Experiences with Luminescence Monitors at GSI

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Outline of the talk:

- Technical realization for single photon detection generated by residual gas
- Energy scaling of signal strength and background, 1.4MeV/u< E_{kin}< 750MeV/u
- Spectroscopic investigations for **rare gases** and ***N_2***
- Profiles & spectroscopy for pressure range 10^{-3} mbar < p < 30 mbar
- Conclusion

Application: Transfer lines and target diagnostics

Beam-based tests at: GSI UNILAC: 1.4 MeV/u < E_{kin} < 11.4 MeV/u
GSI behind SIS: 60 MeV/u < E_{kin} < 750 MeV/u
Tech. University München TANDEM with S: 3 MeV/u

Expected Signal Strength for BIF-Monitor

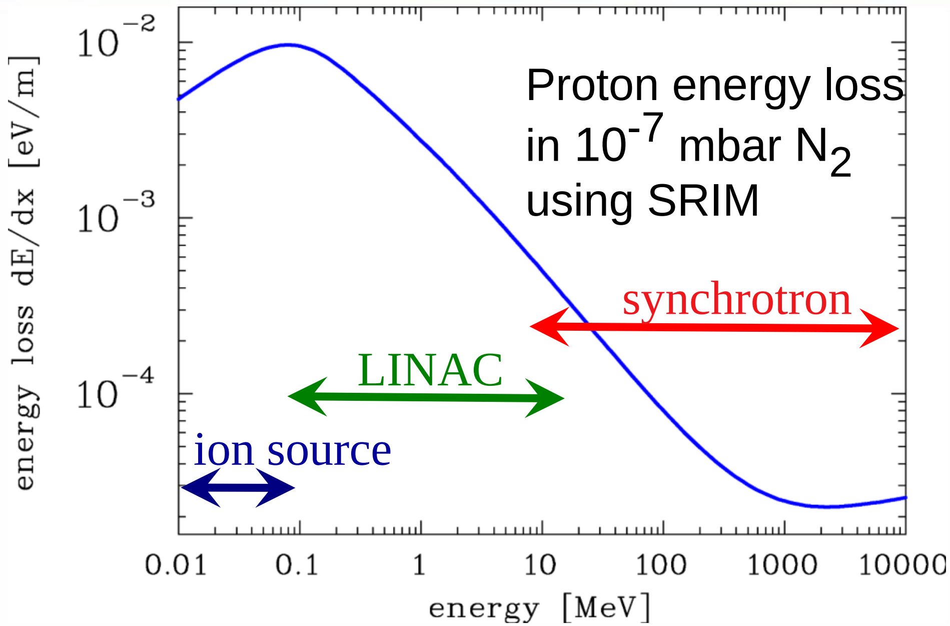
***Physics*:**

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

⇒ Profile determination from residual gas

➢ **Ionization:** ≈ 100 eV/ionization

➢ **Excitation + optical photon emission:**
≈ 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 Z_p^2

Beam Induced Fluorescence Monitor: Principle

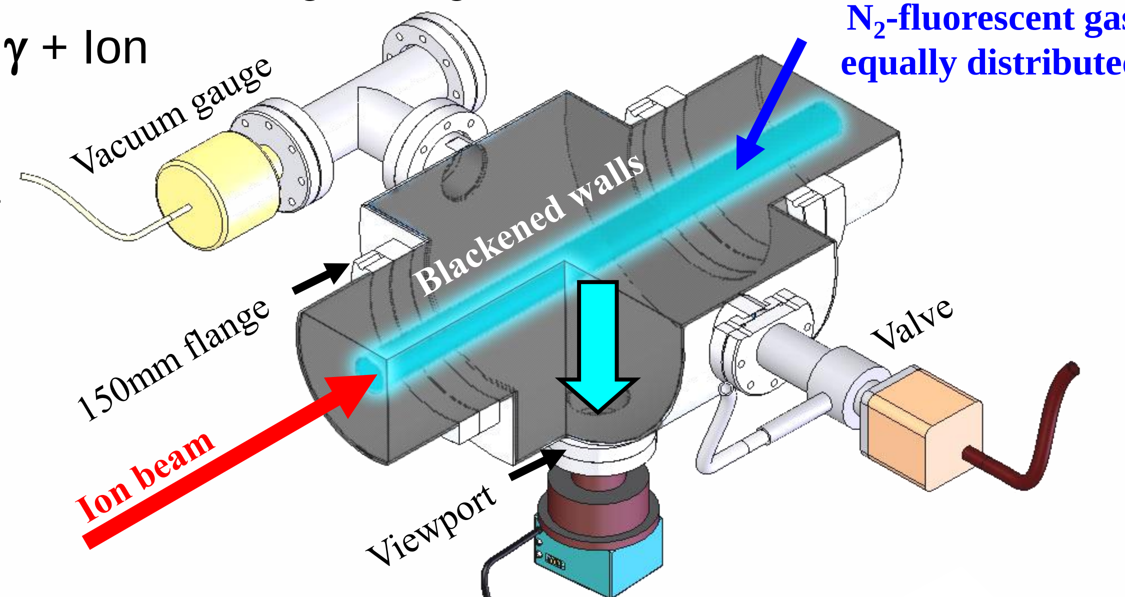
Detecting ***photons*** from residual gas molecules, e.g. Nitrogen

$\boldsymbol{N_2}$ + Ion $\rightarrow$ $\boldsymbol{(N_2^{+})^{*}}$ + Ion $\rightarrow$ $\boldsymbol{N_2^{+}}$ + γ + Ion

390 nm< λ< 470 nm

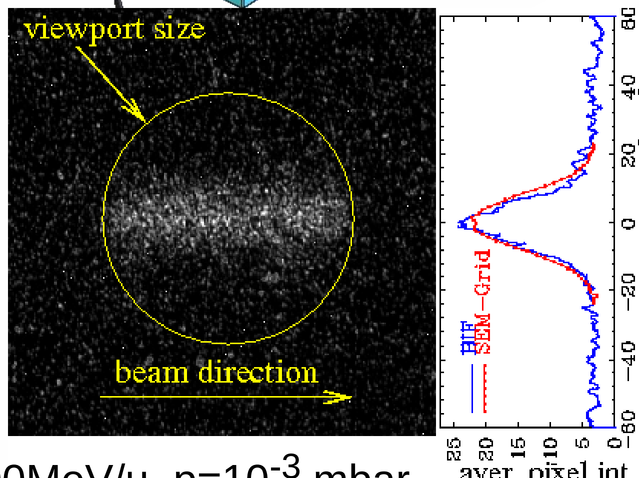
emitted into solid angle Ω to camera

single photon detection scheme



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

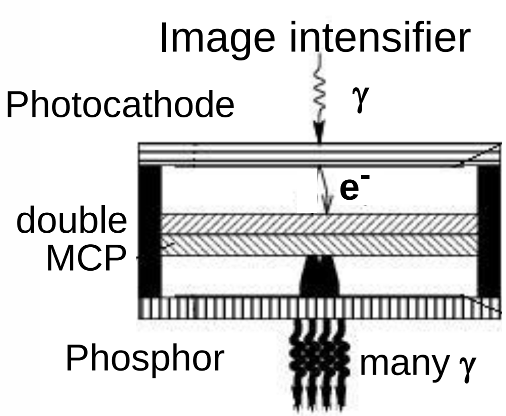


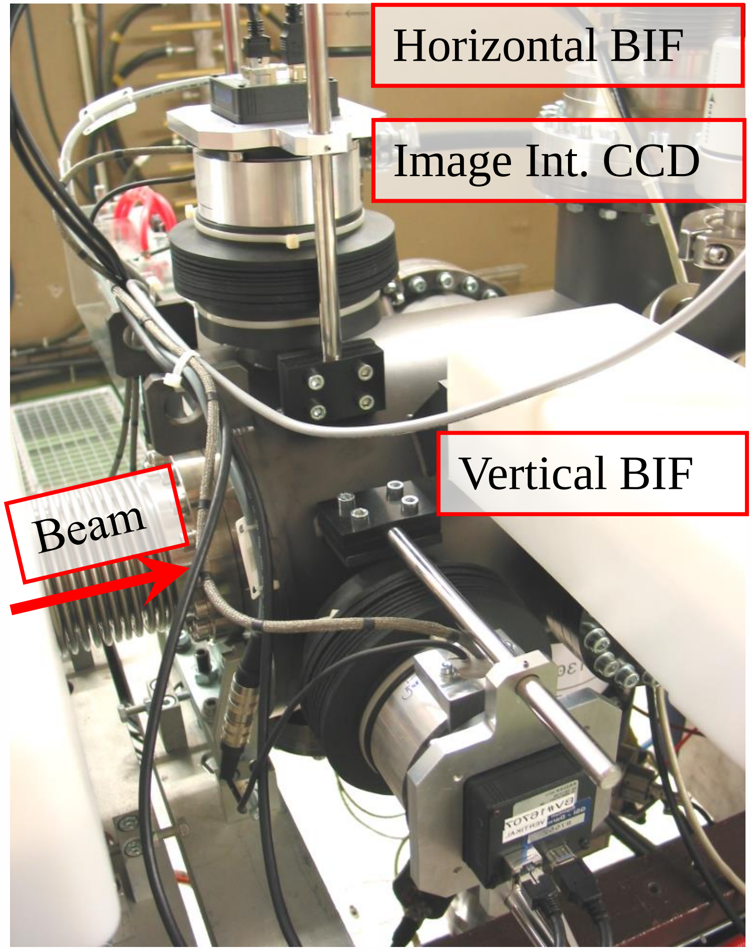
Beam: 4×10^{10} $\boldsymbol{Xe^{48+}}$ at 200MeV/u, p=10^{-3} mbar

BIF-Monitor: Technical Realization at GSI LINAC

BIF stations at GSI-LINAC (4 realized, 2 in preparation):

- 2 x image intensified CCD cameras
- double MCP (‘Chevron geometry’)
- Optics with reproduction scale 0.2 mm/pixel
- Gas inlet + vacuum gauge
- Pneumatic actuator for calibration
- Insertion length 25 cm for both directions only
- **Advantage**: single macro-pulse observation





F. Becker (GSI) et al., Proc. DIPAC’07, C. Andre (GSI) et al., Proc. DIPAC’11

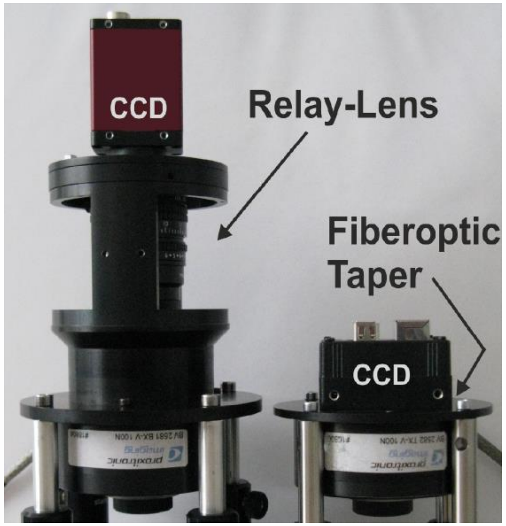
BIF-Monitor: Technical Realization

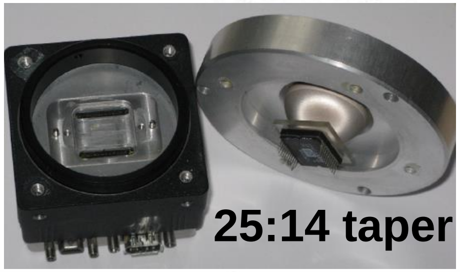
BIF station for single photon detection at GSI-LINAC:

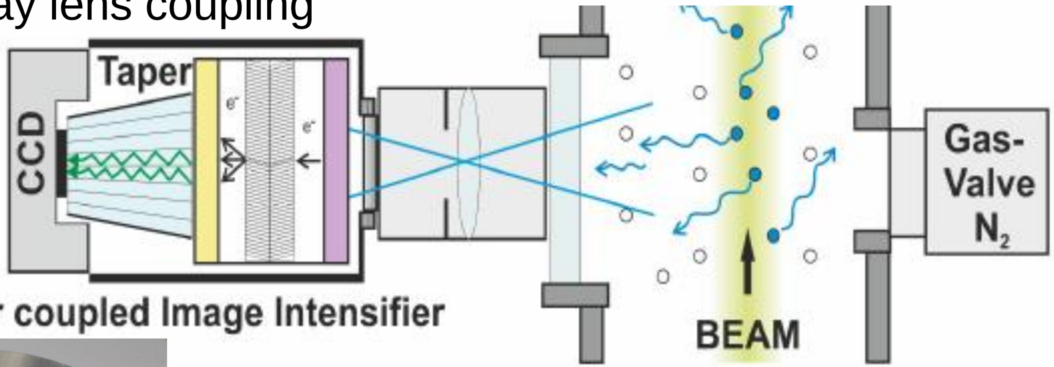
→ Comparison taper coupling versus relay lens coupling

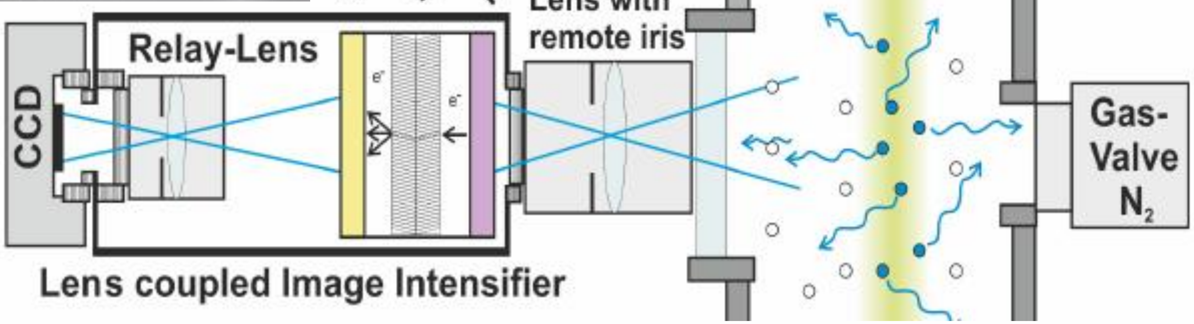
Advantage of taper coupling:

- ➢ higher light transmission
- ➢ no vignetting









Advantage of relay coupling:

- ➢ CCD camera is changeable
- ➢ lower light transmission acceptable due to high MCP gain

