Fluorescence Monitors at GSI

--- Lessons learned ---

Collaboration Meeting the 30th of March 2022

Peter Forck & Serban Udrea, GSI

Goal: Preparation of experiments at HEL-test-bench and LHC

Experiences from single pass ion beams:

University München TANDEM: 3 MeV/u < E_{kin} < 5 MeV/u

GSI LINAC: 5 MeV/u < E_{kin} < 11 MeV/u

GSI synchrotron: 100 MeV/u < E_{kin} < 800 MeV/u

For peace and freedom

Violence must be rejected

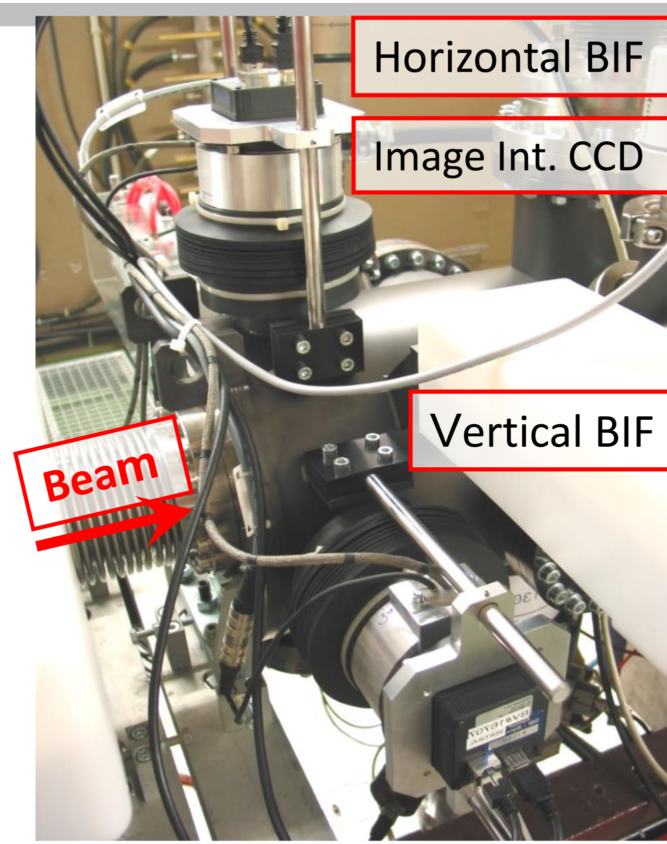
BIF-Monitor: Technical Realization at UNILAC@GSI

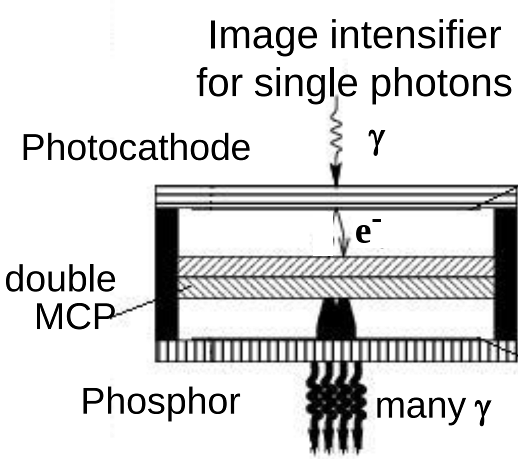
Example: BIF station at GSI UNILAC:

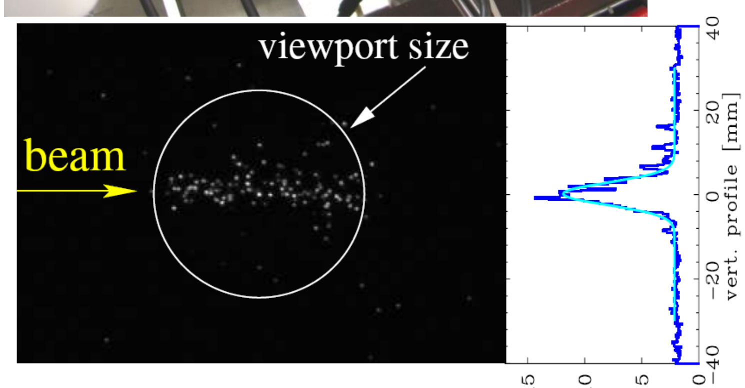
- Using transition with N_2

$N_2 + \text{Ion} \rightarrow (N_2^{+})^{*} + e^{-} + \text{Ion} \rightarrow N_2^{+} + \gamma + e^{-} + \text{Ion}$

- Insertion length 25 cm
- 2 x image intensified CCD cameras
- Optics with reproduction scale typ. 0.2 mm/pixel
- Gas inlet + gauge, pneumatic actuator for calibration
- **Advantage:** Compact insertion, resolution adaptable
  of-the-shelf components







C. Andre (GSI) et al., Proc. IBIC 2014

Beam: Ar^{10+}@4.7 MeV/u, I=2.5 mA⇔10^{11} ppp, p=10^{-5}mbar aver. pixel int.

BIF-Monitor: N_2 Fluorescence Spectra for different Ions

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

Fluorescent transitions:

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

N_2^+ : $B^2\Sigma_u^+ (v'') \rightarrow X^2\Sigma_g^+ (v')$,

λ = 391, 427 & 471 nm,

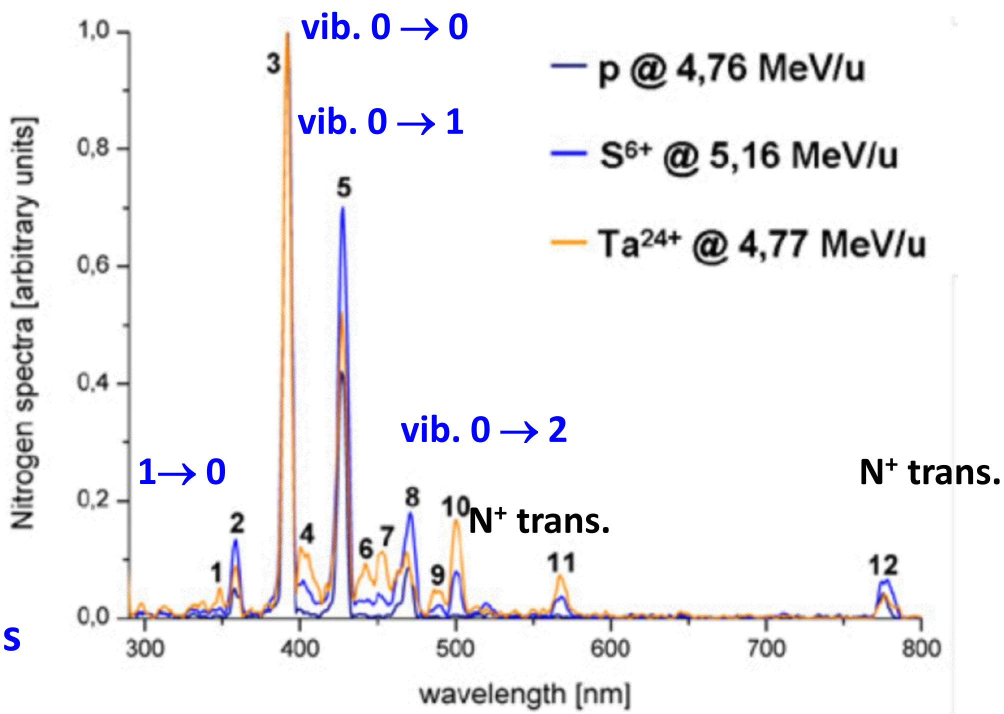
life time τ ≈ 60 ns

GSI UNIAC: ion energy ≈ 5 MeV/u

Results:

