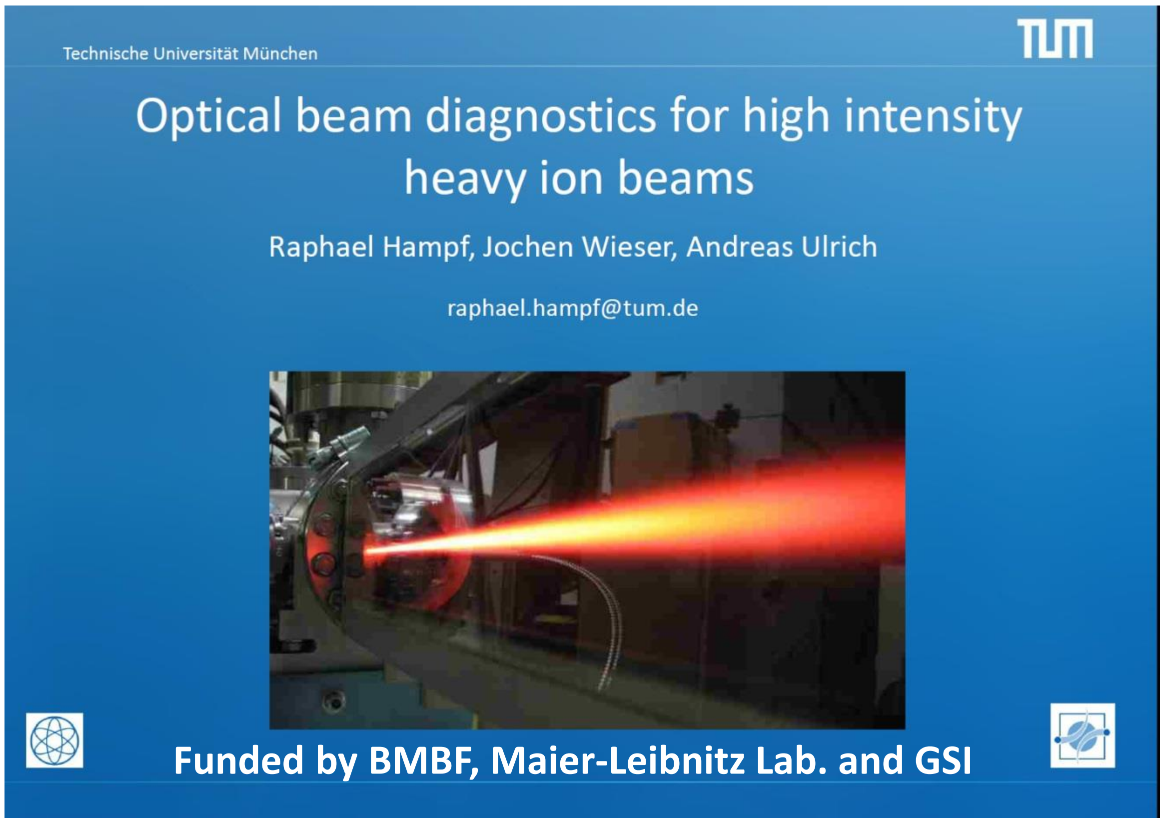
Developments at GSI

Peter Forck & Serban Udrea

Summary of Fluorescence Investigations at Technical University München

Raphael Hampf, Jochen Wieser, Andreas Ulrich (only peripheral with GSI participation)