⇒ **final choice !**

C. Andre (GSI) et al., Proc. DIPAC'11

Examples from Ion LINAC at GSI

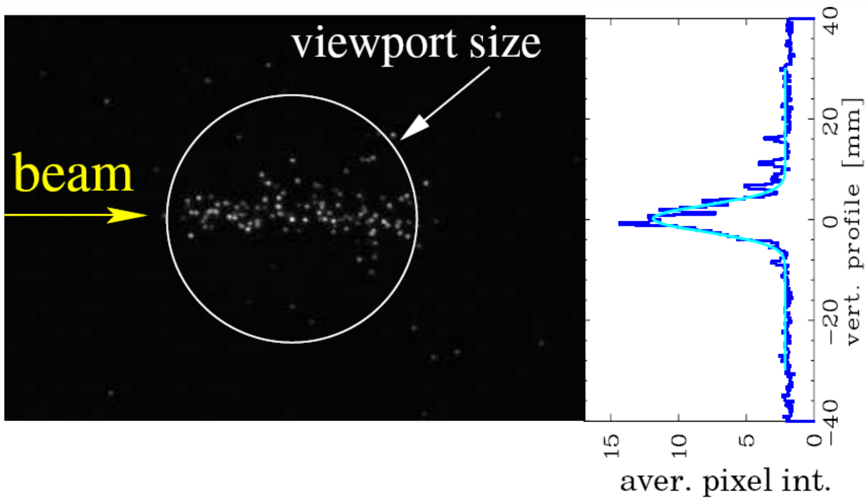
Single pulse observation

4.7 MeV/u Ar^{10+} beam

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

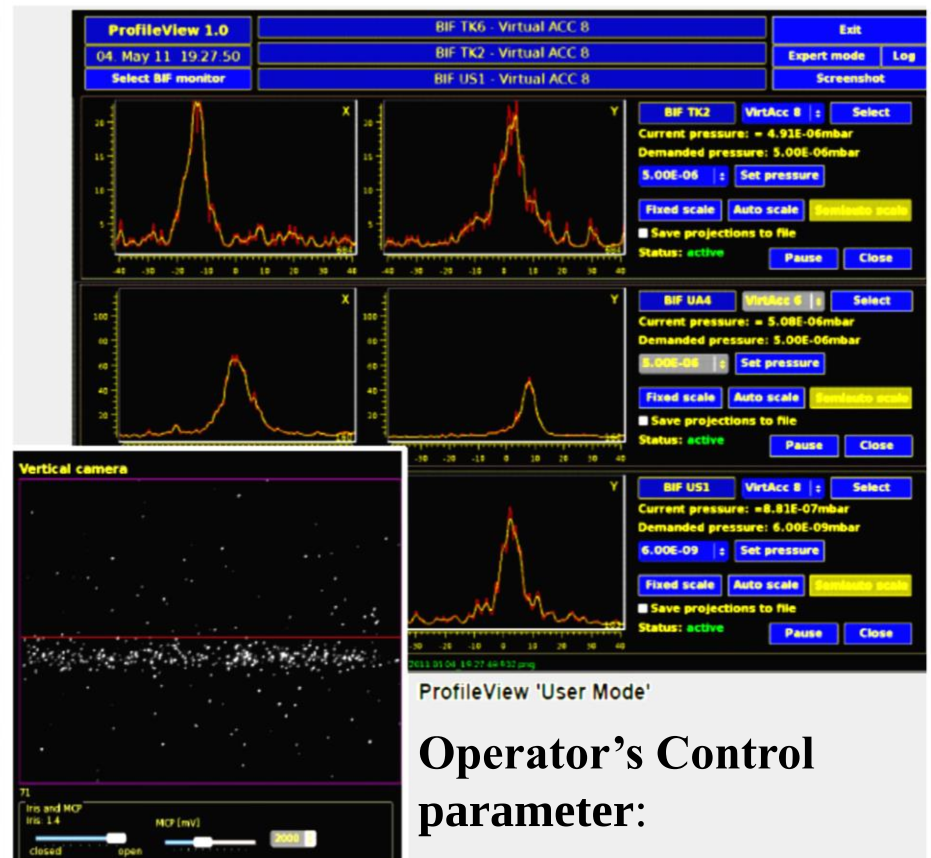
One single macro pulse of 200 μs

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



Operating software at UNILAC

Partly used by operators



Operator's Control parameter:
Vacuum pressure only

Examples from Ion LINAC at GSI

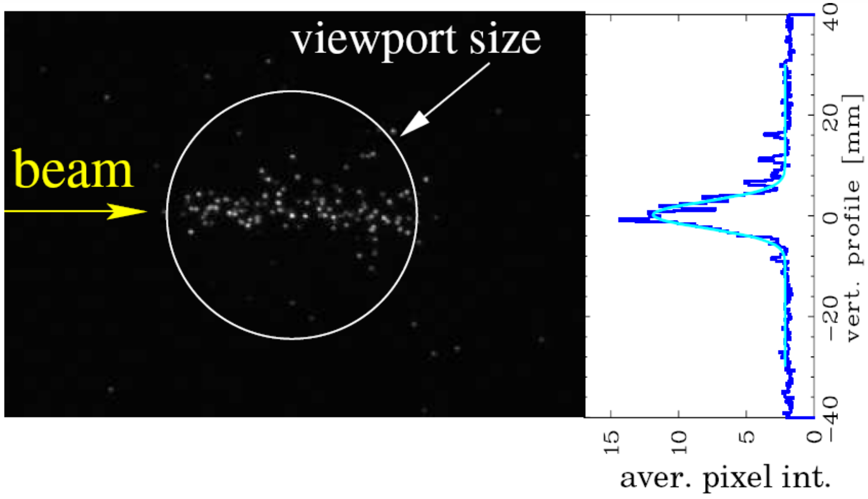
Single pulse observation

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)

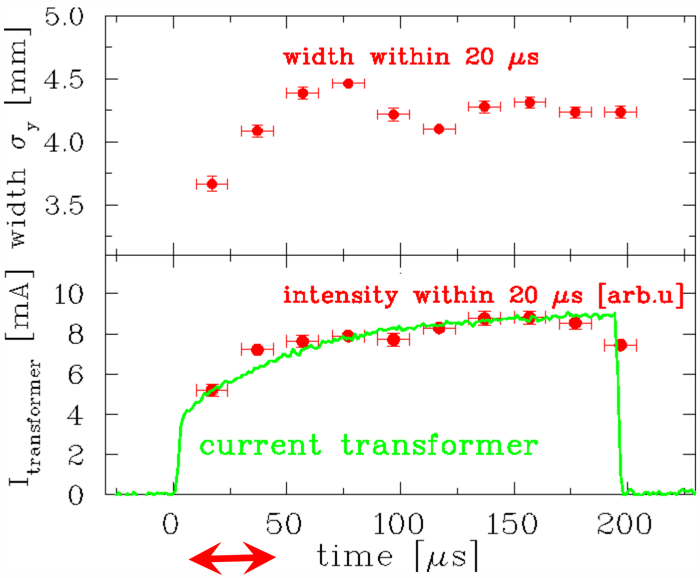


Time resolved observation

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

Time range for SEM-Grid

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

Energy Scaling behind SIS18 at GSI

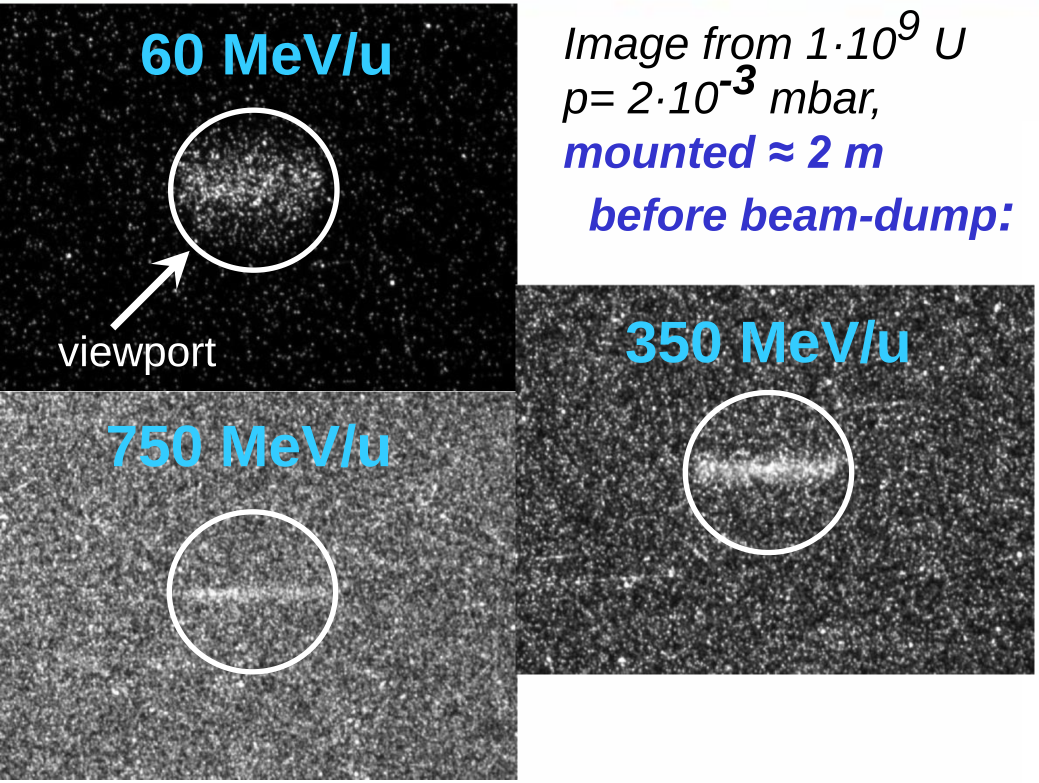
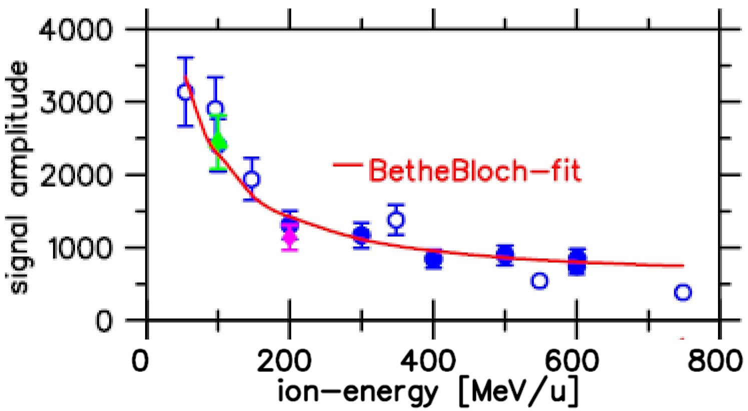


Image from $1\cdot10^{9}$ U
p= $2\cdot10^{-3}$ mbar,
mounted ≈ 2 m
before beam-dump:

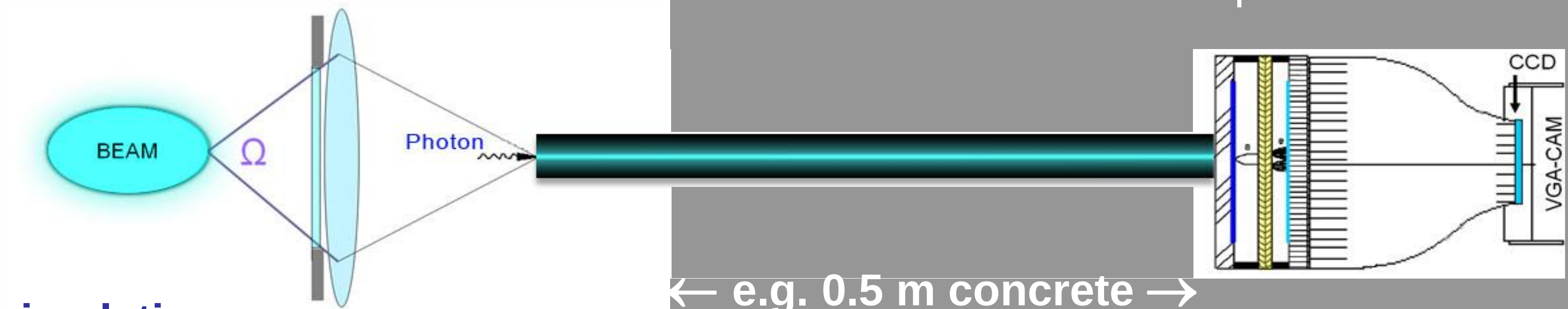
E_{kin} dependence for signal
*& background **close** to beam-dump:*



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

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 %

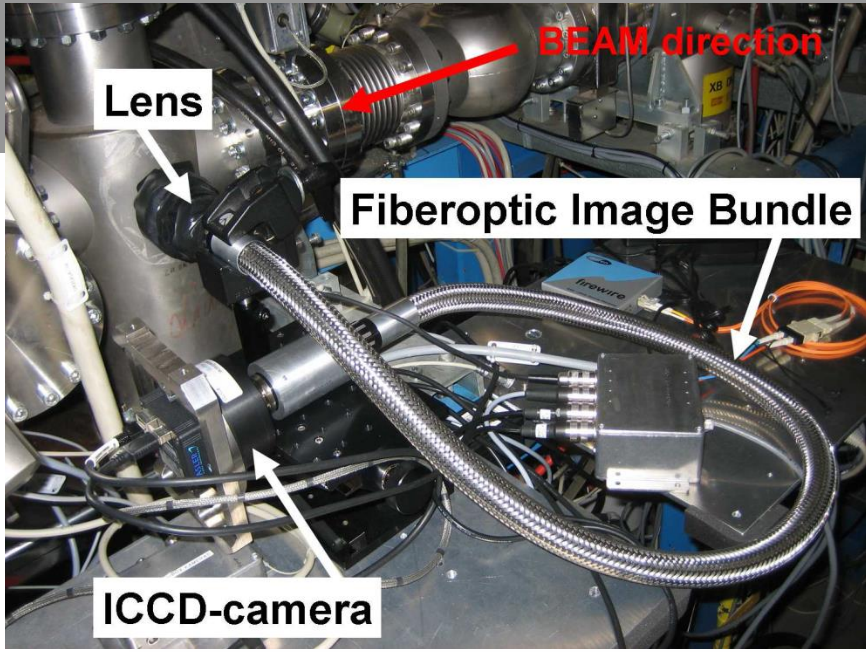
Fiber-optic bundle with ≈1 million fibers:

