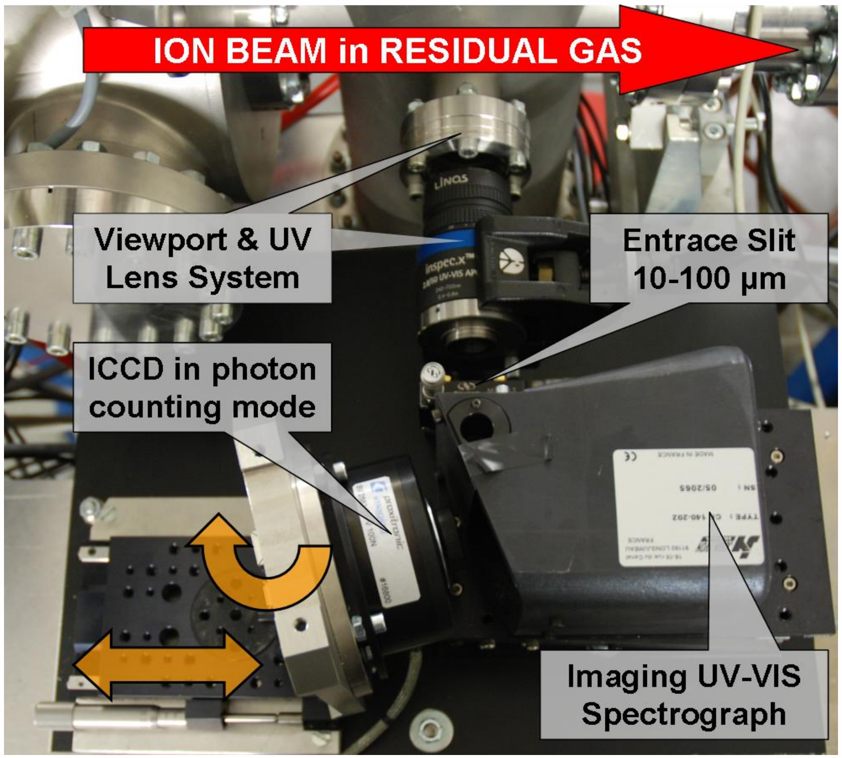
Acknowledgement: F. Bieniosek(LBNL), A. Ulrich (TU-München)

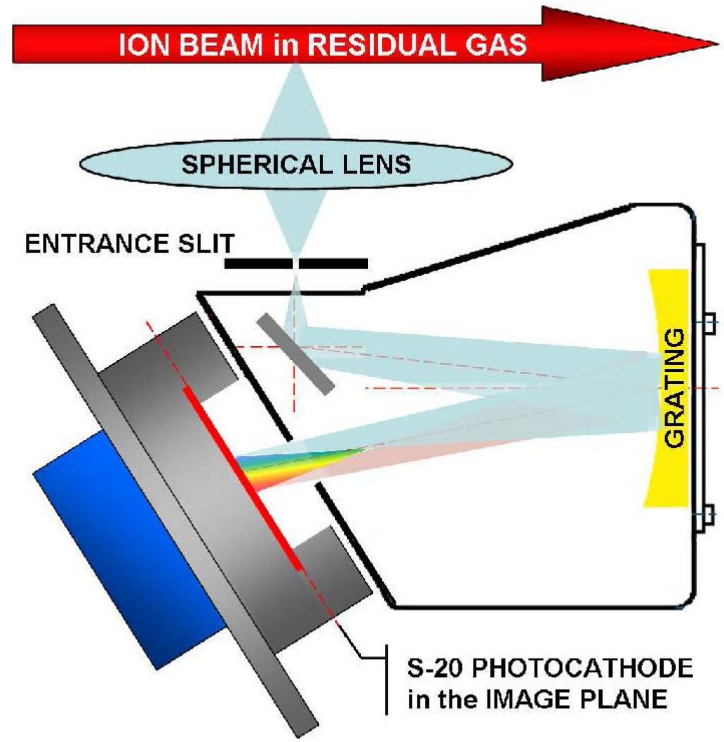
Thank you for your attention!

Spare transparencies

Investigations of light yield and wavelength spectrum for N_2 and rare gases.