- Comparable spectra for all ions
- Small modification due to N_2^+ dissociation by heavy ion impact

⇒ Stable operation with constant spectrum for highly ionized ions



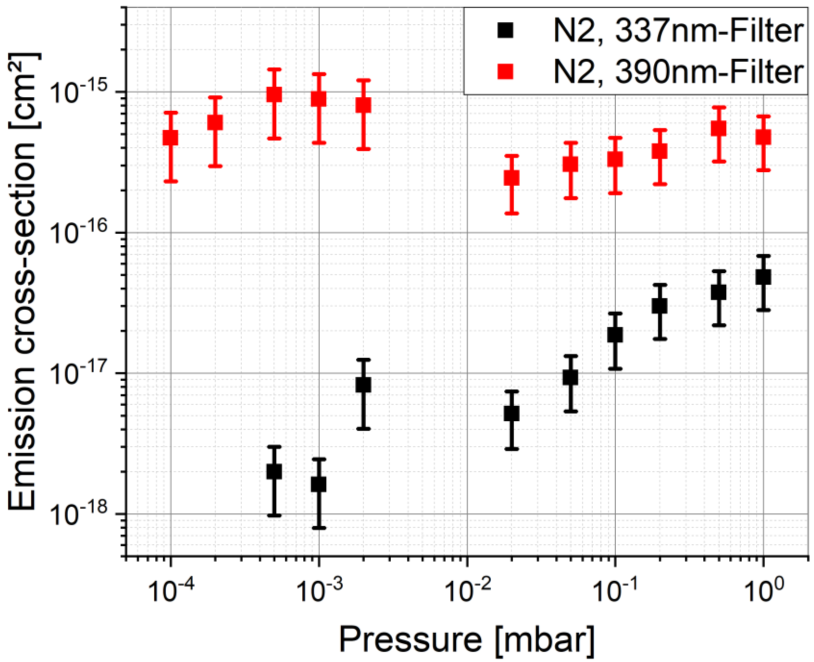
C. Andre (GSI) et al., Proc. IBIC 2014

Nitrogen Molecule Spectra with Ion Impact: Cross Section

N_2 as working gas for process:

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

$\rightarrow N_2^+ + \gamma +$ e^- + ion



Result for cross section:

- **Ionic lines**: $B^2\Sigma_u^+$ (v''=0) $\rightarrow$ $X^2\Sigma_g^+$ (v'=0)
  $\Rightarrow$ Constant σ over entire range
- **Neutral lines:** $C^3\Pi_u$(v''=0) $\rightarrow$ $B^3\Pi_g$(v'=0)
  Increasing σ
  as generated by secondary electrons **only**
  (spin forbidden by proton impact)

Estimation of cross section:

- **Ionic**: σ_S(2.7 MeV/u) = 4 · 10^{-16} cm^2
  $\Rightarrow$ Proton σ_p(2.7MeV/u) = σ_S(2.7MeV/u) / q^2 = 6.3 · 10^{-18} cm^2
  $\Rightarrow$ Bethe-Bloch scaling σ_p(7TeV) = 0.03 · σ_p(2.7MeV) = 1.8 · 10^{-19} cm^2
  Serban's estimation: σ_p(7TeV) = 3.7·10^{-20} cm^2 $\Rightarrow$ factor 5 too large
- **Neutral**: Can **not** be excited by proton & ion impact!

BIF Monitor: Different Gas Pressures and Profile Width

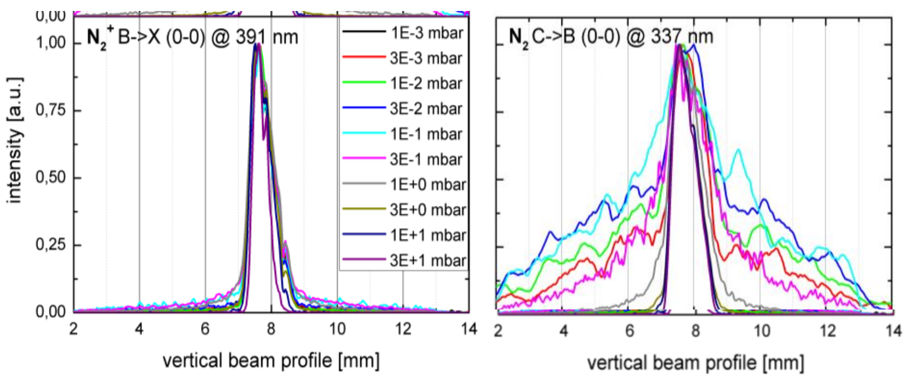
Observation: Trans. of ionic states e.g. N_2^+ → profile width independent on pressure
Trans. of neutral states e.g. N_2 → width strongly dependent on pressure!