- 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

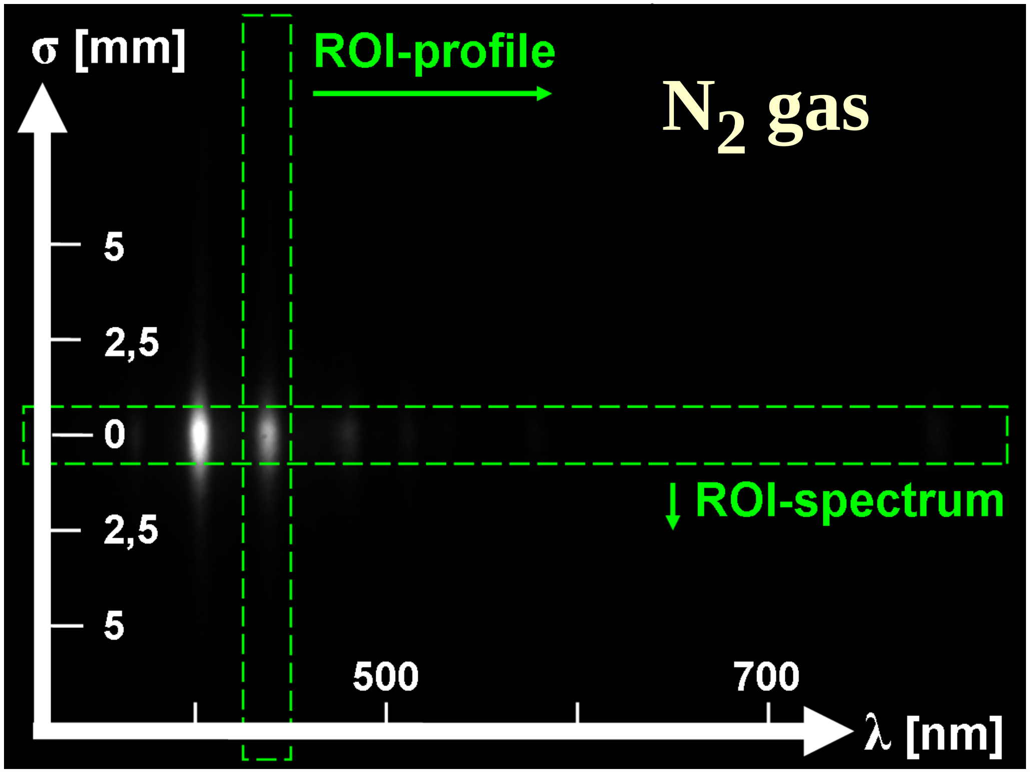
  un-shielded: ≈30 % increase of background

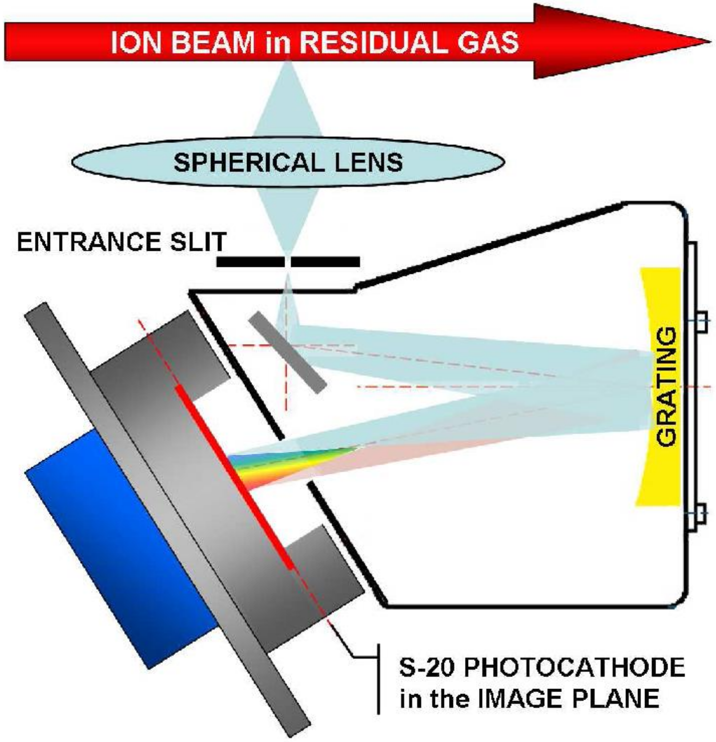


Spectroscopic Investigations for N_2 and Rare Gases

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

Imaging Spectrograph installed behind UNILAC: Wavelength selective beam profile





Beam parameter for detailed exp. at GSI (different gases, constant pressure):
S^{6+} at 5.16 MeV/u with $3\cdot10^{11}$ pps, 2000 macro-pulses, $p_{N2}=10^{-3}$ mbar

Results of detailed investigations:

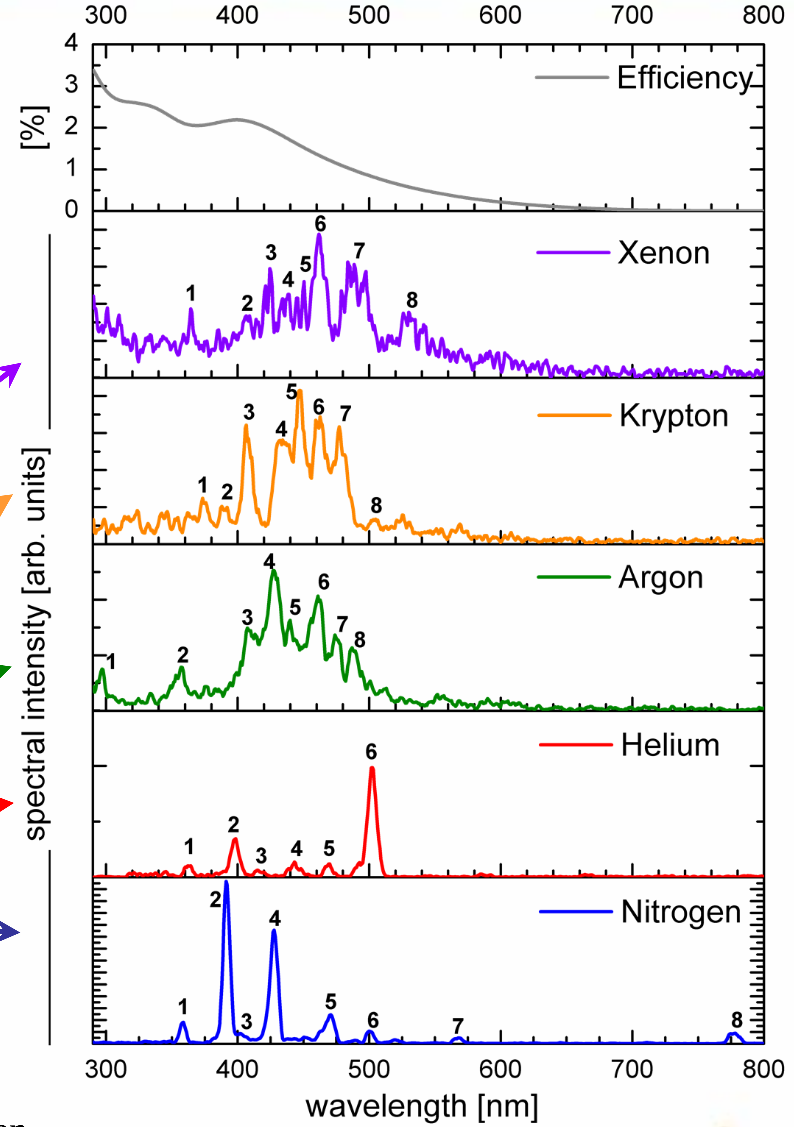
- Rare gases and N_2: green to near-UV
- Compact wavelength interval for N_2
- Fluorescence yield: $N_2 \approx$ 4x higher as rare gases

⇒ 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 %

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



***n_e*: gas electron density ∝ energy loss ⇔ beam influence**

F. Becker (GSI) et al., Proc. DIPAC'09, Collaboration with TU-München

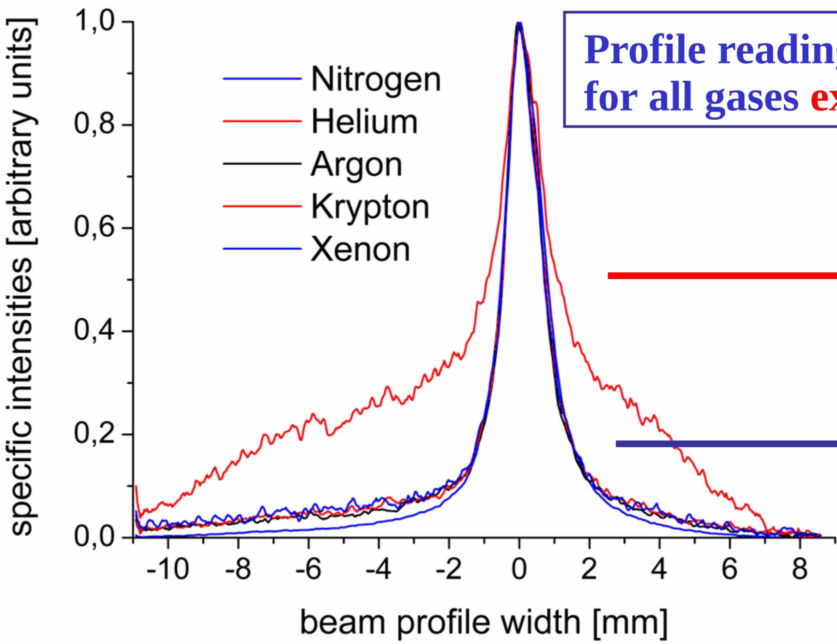
BIF-Monitor: Spectroscopy – Profile Reading

Results of detailed investigations:

- Rare gases and N_2: green to near-UV
- Compact wavelength interval for N_2
- Fluorescence yield: $N_2 \approx 4$x higher as rare gases
- Same profile reading for all gas except He

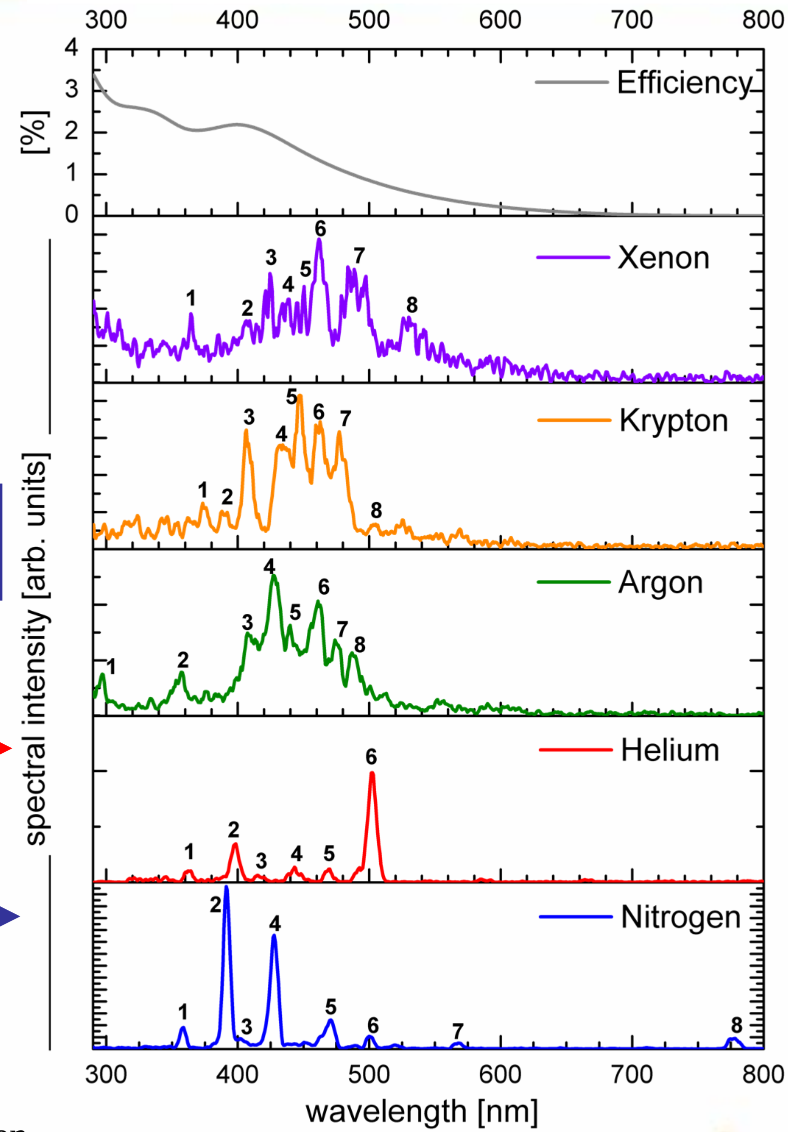
⇒ N_2 and Xe are well suited !