Imaging Spectrograph installed behind UNILAC: Wavelength selective beam profile





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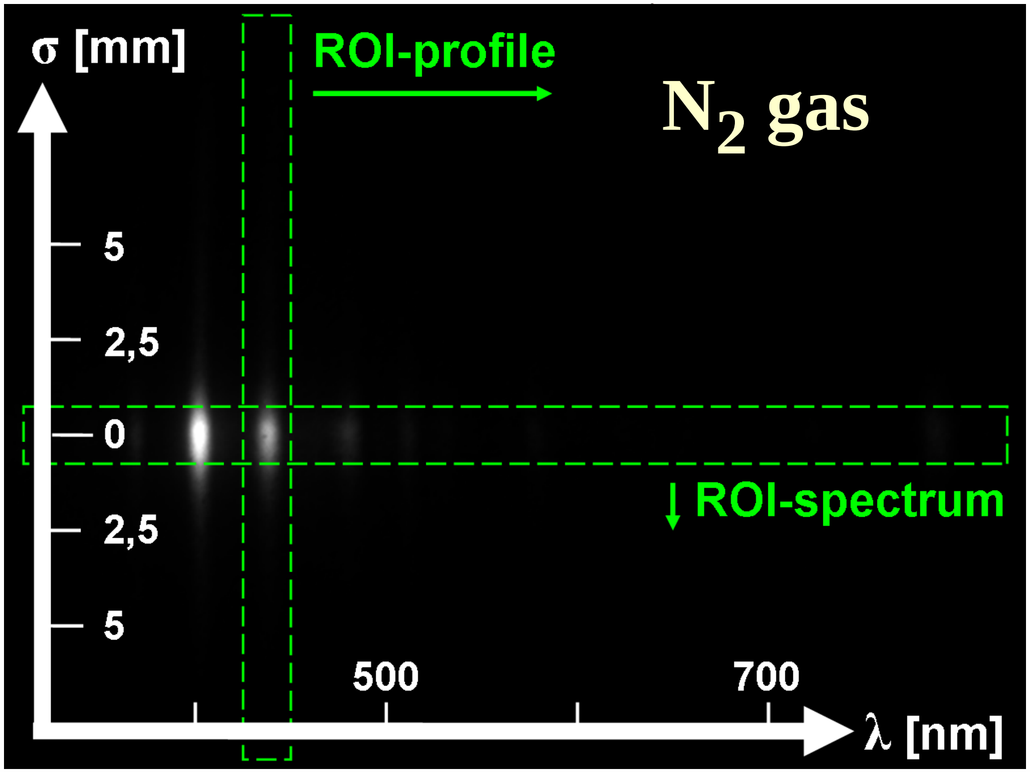
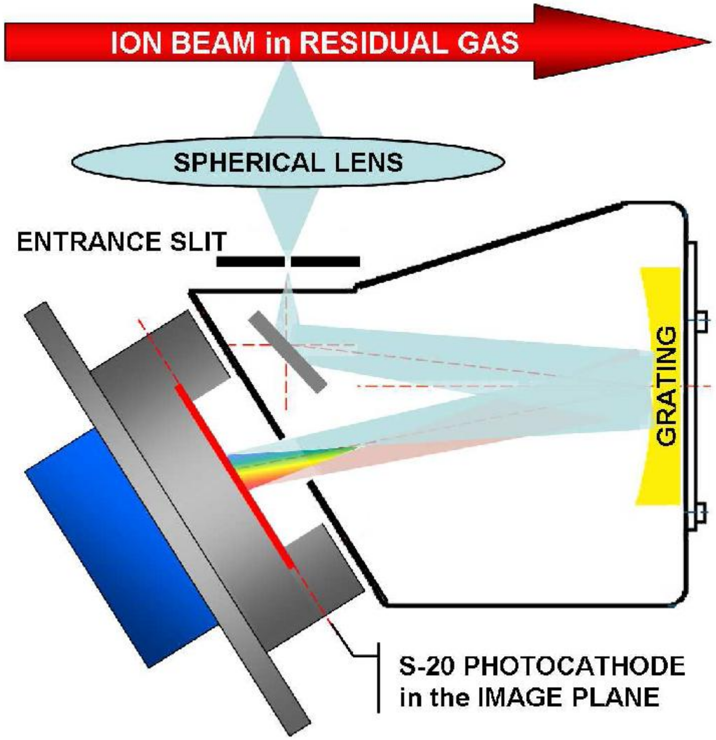
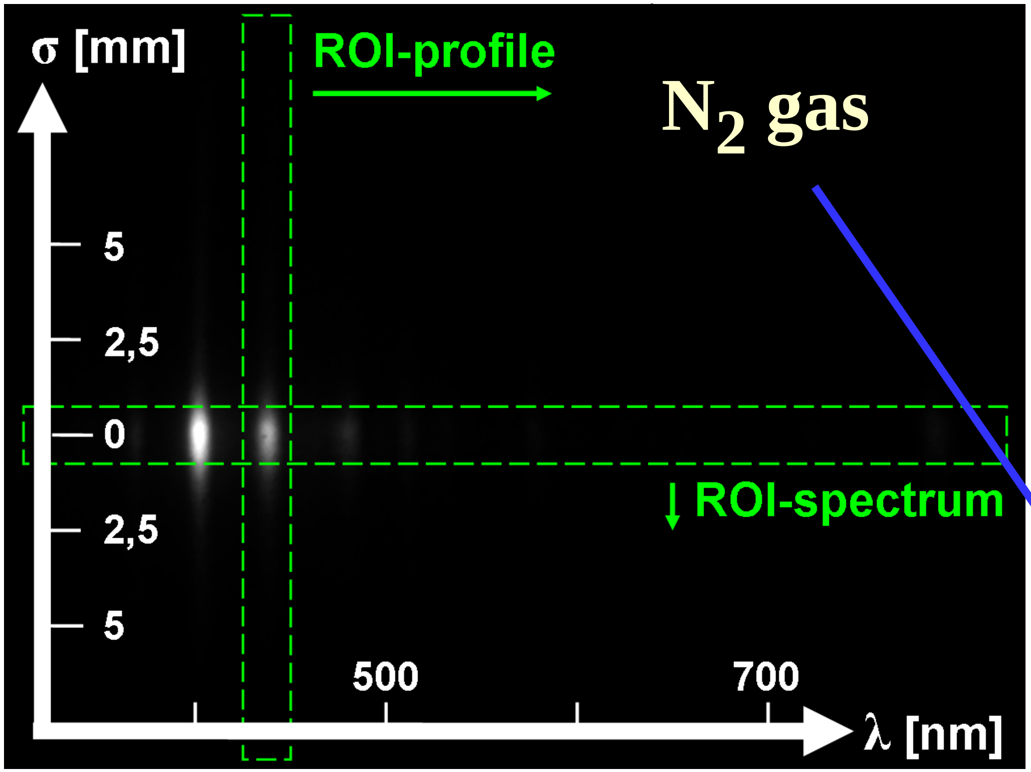
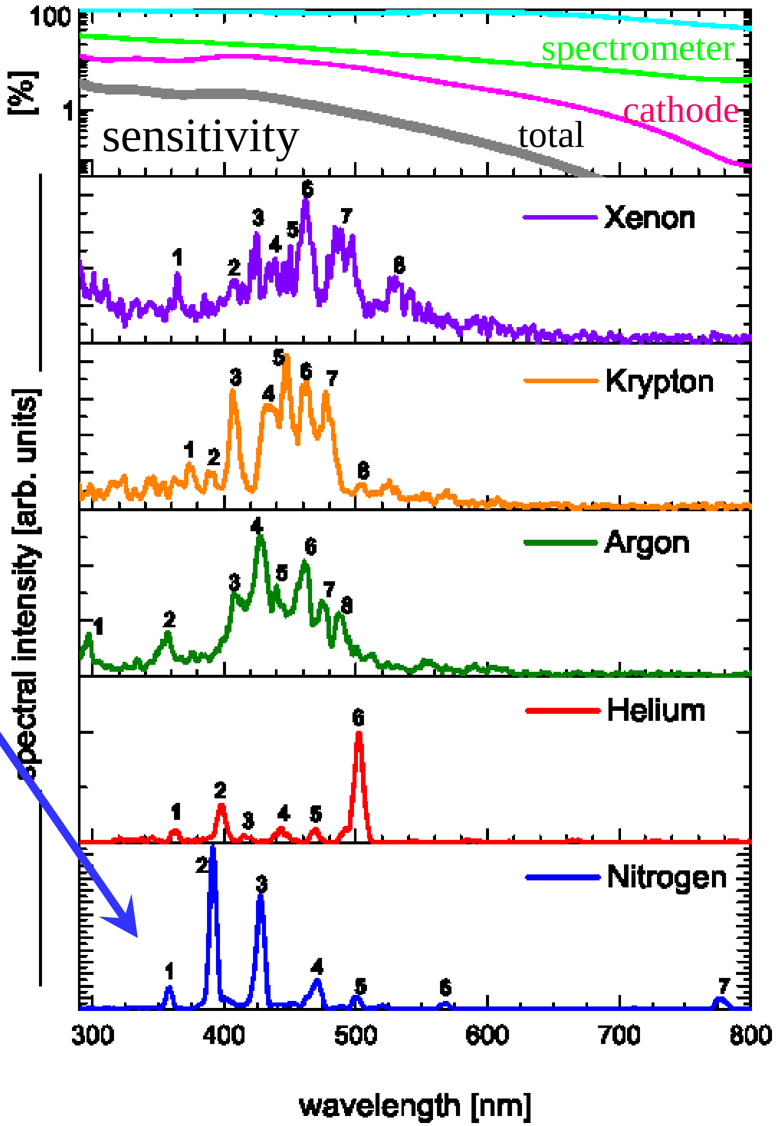