- **Ionic transitions λ=391 nm:**

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

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

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



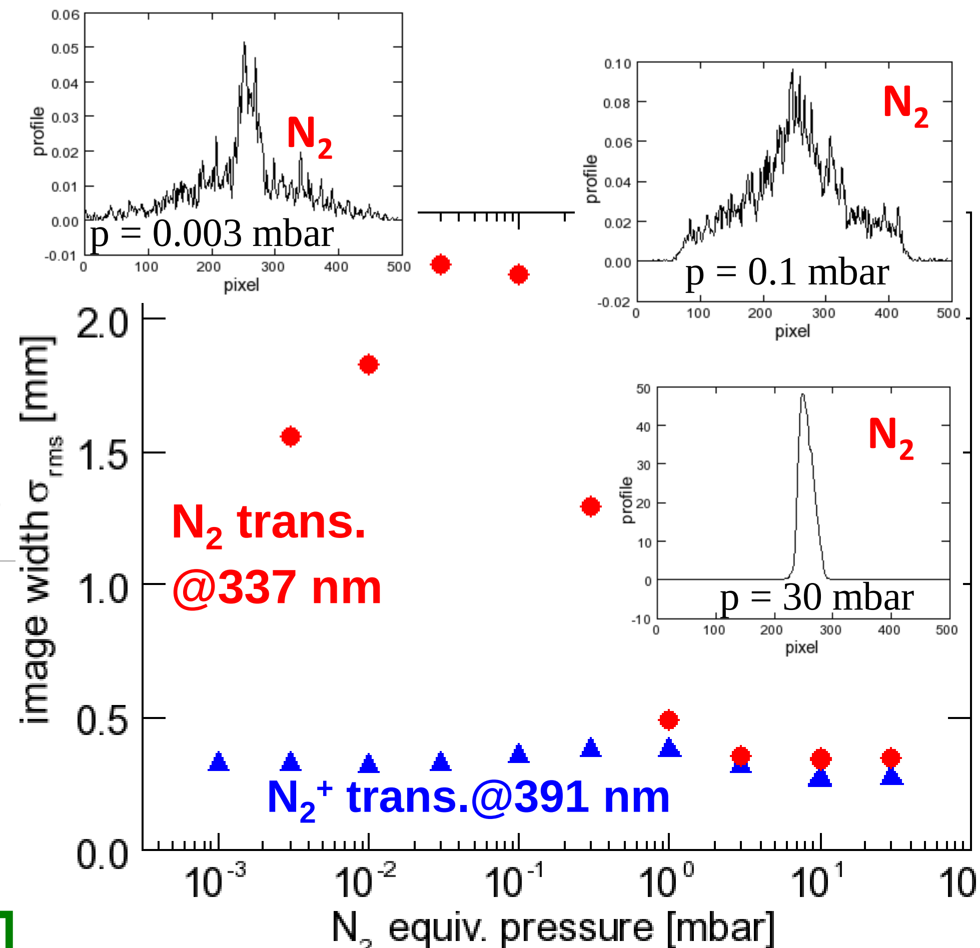
- **Neutral transitions λ=337 nm:**

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

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

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

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



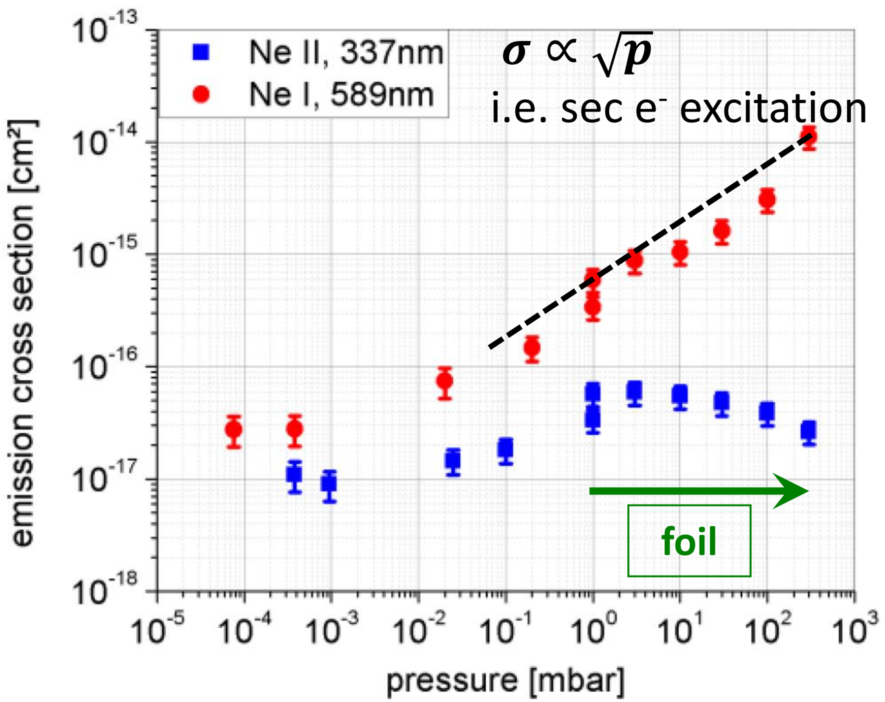
F. Becker et al., IPAC'12 &HB'12

Result: Save operation if $p < 10^{-3}$ mbar

Neon Spectra with Sulfur Ion Impact at 3.1 MeV/u

Result for cross section:

- **Ne^+ : σ** is **in**dependent on pressure
- Ne & high pressure $p > 10^{-2}$ mbar: caused be secondary electrons
- Ne & low pressure $p < 10^{-3}$ mbar: σ is constant i.e. reflects correct beam profile
- Absolute systematic error $\Delta\sigma_{sys} = 50$ %



Estimation of cross section for neutral Ne:

- Sulfur $_{16}S^{8+}$ **no** Titanium foil

  $\sigma_S(2.7\text{MeV/u}) = 2.5 \cdot 10^{-17}$ cm²
- $dE/dx \propto q^2$ scaling with charge state $q = 8$ (Bethe-Bloch scaling)

  $\Rightarrow$ Proton $\sigma_p(2.7\text{MeV}) = \sigma_S(2.7\text{MeV/u}) / q^2 = 3.9 \cdot 10^{-19}$ cm²
- Energy loss from 2.7 MeV to 7 TeV by factor 0.03, but non Bethe-Bloch scaling for neutrals

  $\Rightarrow$ Bethe-Bloch scaling $\sigma_p(7\text{TeV}) = 0.03 \cdot \sigma_p(2.7\text{MeV}) = 1.2 \cdot 10^{-20}$ cm²

  $\Rightarrow$ Bethe-Born scaling $\sigma_p(7\text{TeV}) = 0.007 \cdot \sigma_p(2.7\text{MeV}) = 2.8 \cdot 10^{-21}$ cm²
- Serban's estimation: $\sigma_p(7\text{TeV}) = 4.7 \cdot 10^{-22}$ cm² $\Rightarrow$ factor **6** too large (25 for B-Bloch)

Pressure dependent Profile Reading

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

Process:

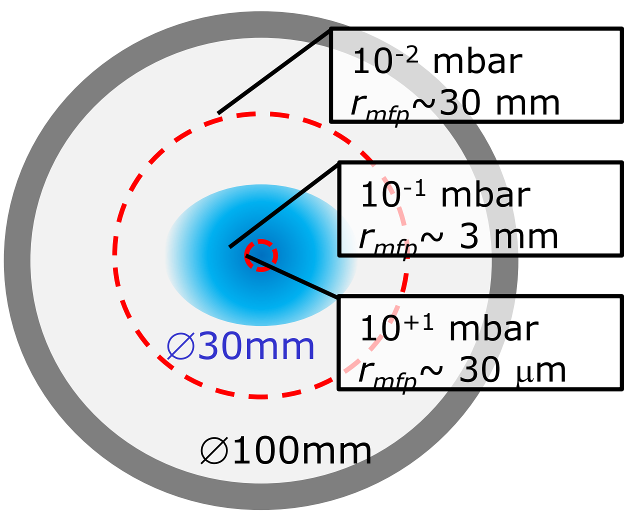
1. Direct excitation e.g.: N_2 + ion $\rightarrow$ $(N_2^+)^*$ + e^- + ion