Normalized profile reading for all λ:



Profile reading equal for all gases except He

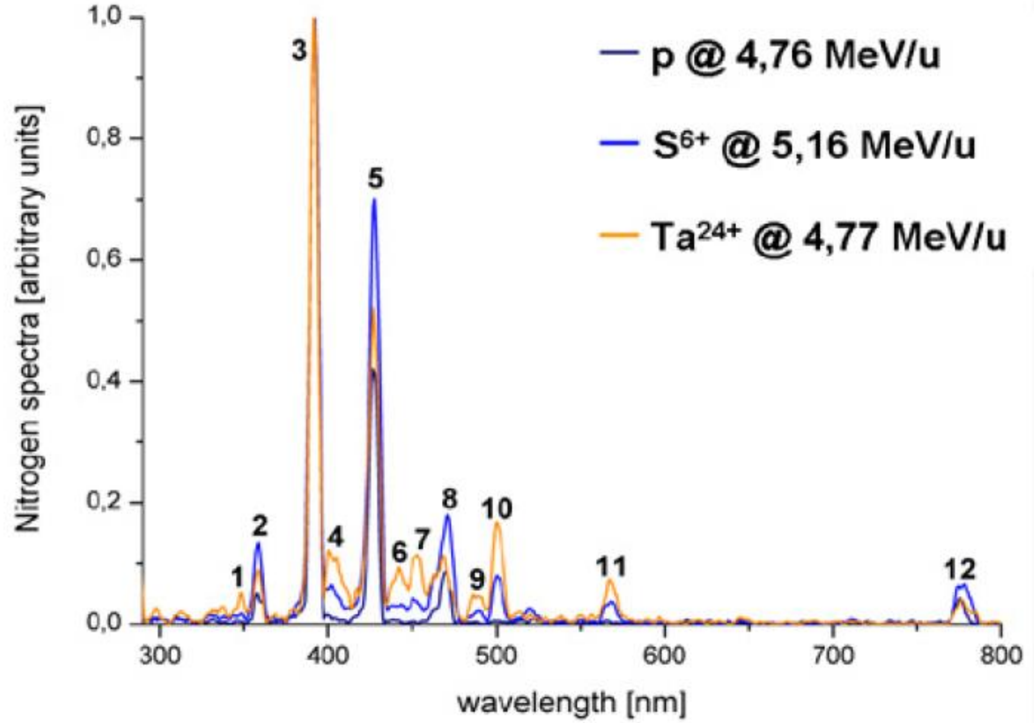
Beam: S^{6+} at 5.16 MeV/u, $p_{N2} = 10^{-3}$ mbar



F. Becker (GSI) et al., Proc. DIPAC'09, Collaboration with TU-München

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

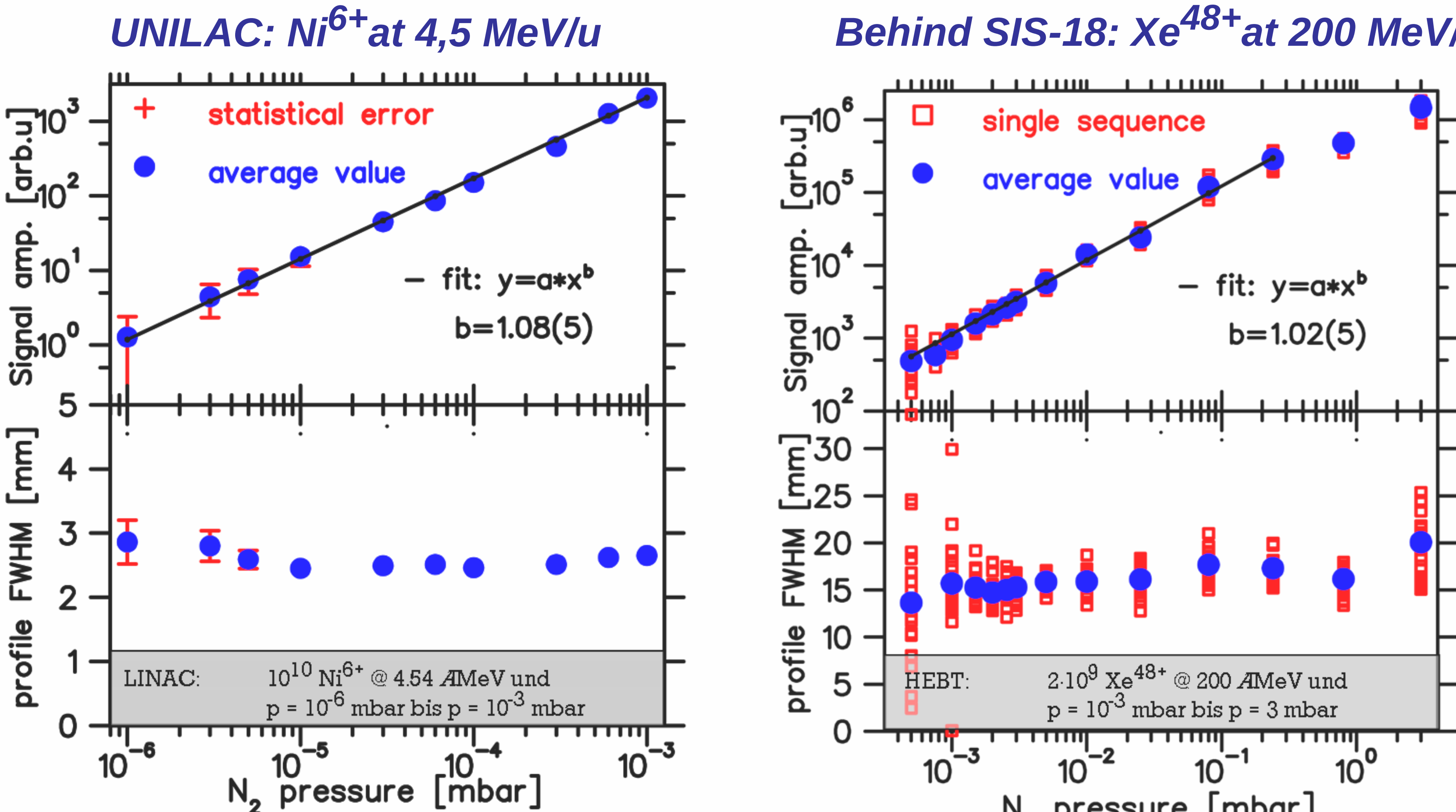
$\Rightarrow$ Stable operation possible for $\boldsymbol{N_2}$

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),

Variation of N_2 Pressure over 6 Orders of Magnitude



Results: signal amplitude ∝ p and σ = constant

⇒ gas pressure up to 1 mbar is a free parameter

Spectroscopy – Variation of Gas Pressure

Task: To which pressure the methods delivers a correct profile reproduction?

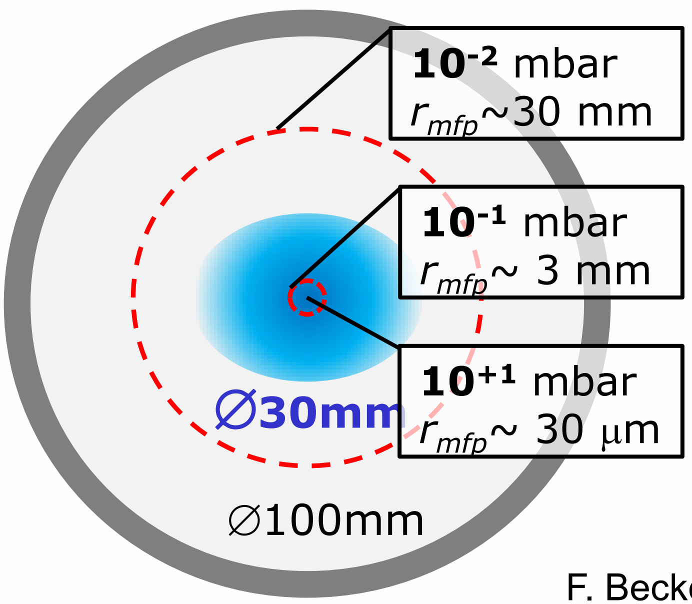
Investigated: 10^{-3} mbar < p < 100 mbar

Secondary electron might excite residual gas:

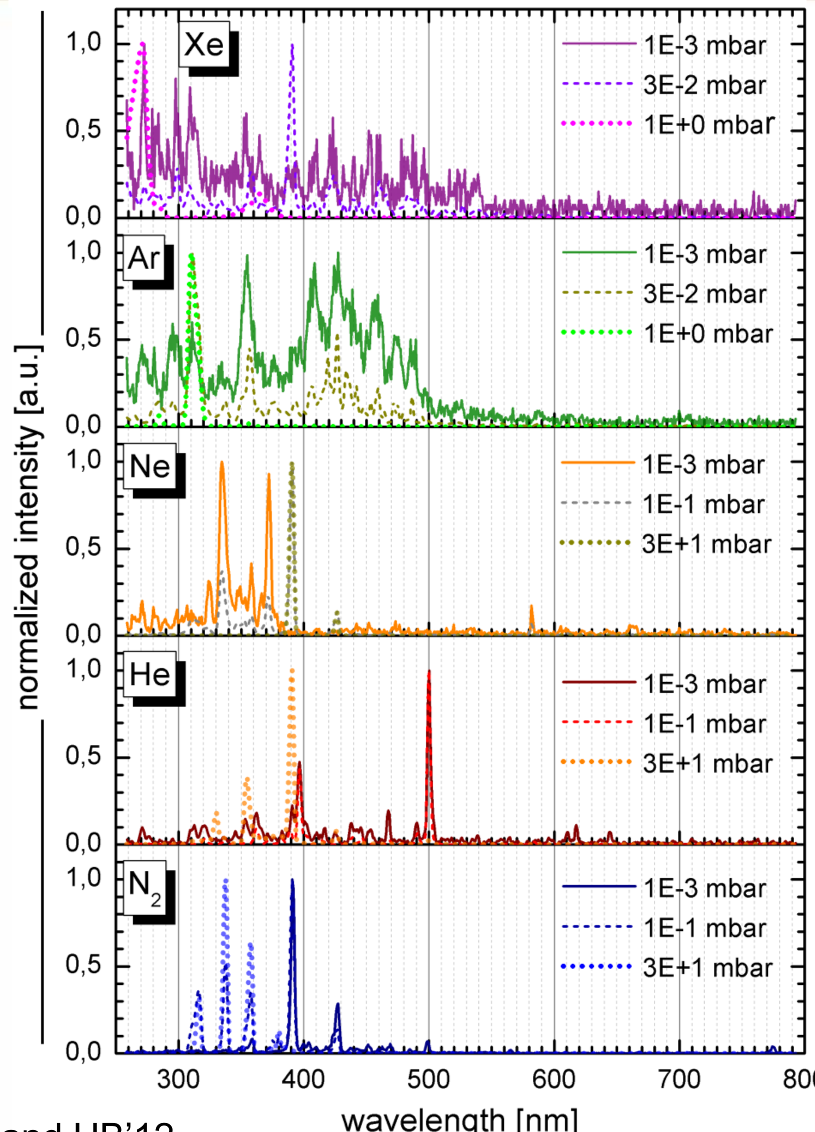
⇒ mean free path at 10^{-3} mbar: $r_{mfp} >> r_{beam}$

⇒ mean free path at 10 mbar: $r_{mfp} << r_{beam}$

Observation: pressure dependent spectrum



Beam: S at 3 MeV/u at TU-München TANDEM

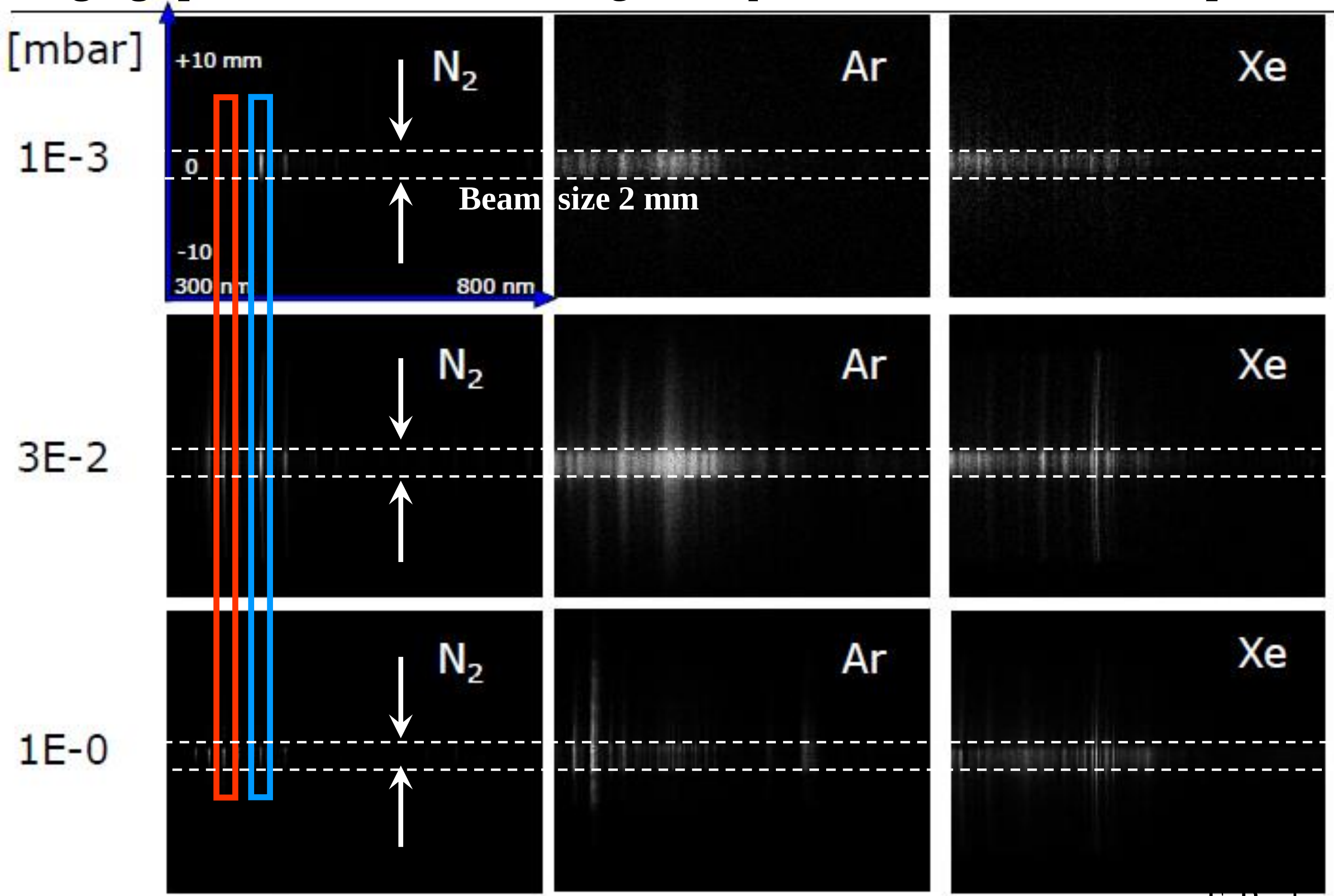


F. Becker et al., IPAC'12 and HB'12

Image Spectroscopy – Different Gas Pressures and Profile Width

Detailed investigations of BIF for various gases from 10^{-3} mbar to 100 mbar

Imaging spectrometer ⇒ wavelength and profile information: status ***preliminary*** data analysis



Beam:

S @ 3 MeV/u

at TANDEM

TU-München

Data analysis preliminary!