Beam parameter: S^{6+} at 5.16 MeV/u with $3\cdot10^{11}$ pps,
2000 macro-pulses, $p_{N2}=10^{-3}$ mbar

⇒ Expected transitions in near-UV to blue
(as for slower and faster collisions with protons)





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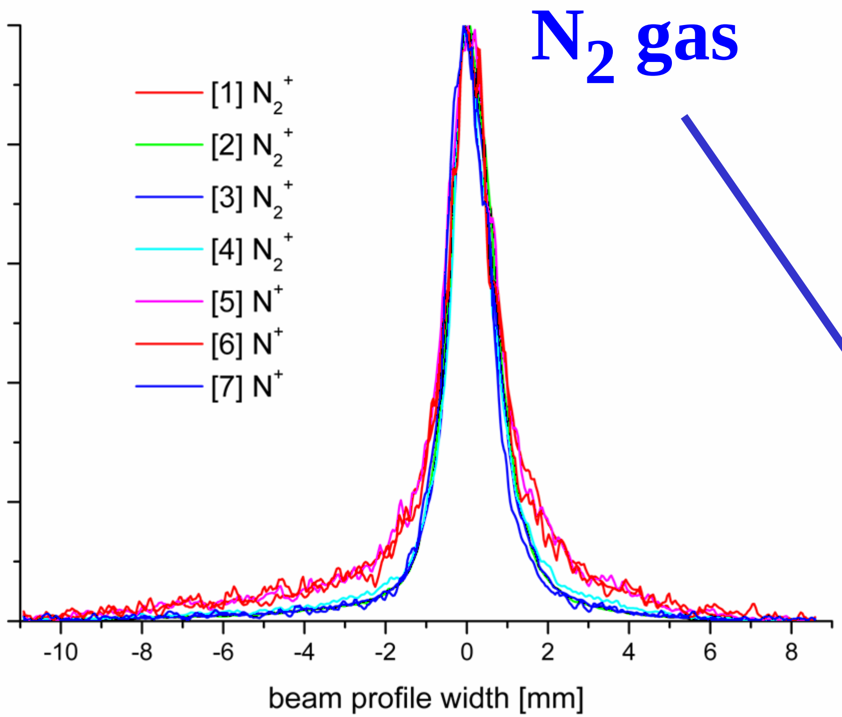
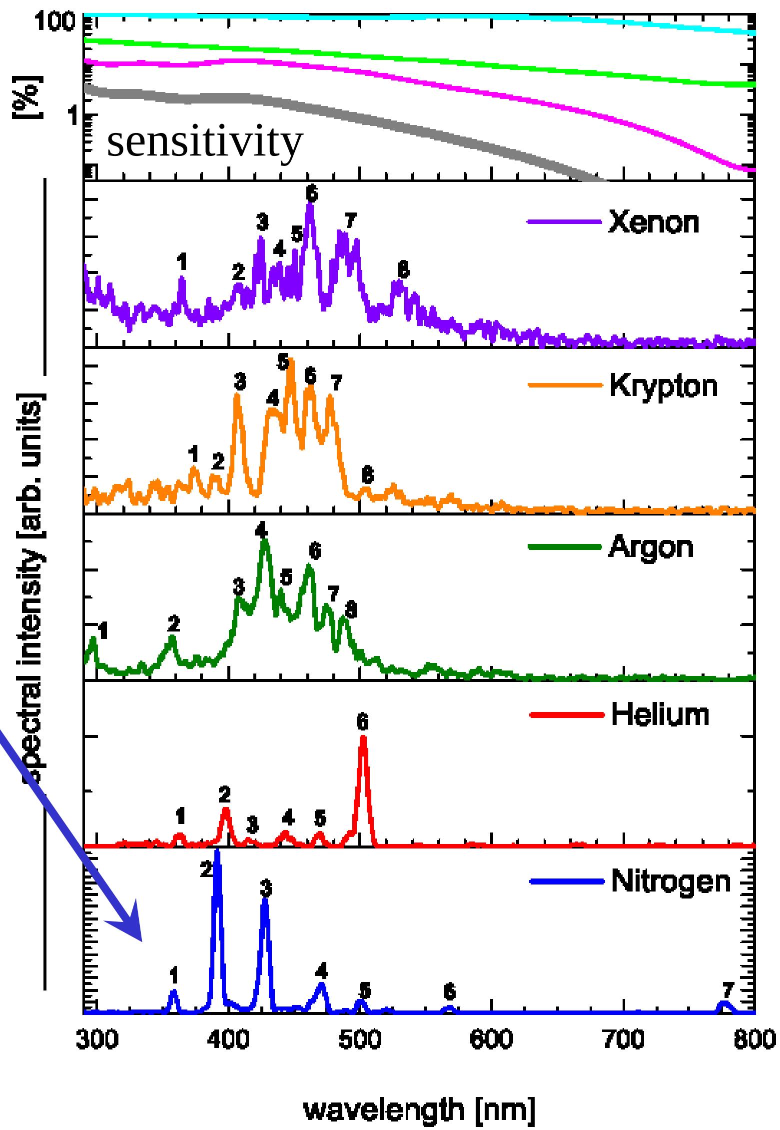
Spectroscopic Investigations for BIF of N_2: Profile Reading