Talk by Raphael Hampf, January 2019, Hirschegg, Austria



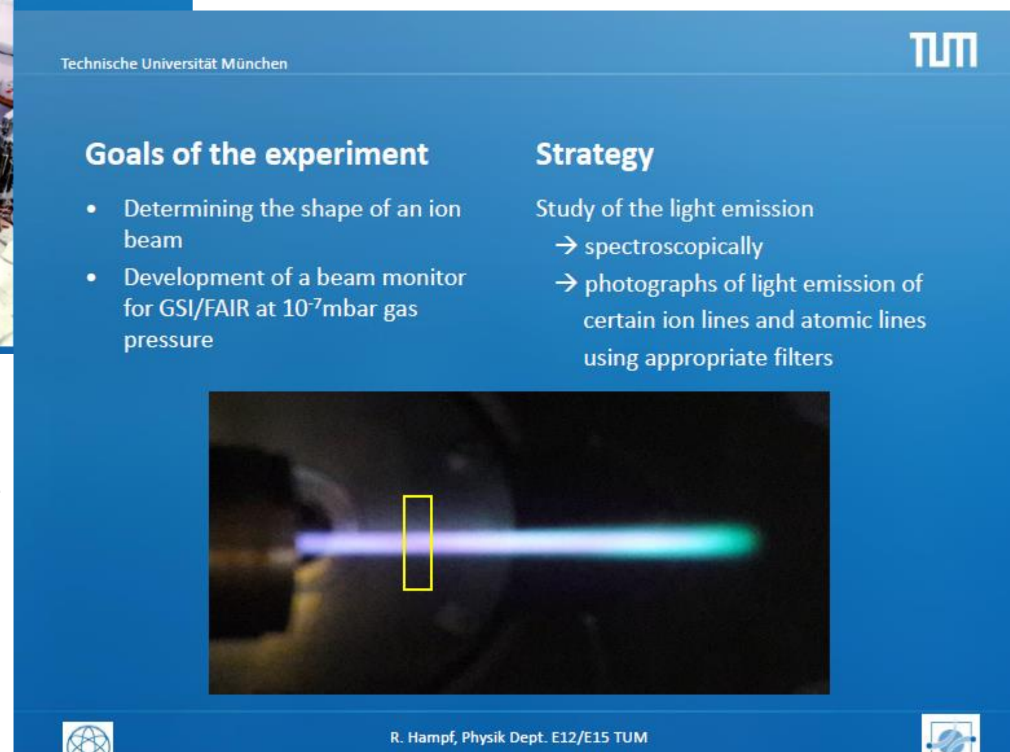
Setup at TANDEM TU München

Ion beams from the Munich Tandem Accelerator

DC beams, ^{32}S ions, ~87MeV & protons 13.8 MeV

Blue underlay:
Measurement and statements from TU München

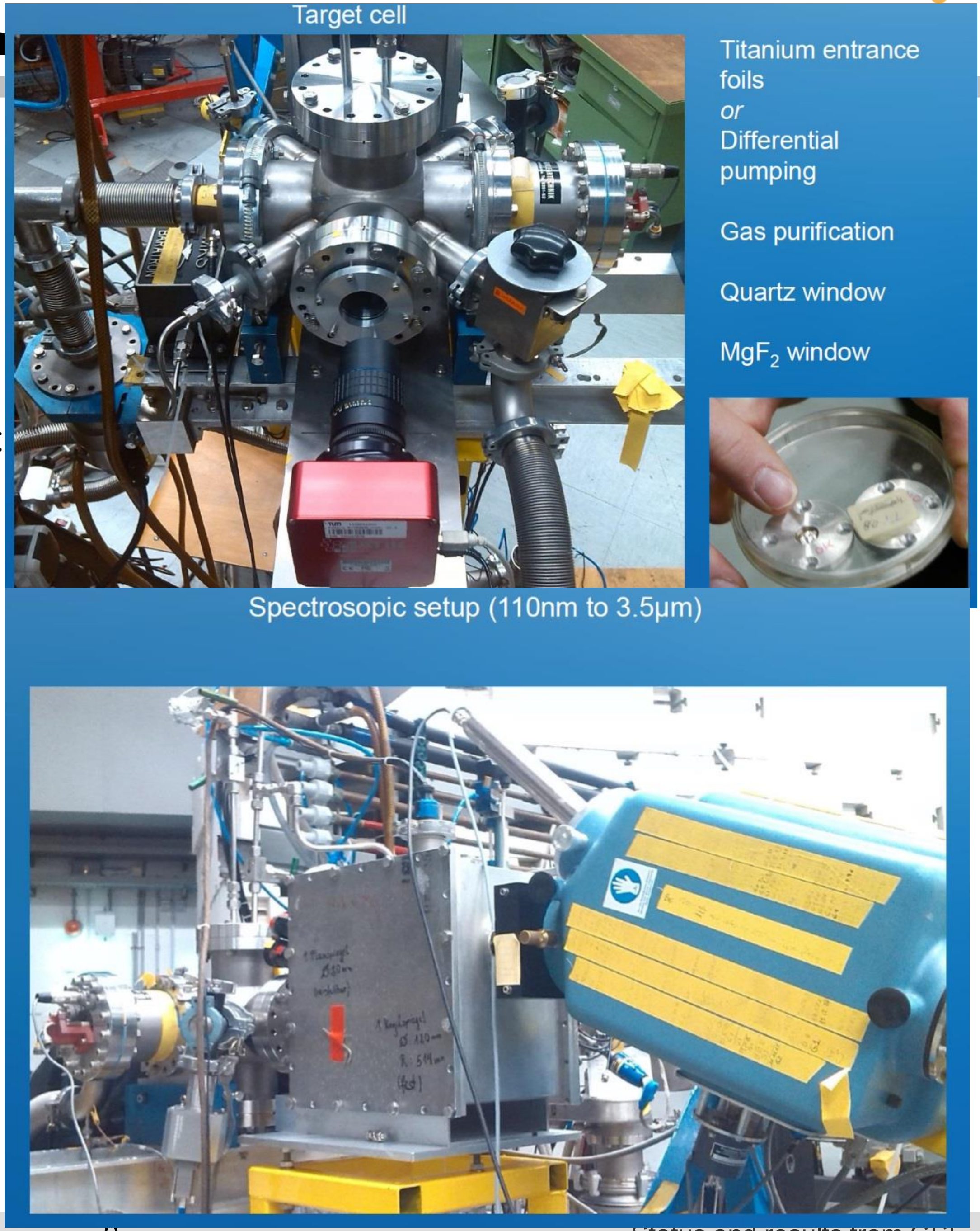
Advantage: Some 100 nA dc beam,
some days exclusive beam time