F. Becker et al., IPAC'12 &HB'12

Image Spectroscopy – Different Gas Pressures and Profile Width

Observation: Trans. of ionic states e.g. N_2^+ → profile width independent on pressure

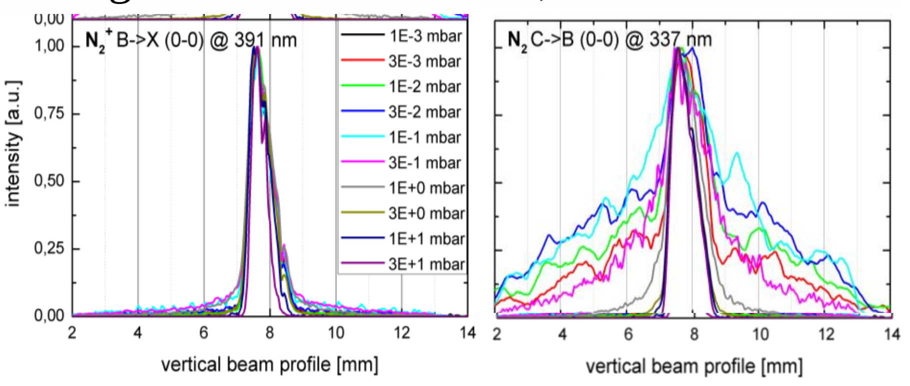
Trans. of neutral states e.g. N_2 → width strongly dependent on pressure!

- **Ionic transitions λ=391 nm:**

N_2 + ion→$(N_2^+)^*$ +e^-+ ion→N_2^++ γ+e^- + ion

N_2^+ @391nm: $B^2\Sigma^+_u(v=0) \rightarrow X^2\Sigma^+_g(v=0)$

large σ for ion-excitation, low for e^-



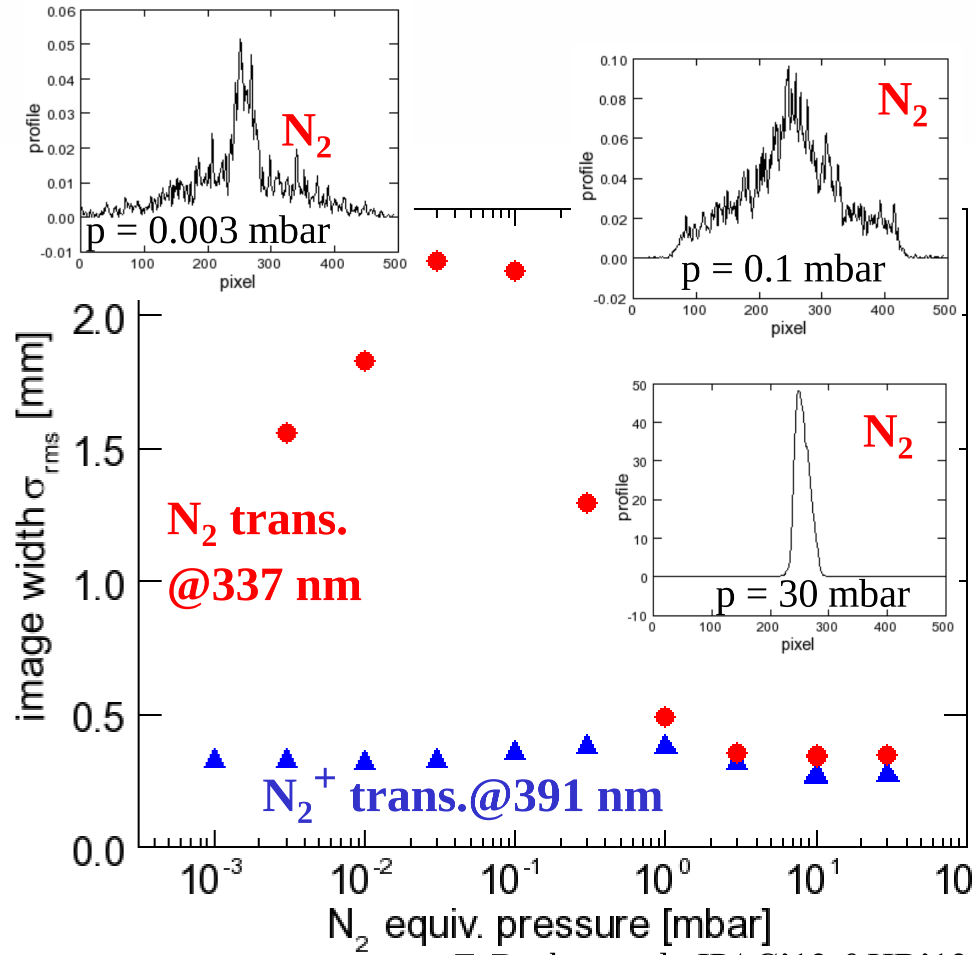
- **Neutral transitions λ=337 nm:**

N_2 + e^- → $(N_2)^*$ + e^- → N_2 + γ + e^-

N_2 @337nm: $C^3\Pi_u(v=0) \rightarrow B^3\Pi_g(v=0)$

large σ of e^- excitation., low for ions

at p ≈ 0.1 mbar→ free mean path ≈1 cm!



F. Becker et al., IPAC'12 &HB'12

Image Spectroscopy – Different Gas Pressures and <u>total</u> Profile Width

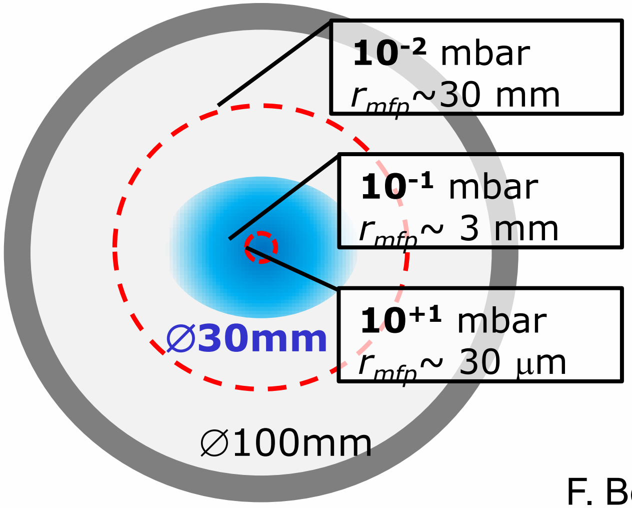
Beam: S at 3 MeV/u at TU-München TANDEM

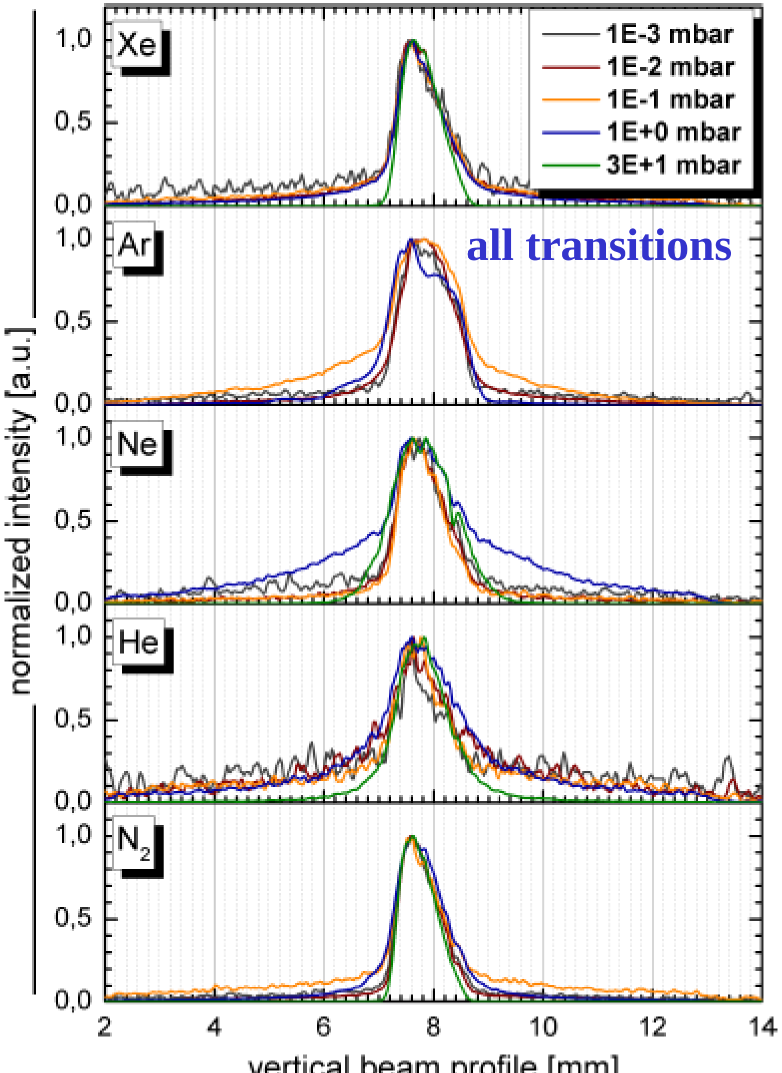
Entire spectral range → effect is smaller but significant disturbance for He and Ne

Task: To which pressure the methods delivers a correct profile reproduction?

Results:

- **avoid** 10^{-2} mbar < p < 10 mbar ⇔ **chose either** $r_{mfp} >> r_{beam}$ **or** $r_{mfp} << r_{beam}$
- ***use transition of the charged specious***

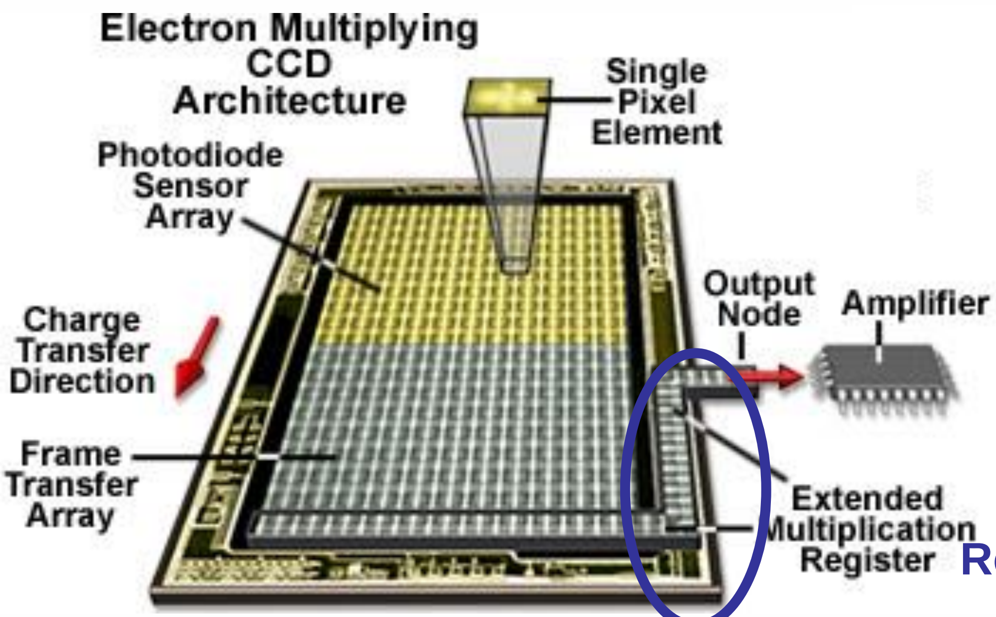




F. Becker et al., IPAC'12 and HB'12

Alternative Single Photon Camera: emCCD

Principle of electron multiplication CCD:



Multiplication by avalanche diodes:

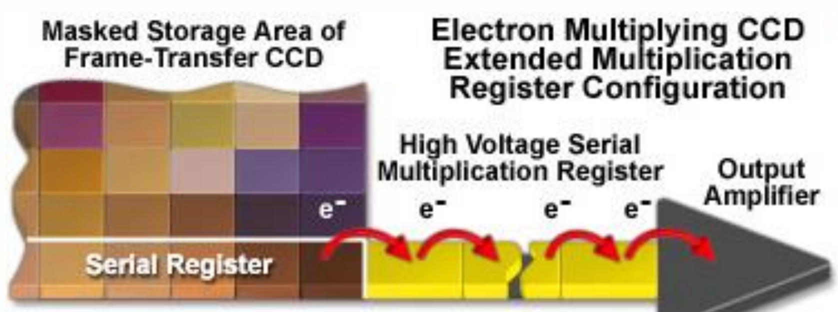
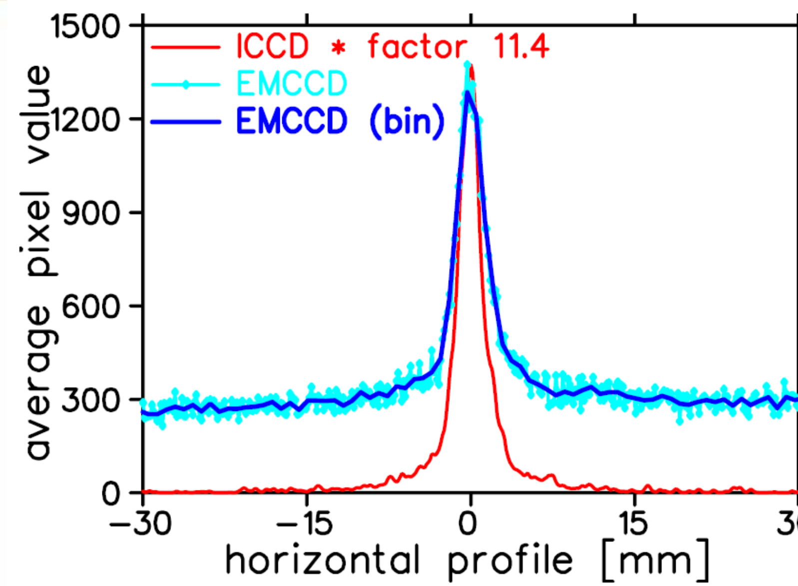