⇒ Expected transitions in near-UV to blue
(as for slower and faster collisions with protons)
⇒ Same profile reading for all lines





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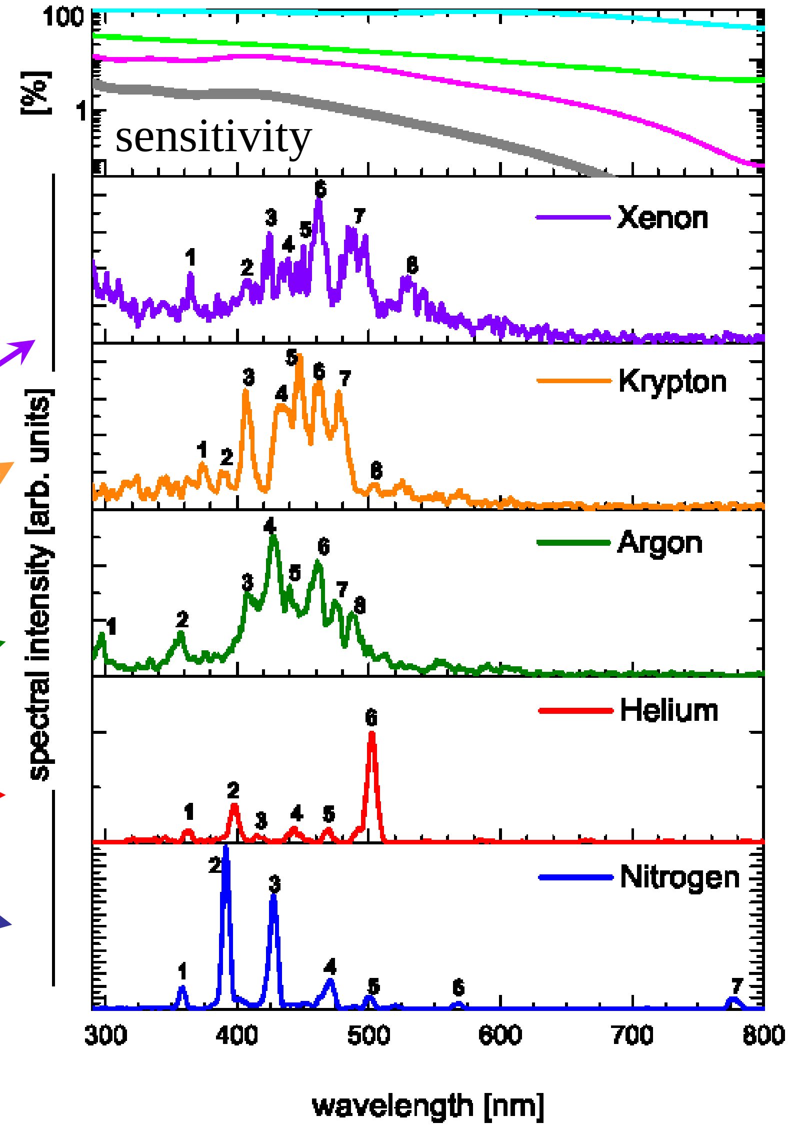
(as for slower and faster collisions with protons)
⇒ Same profile reading for all lines
⇒ Light yield of N_2 is factor 4 higher as rare gases
⇒ ***N_2 is well suited !***

Normalized light yield for all λ:

gas	I:p N2	I: p_{real}	I: p_{real} /Z
Xe	41 %	86 %	22 %
Kr	45 %	63 %	25 %
Ar	50 %	38 %	30 %
He	21 %	4 %	26 %
N_2	100%	100 %	100 %

$p_{real}/Z \propto n_e \propto dE/dx$ stopping power



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Spectroscopic Investigations for BIF of N_2 and He