2. **In**direct processes e.g.: N_2 + e^- $\rightarrow$ $(N_2)^*$ + e^- $\rightarrow$ N_2 + γ + e^-

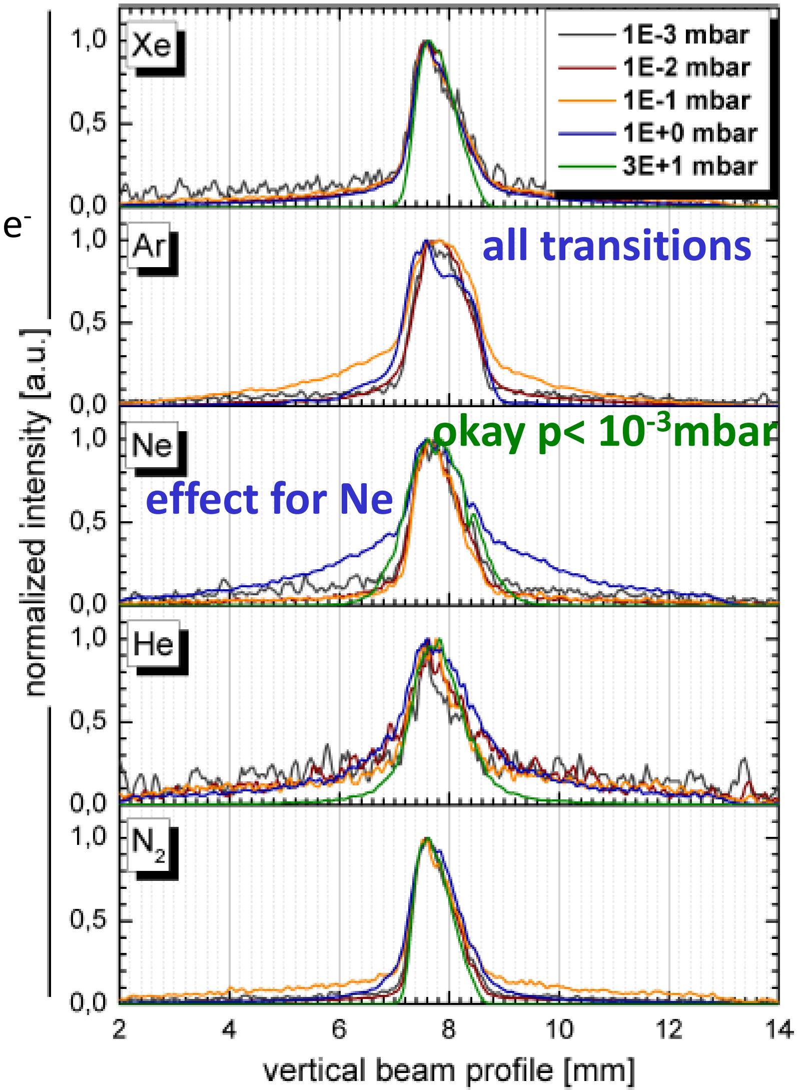
$\Rightarrow$ No all spectral lines are correct

Results: Possible misreading for neutral lines

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



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



F. Becker et al. (GSI) , IPAC'12 and HB'12

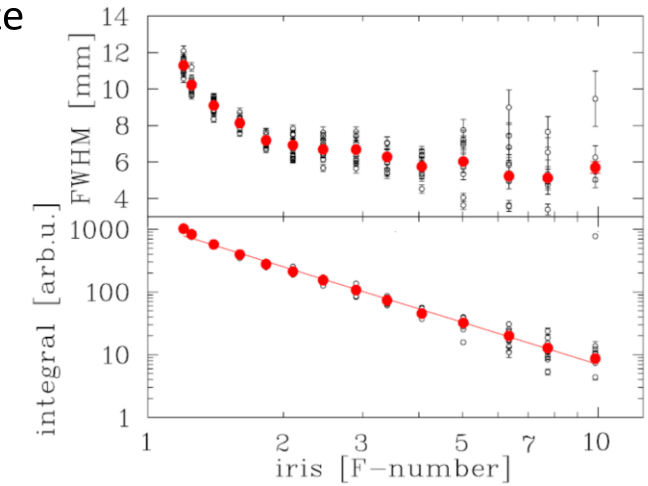
Distortions by Depth-of-focus, Space Charge and Curtain Thickness

Task: The depth-of-focus must fit to the beam size

Method: Determination of beam size

Care: Radial beam density distribution

Additionally: Vignetting → increase for open iris



GSI UNILAC:

Ar^{10+}@4.7 MeV/u,

2.5 mA

P. Forck, A. Bank (GSI), EPAC 2002

Simulations by Ondrej Sedlacek (using GSI-code)

Smearing due to finite curtain size:

Thickness smaller than required resolution

Distortion due to space charge:

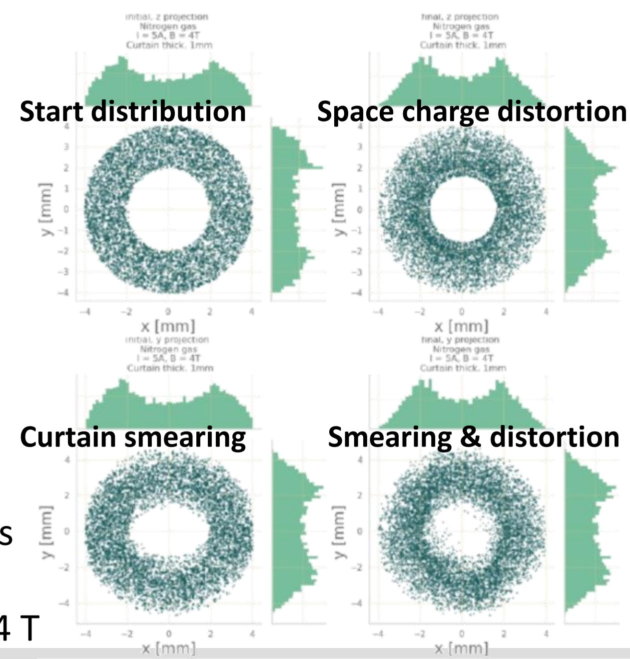
For N_2 gas (fluorescence from N_2^+) not for Ne

Care: Non-uniform electron-beam distribution

For first prove-of-principle:

Thick curtain for large signal strength

Hollow electron beam:



Parameter:

Gas N_2^+ with lifetime τ=60 ns

Curtain: 1 mm thick curtain

Electron beam 5 A, mag. B=4 T

O. Sedlacek et al, IPAC2021

Energy Scaling for N_2 Fluorescence and Background

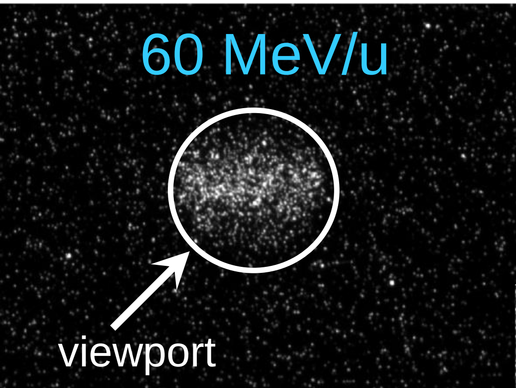
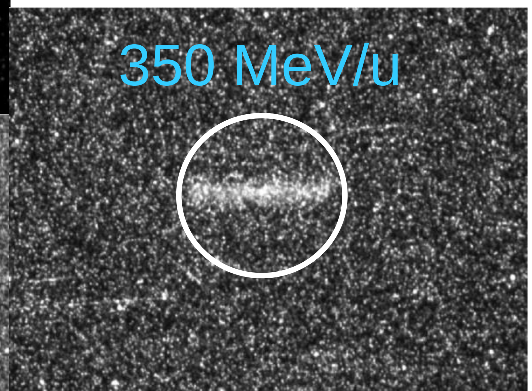
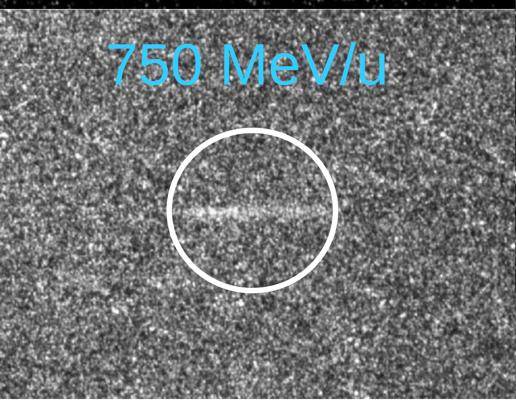
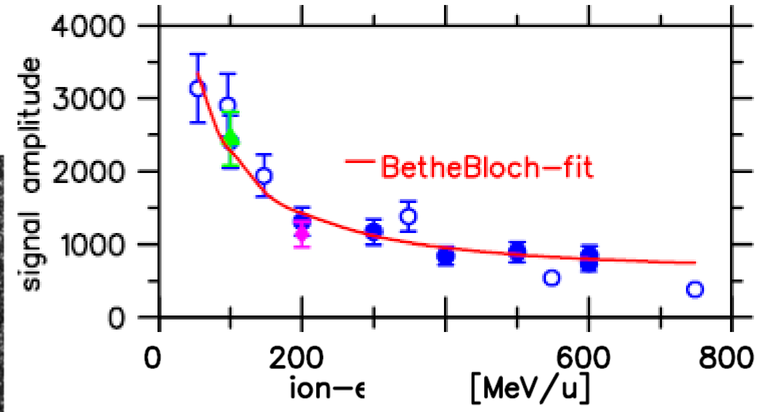


Image from $1\cdot10^9$ U
p= $2\cdot10^{-3}$ mbar,
mounted ≈ 2 m
before beam-dump:





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



- Signal proportional to energy loss
- Suited for single pass with ≥ 10^{10} ions/pulse
- Background prop. $E_{kin}^{2} \Rightarrow$ shielding required
- Background outside of viewport $\Rightarrow$ not optical photons

F. Becker (GSI) et al., Proc. DIPAC'07

Neutron induced Background

Neutron creation by nuclear interactions

Refection at concrete wall, i.e. 'bouncing around'

$\Rightarrow$ Long 'detention' in tunnel; here $\approx$ 1 ms

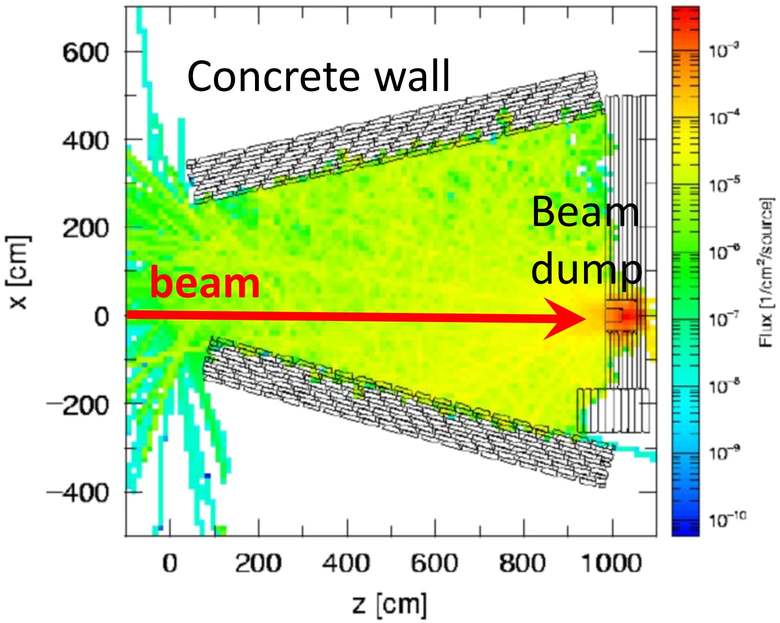
Mitigation:

Image intensifier gate only during beam

However, at LHC not applicable

Neutron flux by PHITS:

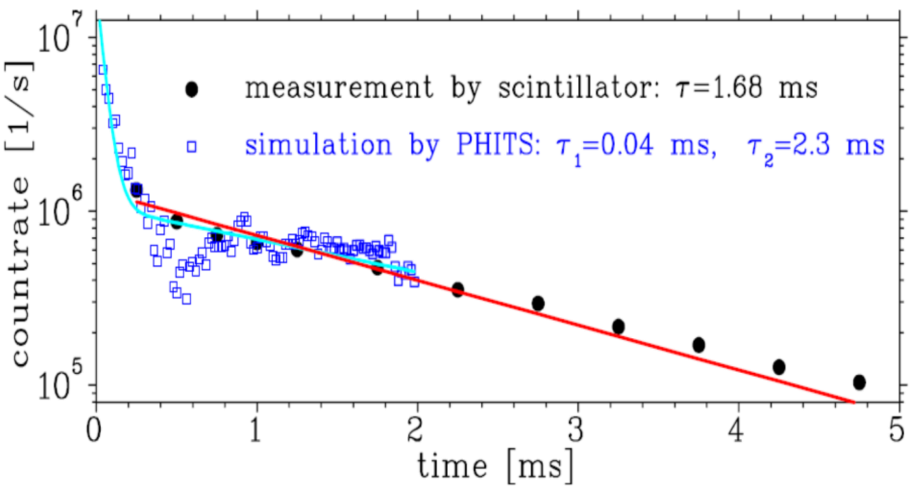
Beam: Xe^{48+} @200MeV/u stopped in dump