Figure 3



Results: Suited for single photon detection

x5 higher spatial resolution as ICCD

more noise due to electrical amplification

⇒ Acts as an alternative

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

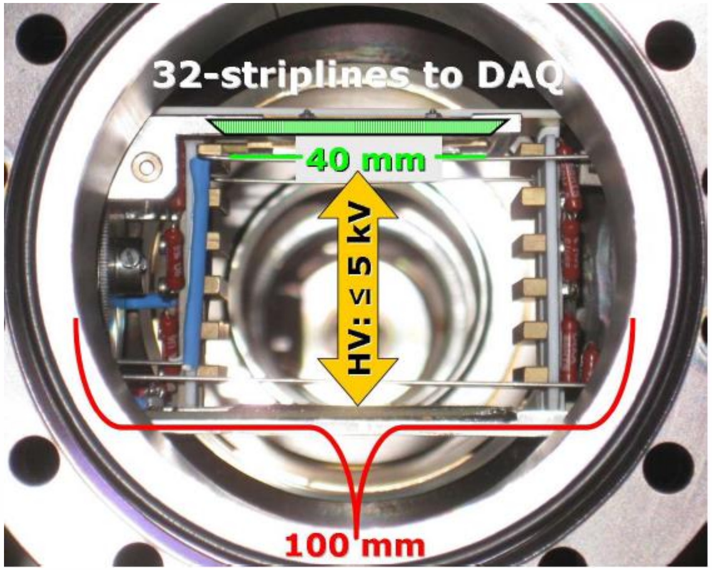
Comparison BIF ↔ IPM at GSI LINAC with 4.7 MeV/u Xe^{21+}

Test with LIPAc design and various beams

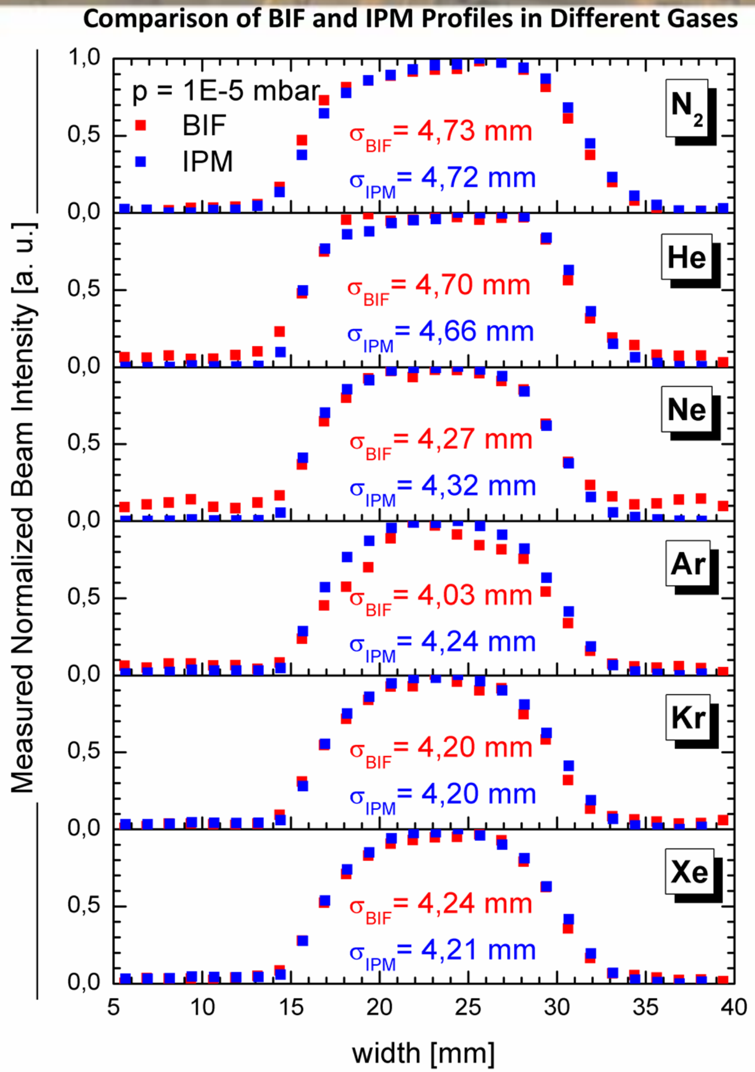
Comparison IPM without MCP and BIF

⇒ ***Advantage IPM:*** 10 x lower threshold as BIF

⇒ ***Disadvantage IPM:*** Complex vacuum installation, image broadening by beam's space charge



Design by CEA for LIPAc



Collaboration with J. Egberts, J. Marroncle, T. Papaevangelou CEA/Saclay

J. Egberts (CEA) et al., DIPAC'11, F. Becker (GSI) et al , DIPAC'11

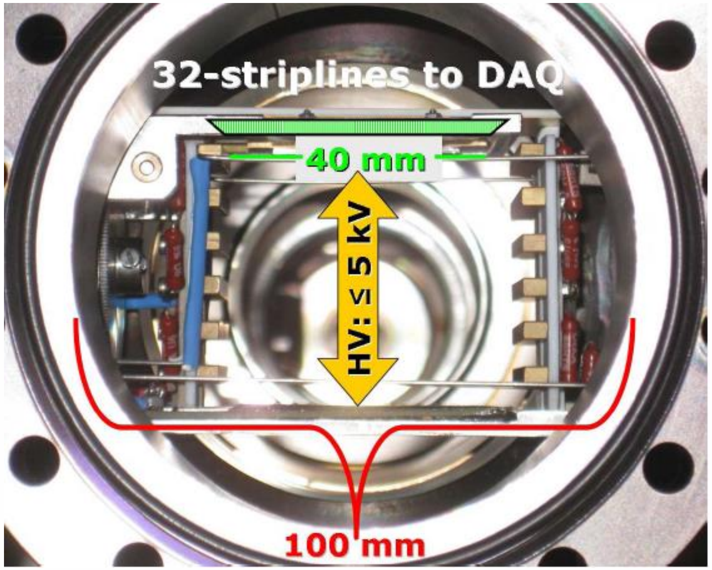
Beam: 1.1 mA Xe^{21+}, 4.7 MeV/u

Comparison BIF ↔ IPM for He Gas

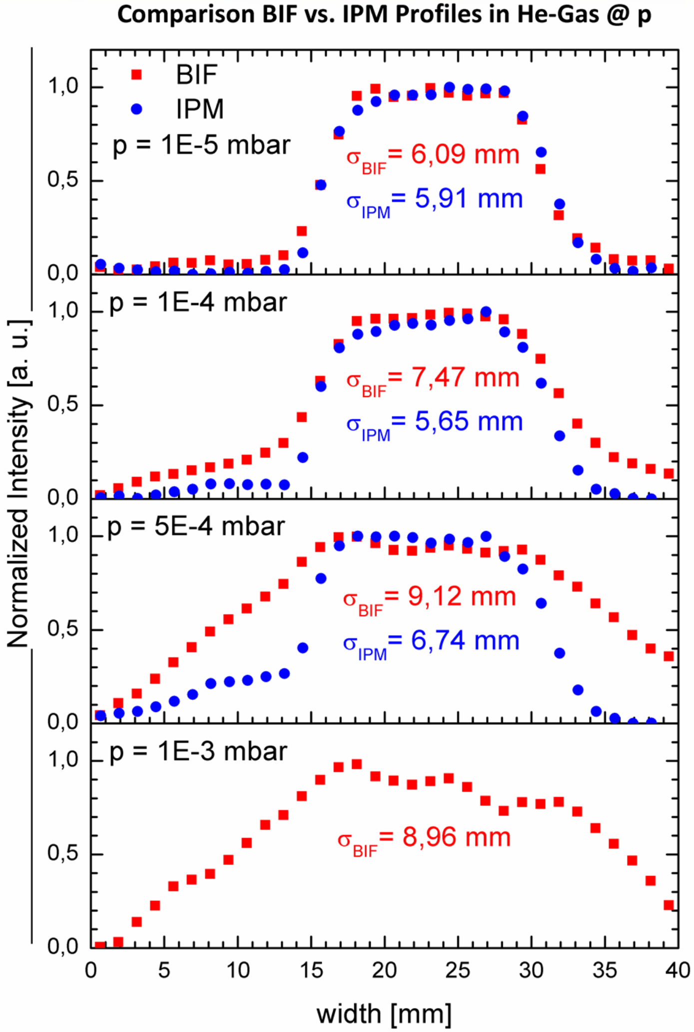
Variation of Helium gas pressure:

- Profile broadening for both detectors
- Large effect for BIF (emission of photons)
- Comparison to SEM-Grid and BIF

⇒ ***Helium is not suited as working gas***



Design by CEA for LIPAc



Beam: 1.1 mA Xe^{21+}, 4.7 MeV/u

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J. Egberts (CEA) et al., DIPAC'11, F. Becker (GSI) et al , DIPAC'11

Summary Beam Induced Fluorescence Monitor

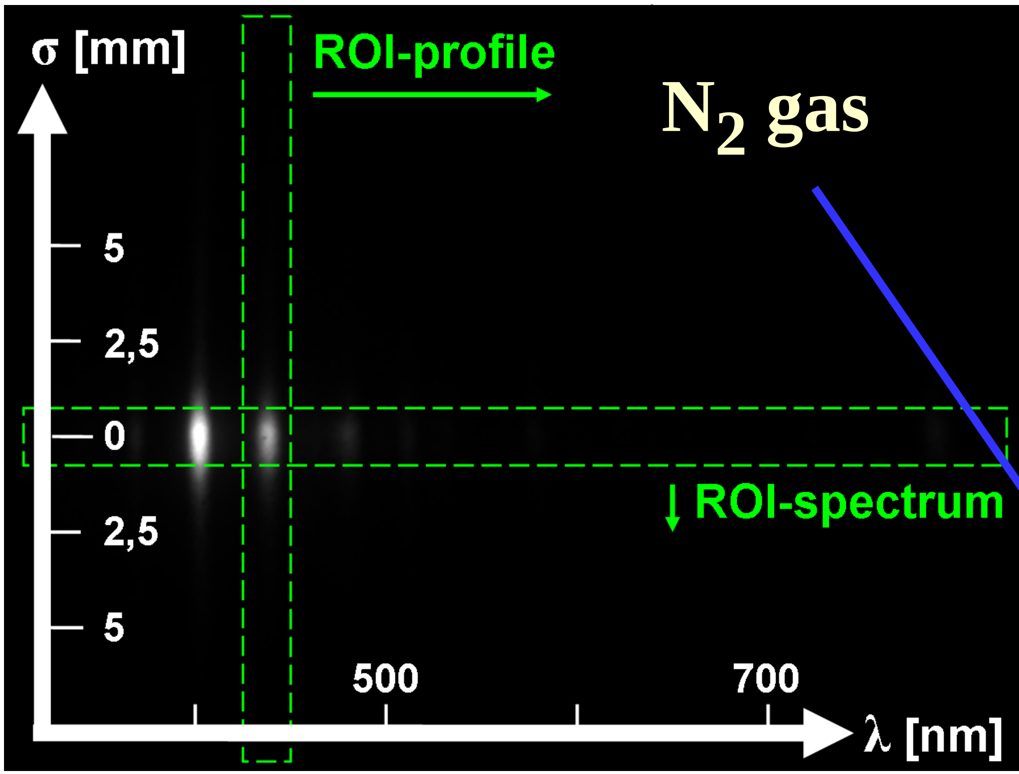
- Non-destructive profile method demonstrated (single photon detection possible)
- Operational usage at UNILAC started, pressure typ. $p < 10^{-5}$ mbar
- Considered for higher beam energies E > 100 MeV/u
- Shielding concept partly demonstrated
- Independence of profile reading for pressures up to 10^{-2} mbar for ***N_2*, *Xe, Kr, Ar***
- Different pressure dependence for several optical transition (preliminary result)
- ***N_2*** is well suited: blue wavelength, high light yield, good vacuum properties
- ***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
- Modern emCCD might be an alternative
- **Future:** Investigation of shielding and radiation hardness of components
- **Future:** Transfer of spectral investigations from 3 MeV/u to E > 100 MeV/u
- **Future:** Investigation as target diagnostics for RIB, neutrons or antiprotons

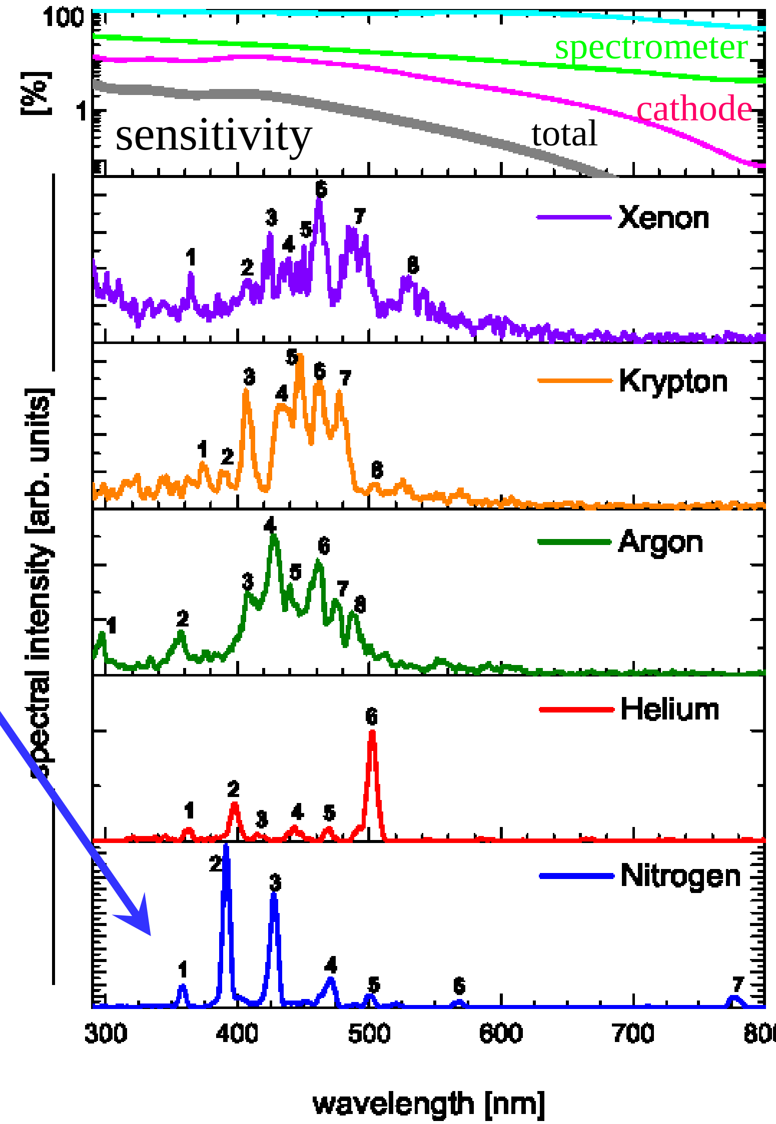
Thank you for your attention!