⇒ Expected transitions in near-UV to blue
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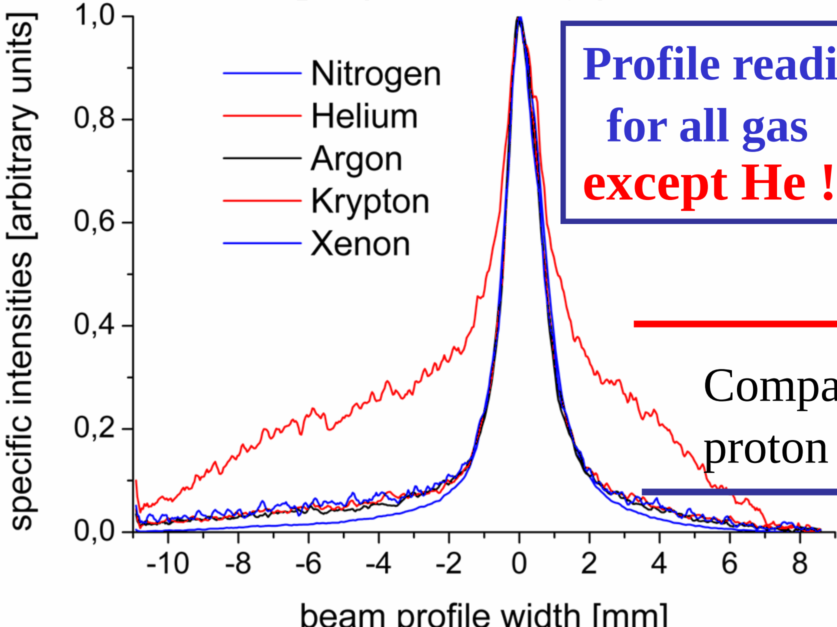
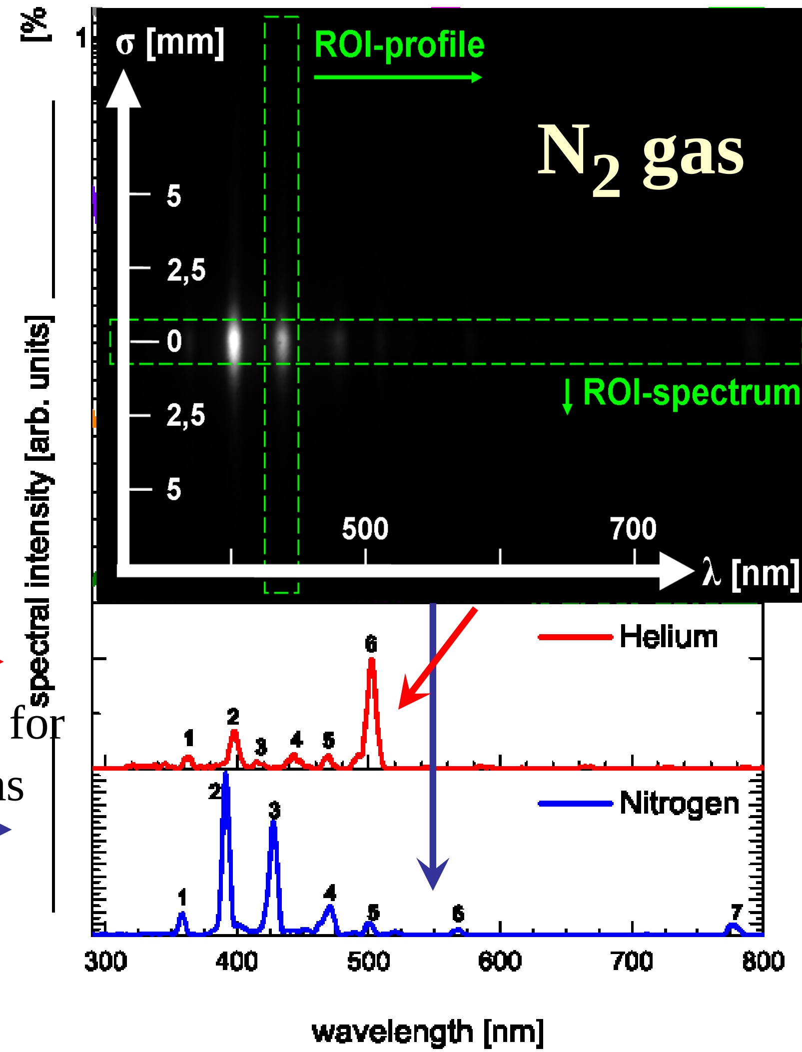


Profile reading equal for all gas
except He !!!