Comparison PHITS & plastic scintillator:

(II comparable background decay):

Beam: Xe^{48+} @200MeV/u stopped in dump



O. Sedlacek et al, IPAC2021

PHITS:

Particle and Heavy Ion Transport code System

(comparable to FLUKA)

Only relevant at LHC; no neutrons at HEL

Fast Proton induced Background (LHC only)

Proton creation by nuclear spallation reaction:

Fast proton emitted in beam direction

Image Intensifier window with photo cathode

→ Cherencov radiation in glass

→ Sometimes 'comets' appeared

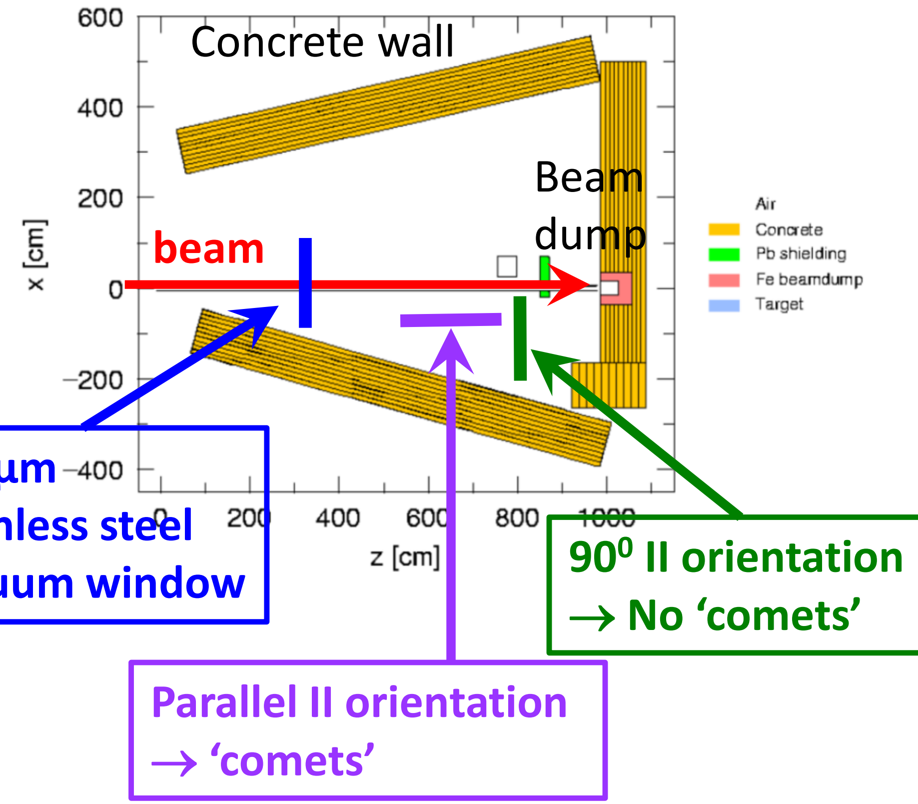
for **parallel orientation of Image Intensifier**

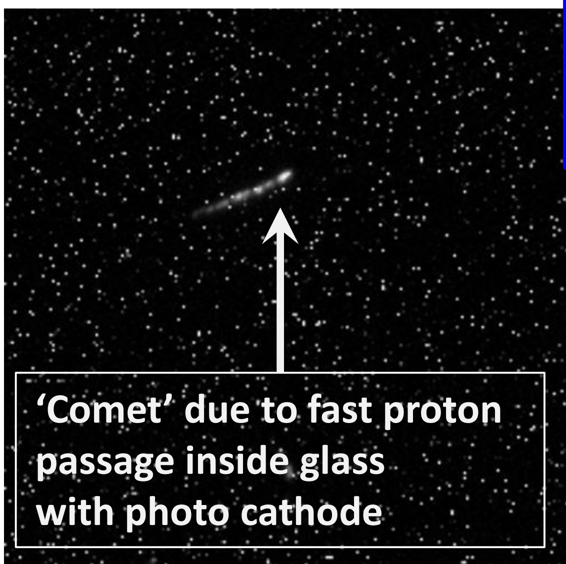
Mitigation:

- Shielding by lead between vacuum window
- Image Intensifier **90^0 rotation of II plane**

Neutron flux by PHITS:

Beam: Xe^{48+} @200MeV/u stopped in dump





Only relevant at LHC; no fast protons at HEL

Some experimental 'Lessons learned'

Image Intensifier gate:

- Voltage photo cathode $\leftrightarrow$ MCP follows gate TTL-gate,
- input $\approx 1\ \mathrm{M}\Omega$ impedance
- Maximum trigger rate 10 kHz

For long cable > 20 m (at LHC):

$\Rightarrow$ External 50 Ω termination via T-piece **required** & 50 Ω TTL driver electronics

Test: Background contribution must scale with gate length

Image Intensifier gate and camera exposure

- II gate only if beam is present (HEL is pulsed, LHC quasi cw operation)
- Camera exposure only slightly longer than II gate

Image Intensifier operation:

- Avoid high illumination
- Amplification by MCP voltage: Start with low value increase only to required voltage

Background:

- Optical photons though viewport ($\rightarrow$ blackening methods detailed investigated by CERN)
- Homogeneous distributed background by ionizing radiation (i.e. also outside of viewport)

Conclusion

Working gas:

N_2 and Ne properties fairly well investigated (more light from N_2)

- experimental knowledge for **low electron** currents at CI
- Scaling with one order of magnitude for LHC beams

Proposal: If possible, start with N_2 at HEL and large skimmer ('first we have to see a signal…')

Image intensifier, optics and camera:

Robust and well designed system, remote controlled at LHC, accessible at HEL test-bench

Proposal: Image Intensifier gate and camera exposure only during beam presence

LHC test operation:

Background measurement urgently required, dependence on optical filters

HEL test bench:

High beam current, high magnetic field, 'exotic' beam shape $\Rightarrow$ surprises possible

High magnetic field and space charge: $\Rightarrow$ surprises due to captured residual gas electrons or ion

Thank you for your attention!

Questions and comments?