Spare transparencies

Spectroscopic Investigations for BIF of N_2: Wavelength

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

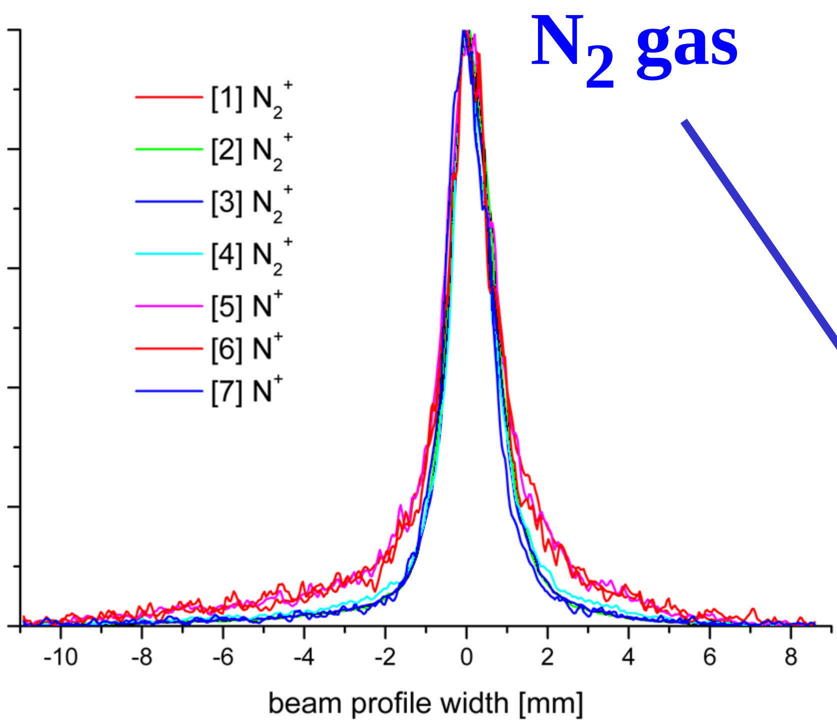


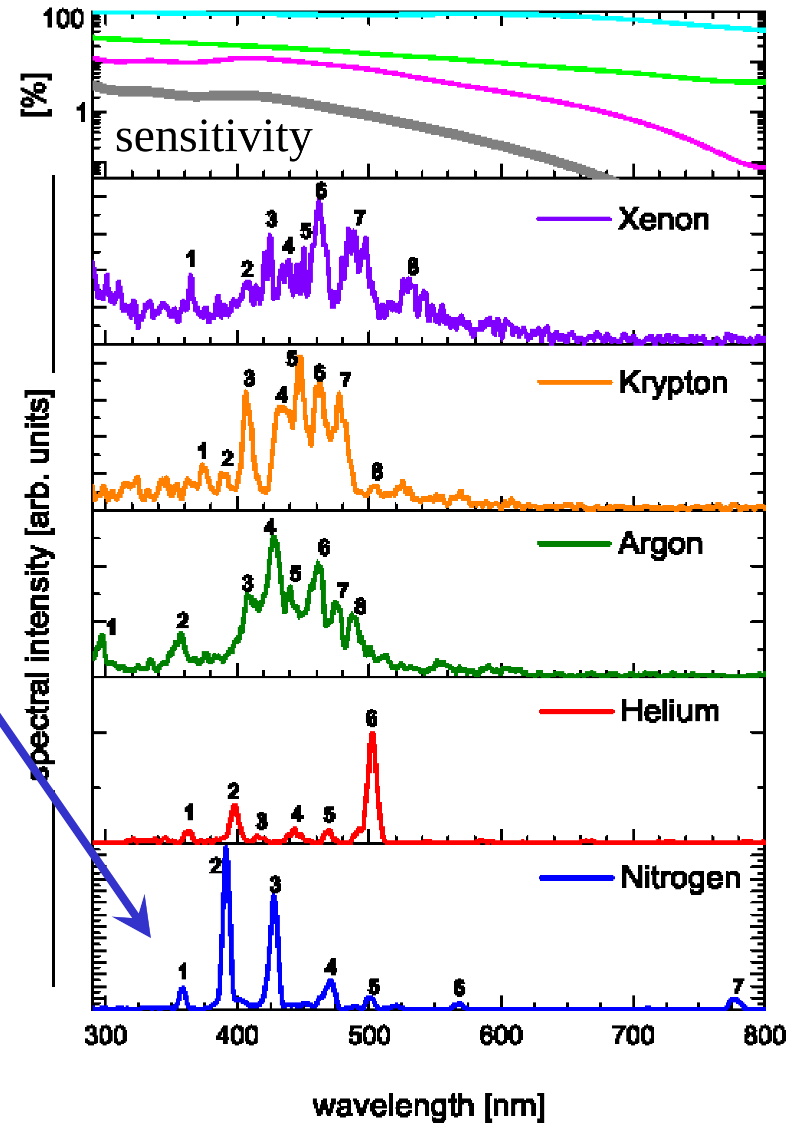


Beam parameter: S^{6+} at 5.16 MeV/u with $3\cdot10^{11}$ pps,
2000 macro-pulses, $p_{N2}=10^{-3}$ mbar

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





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

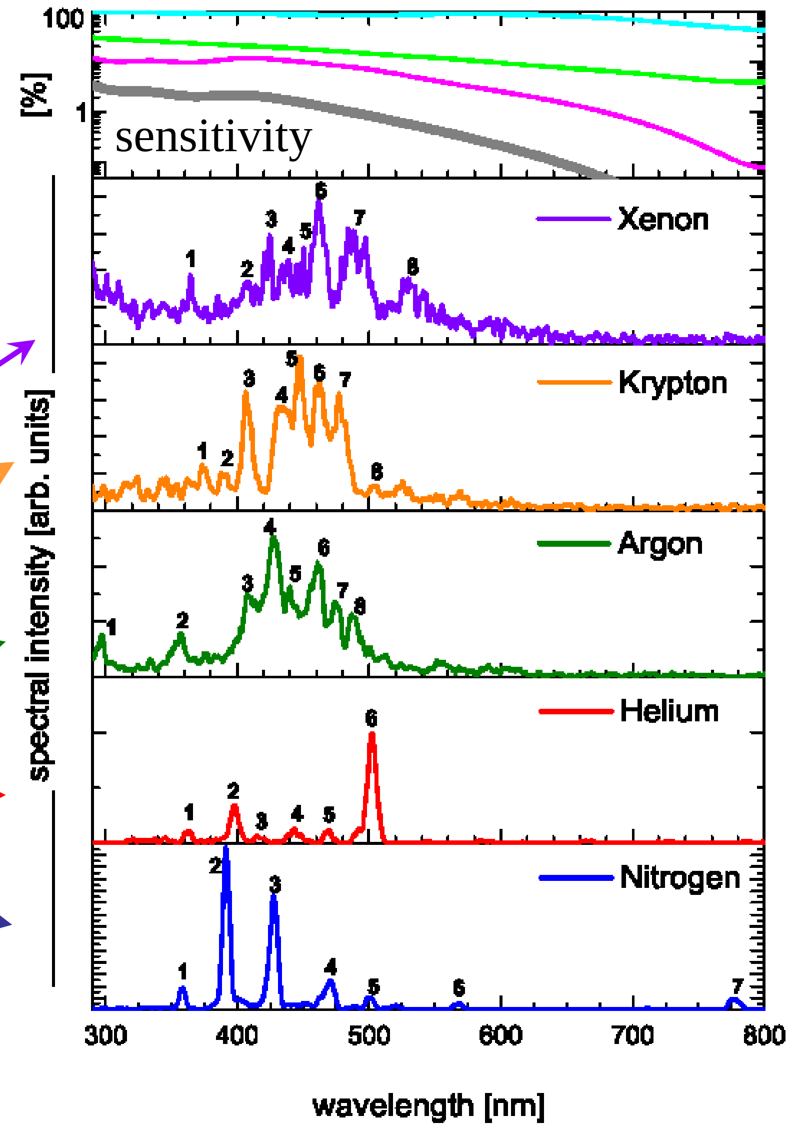
Spectroscopic Investigations for BIF of N_2: Light Yield

⇒ Expected transitions in near-UV to blue
(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

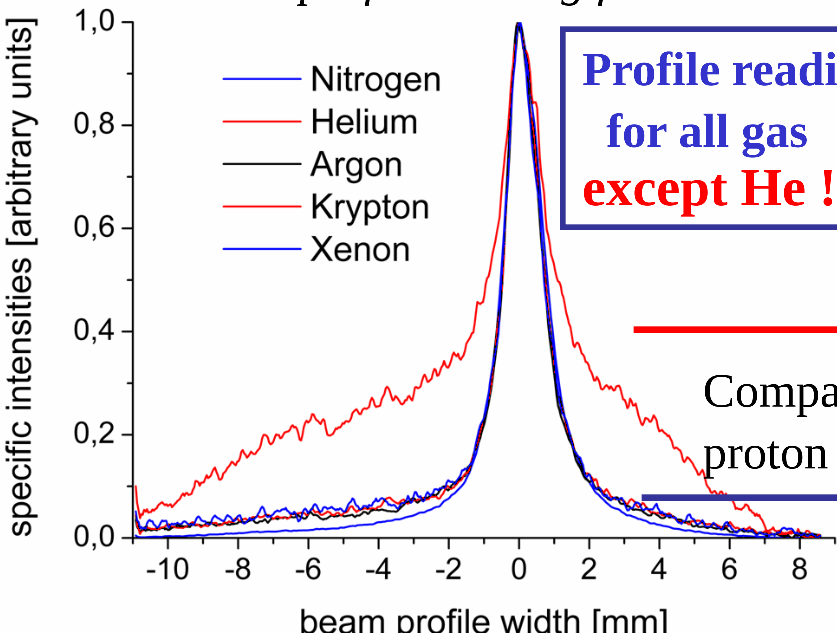


Beam parameter: S^{6+} at 5.16 MeV/u with $3 \cdot 10^{11}$ pps,
2000 macro-pulses, $p_{N2} = 10^{-3}$ mbar

Spectroscopic Investigations for BIF of N_2 and He

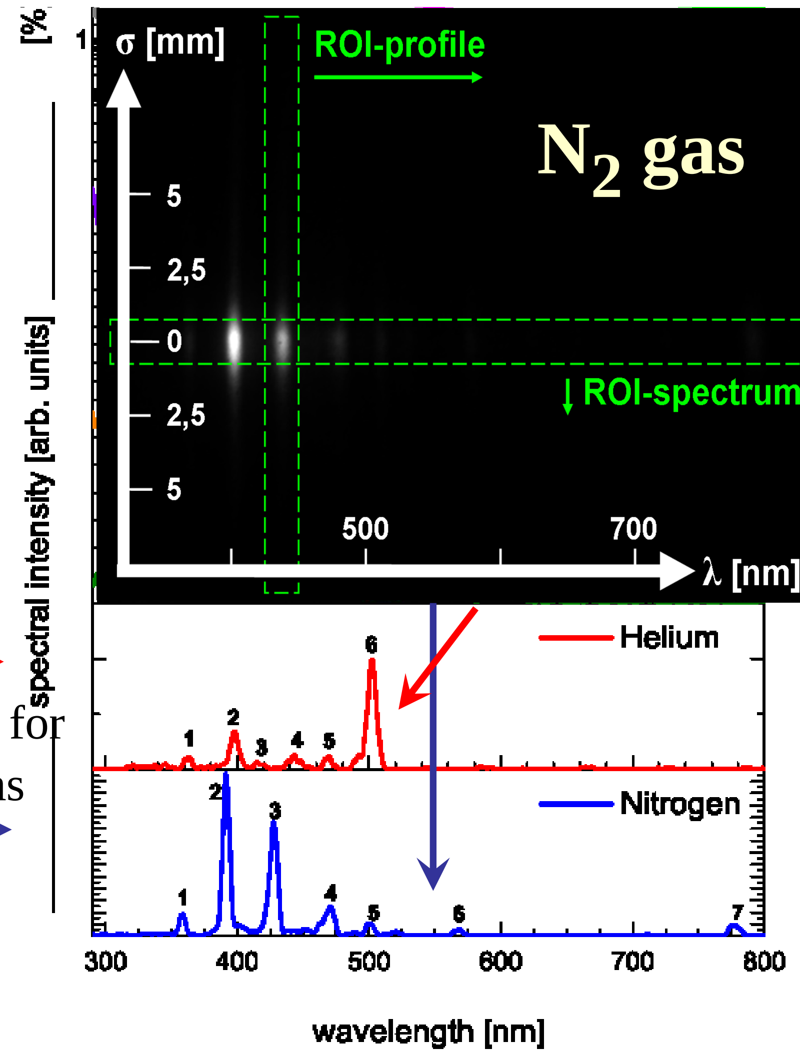
⇒ Expected transitions in near-UV to blue
(as for slower and faster collisions with protons)
⇒ Same profile reading for all lines
⇒ Light yield of N_2 is factor 4 higher as rare gases
⇒ ***N_2 is well suited !***

Normalized profile reading for all λ:



Profile reading equal for all gas except He !!!