Comparable results for proton and Ta beams



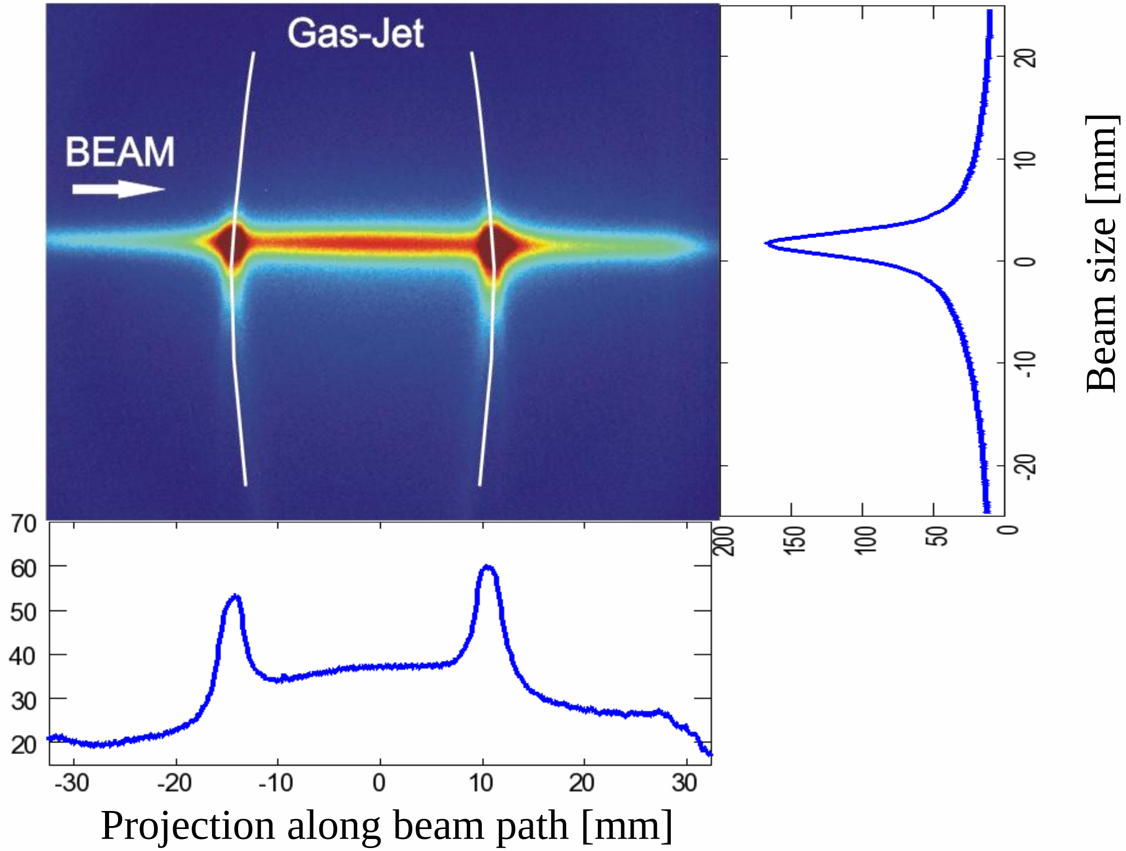
Beam parameter: S^{6+} at 5.16 MeV/u with $3\cdot10^{11}$ pps,
2000 macro-pulses, $p_{N2} = 10^{-3}$ mbar

Usage as a Diagnostics of a Gas Target

The properties of a gas target including beam overlap can be monitored:

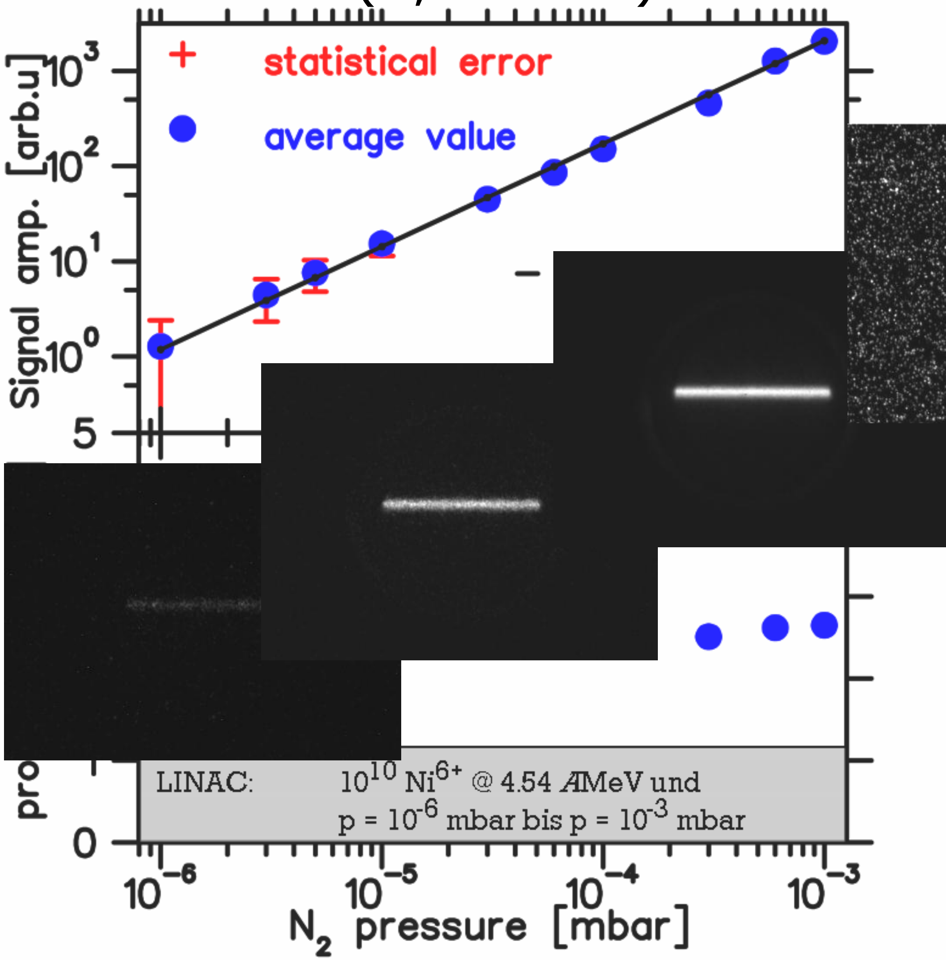
The light yield is proportional to beam current x gas density