Backup slide

BIF-Monitor: N_2 Scaling for different Ions

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

Scaling for different ions A^{q+} beams:

GSI-UNILAC: 5 to 11 MeV/u

Care: recording within several years

$\Rightarrow$ Systematic errors possible

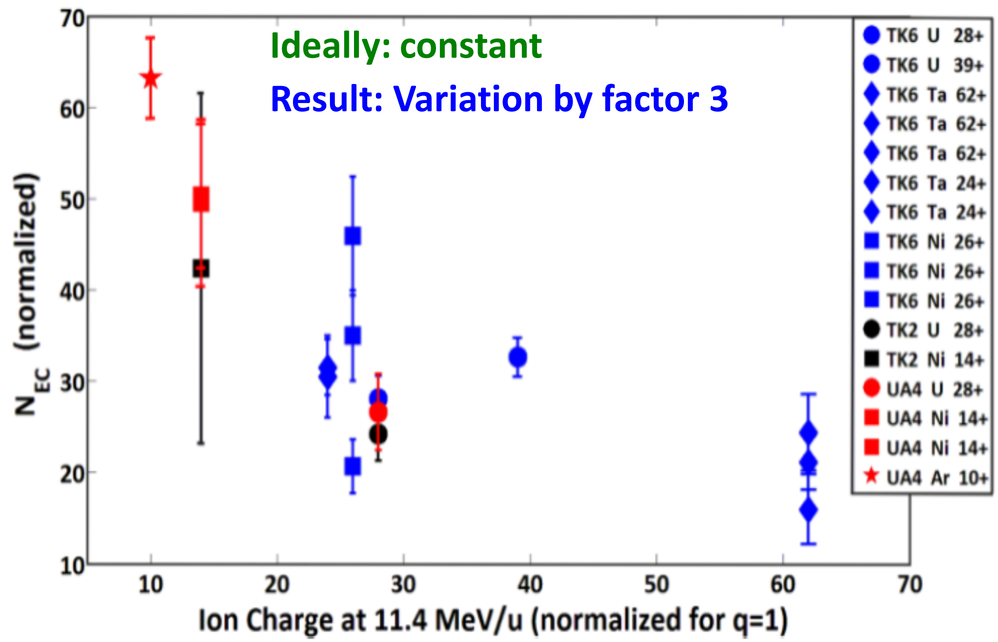
➢ Basically $\frac{dE}{dx}(\text{ion}) = q^2 \cdot \frac{dE}{dx}(\text{proton})$

Experiment: At GSI LINAC with 11.4 MeV/u

$\Rightarrow$ scaling confirmed within a factor of 3

$$N_{EC} \propto \frac{1}{q^2} \cdot \frac{dE}{dx}(\text{ion}) \propto \frac{dE}{dx}(\text{proton})$$

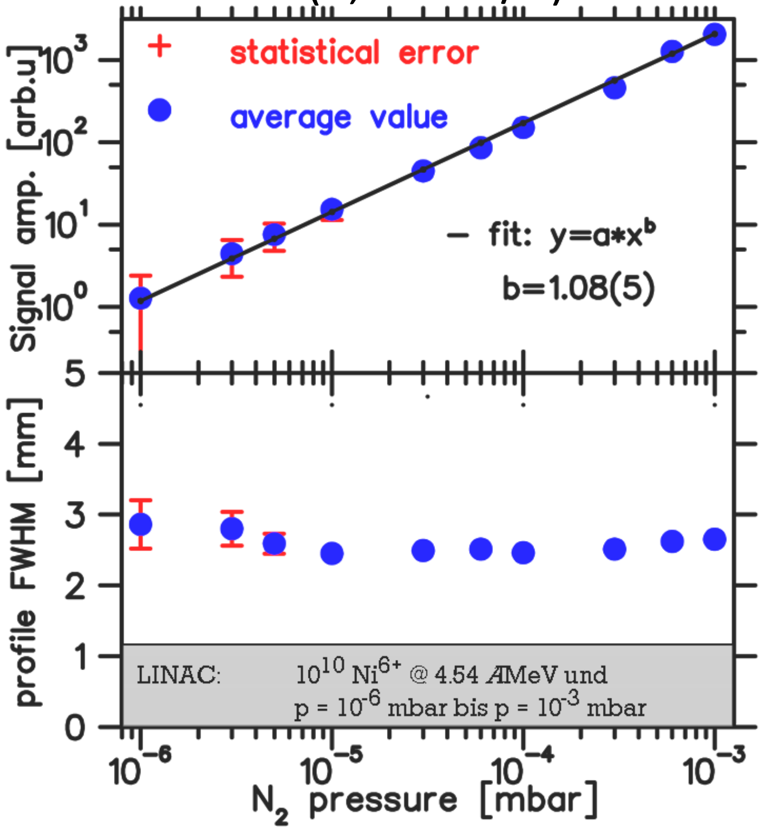
$\Rightarrow$ Bethe-Bloch scaling is reasonable

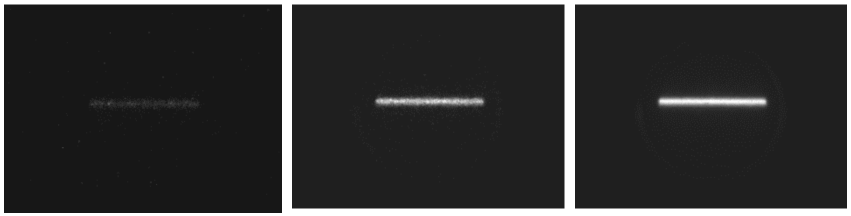


C. Andre (GSI) et al., Proc. IBIC 2014

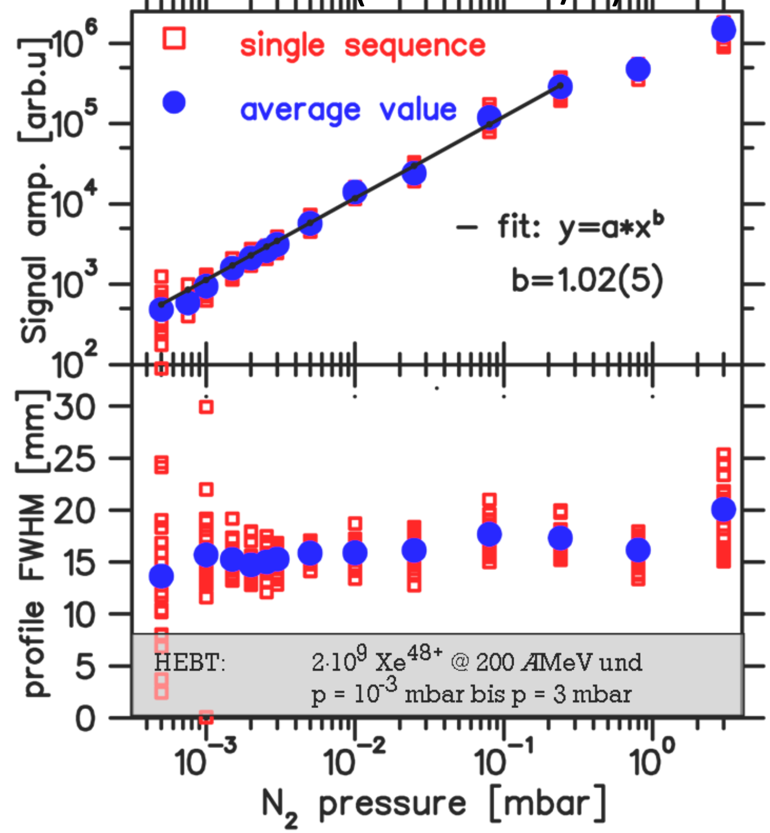
Pressure -Variation by 6 Orders of Magnituden