Comparable results for proton and Ta beams



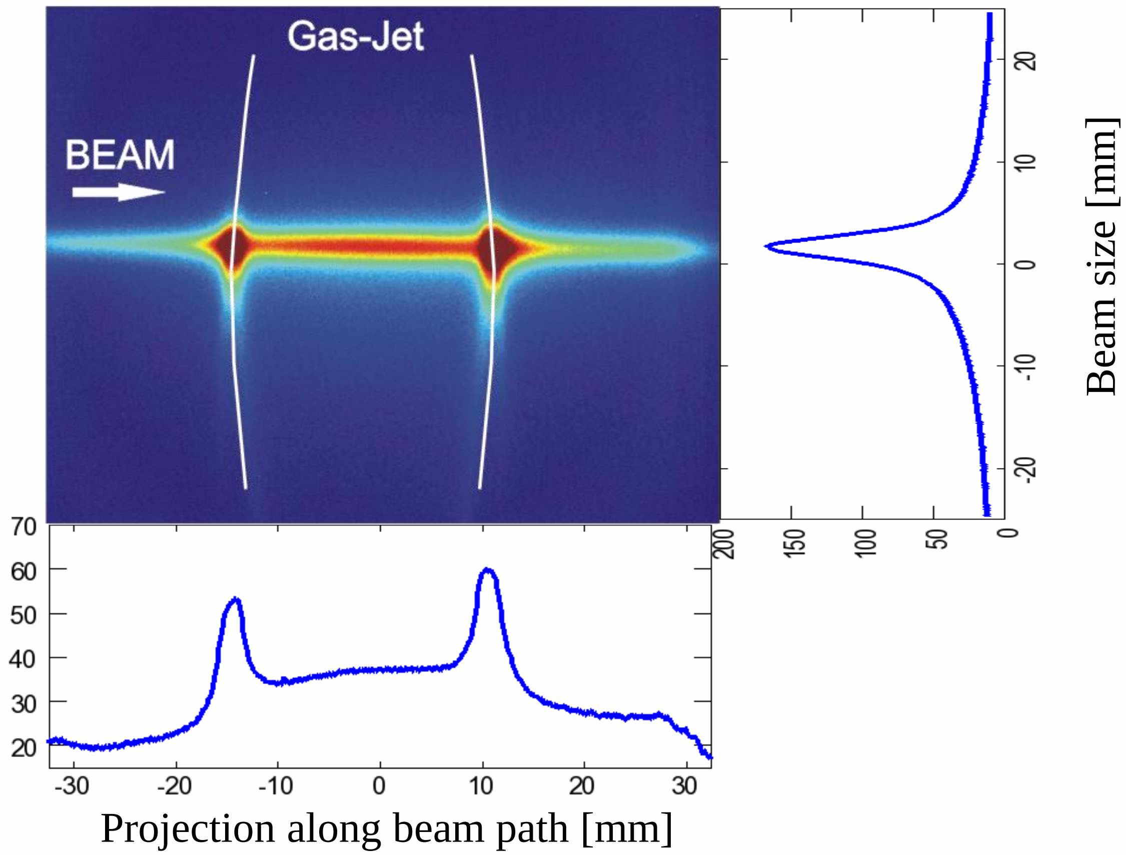
Beam parameter: S^{6+} at 5.16 MeV/u with $3 \cdot 10^{11}$ pps,
2000 macro-pulses, $p_{N2} = 10^{-3}$ mbar

Usage as a Diagnostics of a Gas Target

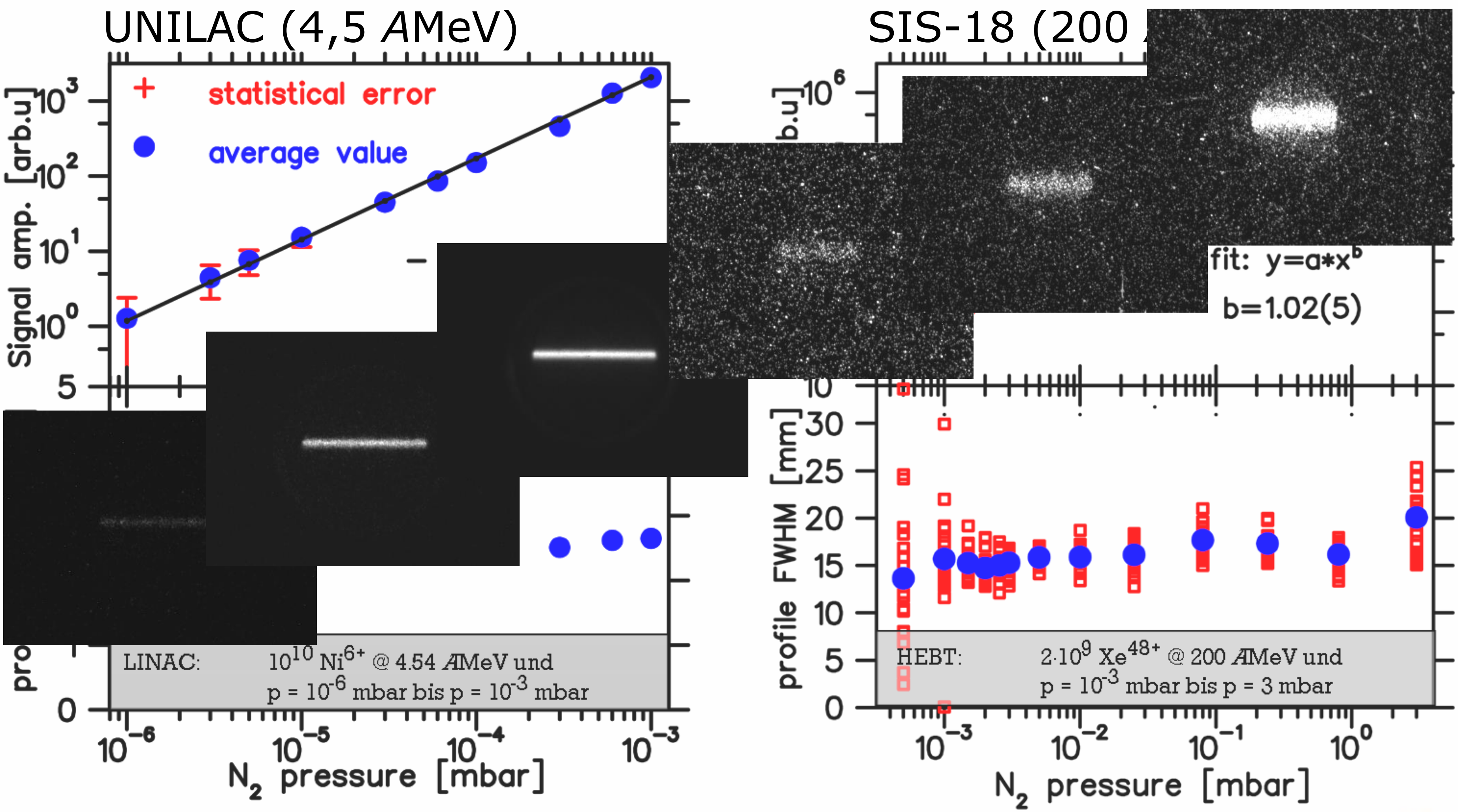
The properties of a gas target including beam overlap can be monitored:

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



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

Spectroscopy – Color and Fluorescence Yield

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

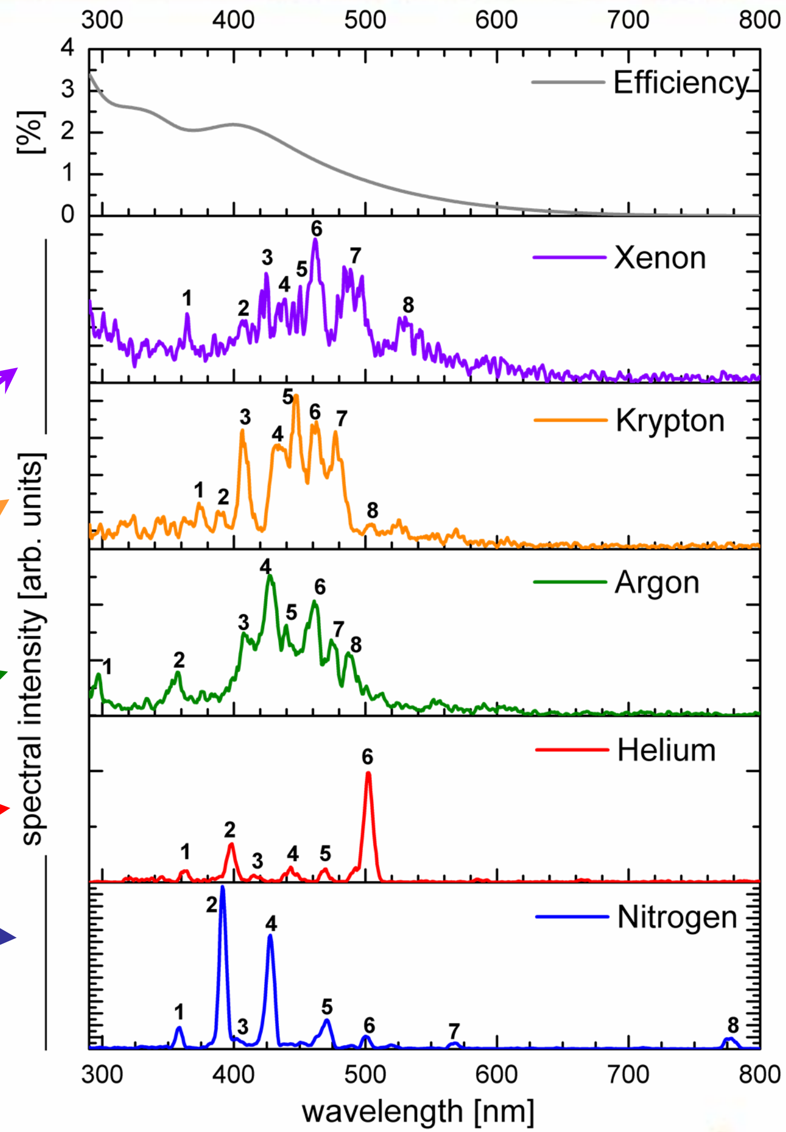
⇒ N_2 *and Xe are well suited !*

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

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



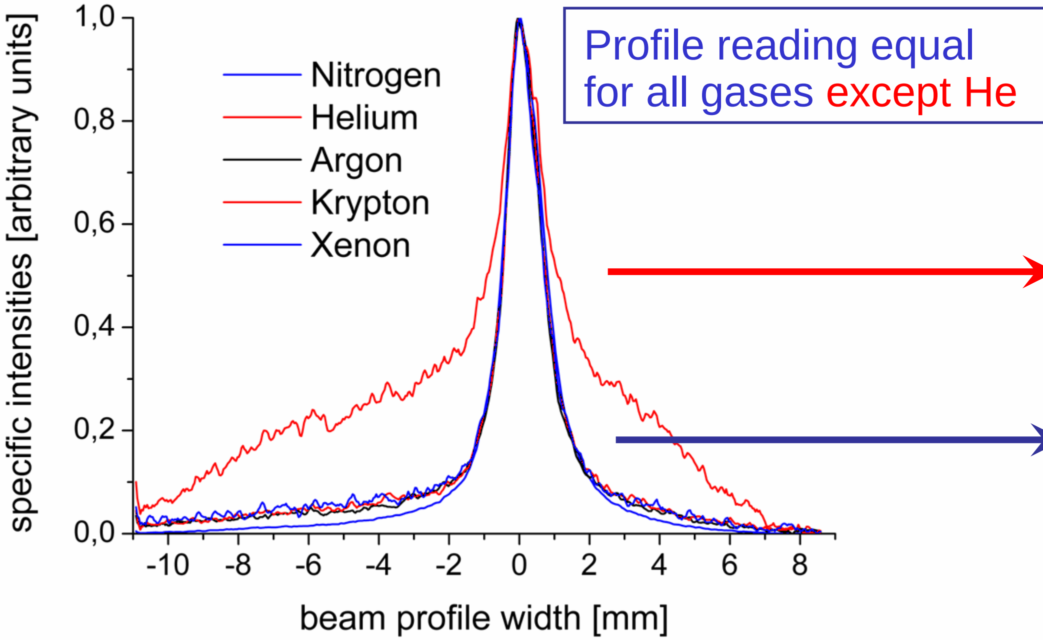
Spectroscopy – Profile Reading

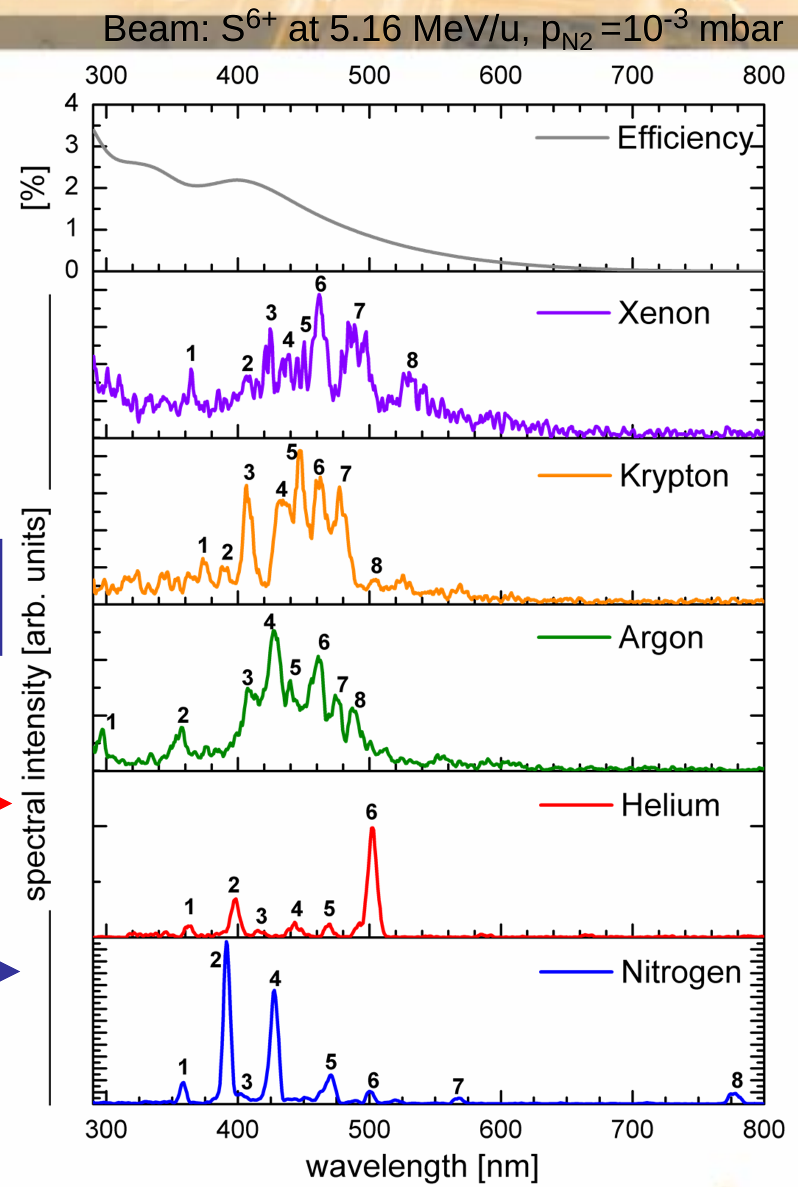
Results of detailed investigations:

- 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
- Same profile image for **all** gas, **except He**

⇒ ***N_2 and Xe are well suited !***

Normalized profile reading for all λ:





BIF-Monitor: Technical Realization

Example BIF station at GSI-LINAC:

- 2 x image intensified CCD cameras with reproduction scale 0.2 mm/pixel
- Gas inlet + gauge