Example: UNILAC Gas stripper at 1.4 MeV/u

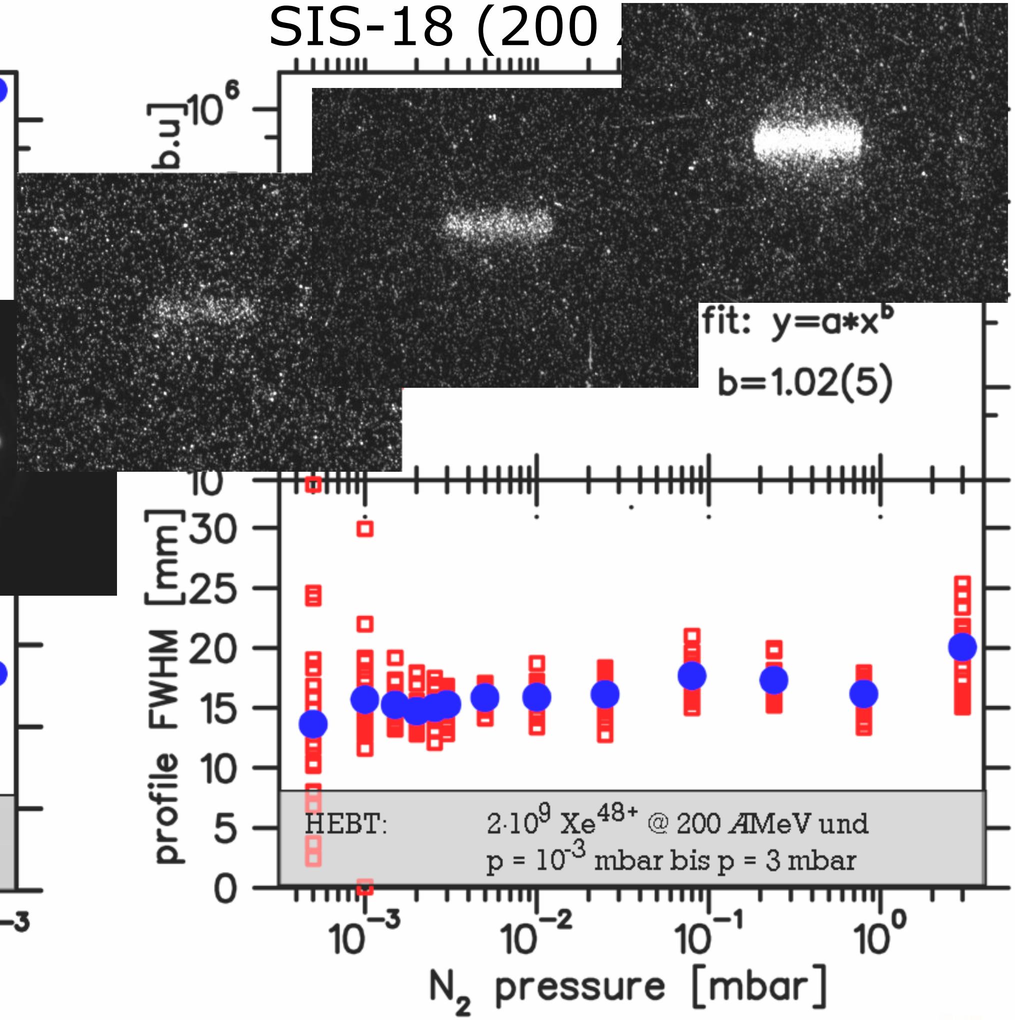


Pressure-Variation by 6 OM

UNILAC (4,5 *A*MeV)



SIS-18 (200



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