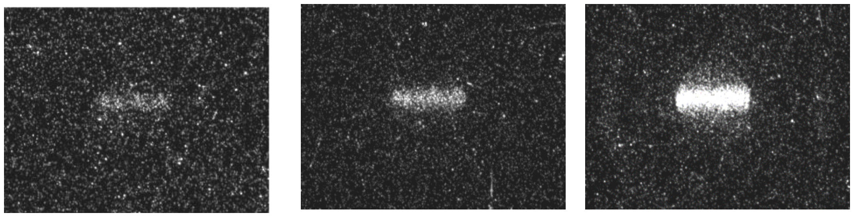
UNILAC (4,5 MeV/u)





SIS-18 (200 MeV/u)





BIF-Monitor: Spectroscopy & Fluorescence Yield

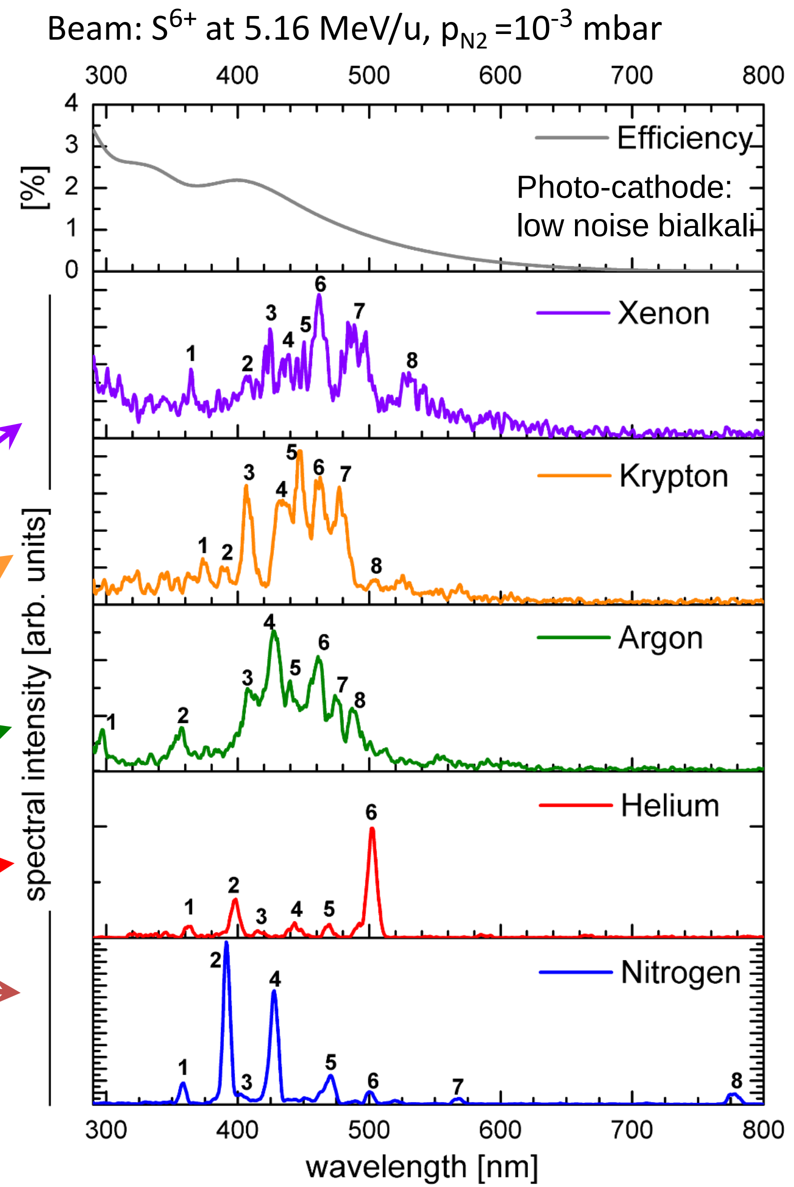
Results of detailed investigations:

- 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 %



n_e: gas electron density ∝ energy loss ⇔ beam influence

F. Becker et al. (GSI, TU-München), IPAC'12 and HB'12

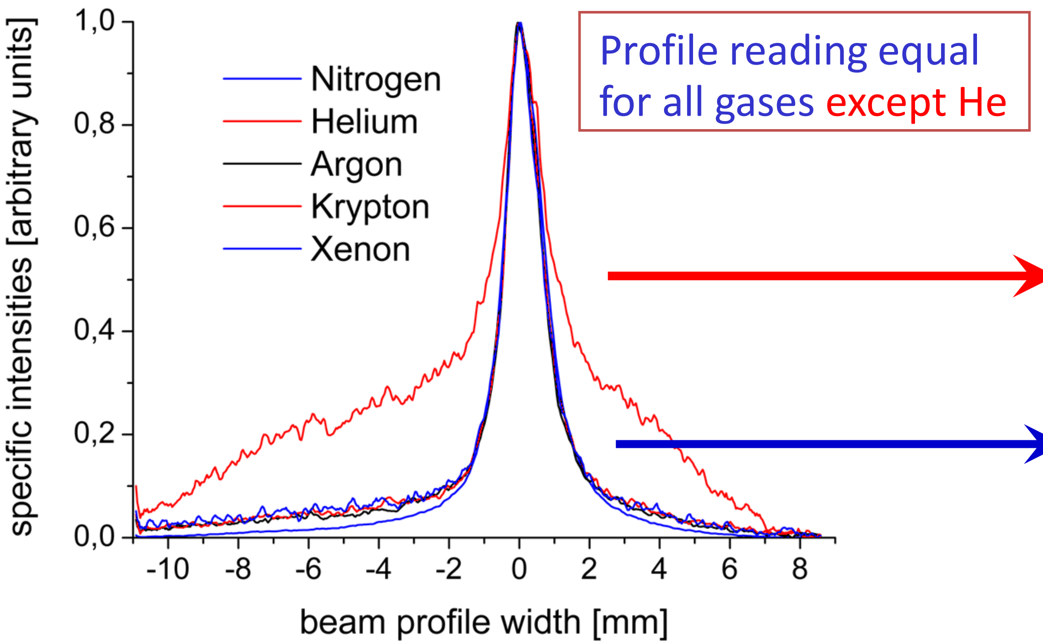
BIF-Monitor: Spectroscopy & Profile Reading

Results of detailed investigations:

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

$\Rightarrow$ ***N_2 and Xe are well suited !***

Normalized profile reading for all λ:



F. Becker et al. (GSI, TU-München), IPAC'12 and HB'12

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