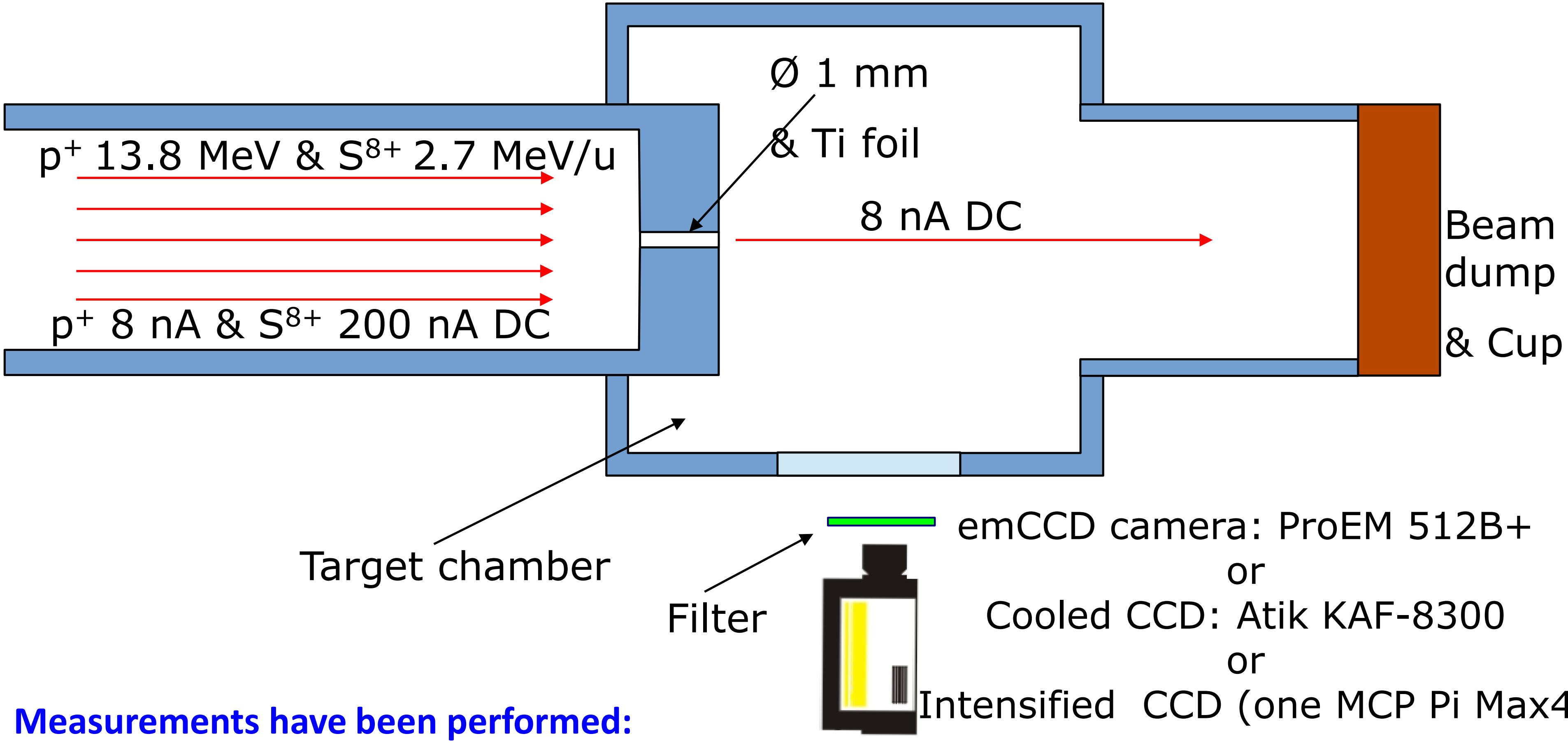
Setup at TANDEM TU München

- **Beam:**
  S^{8+} at 2.7 MeV/u and proton 13.8 MeV
- **Optical spectrum:**
  VUV monochromator with PMT (S20)
  → spectral lines
- **Images:**
  $\boldsymbol{f}$ = 60mm λ = 315...1100nm apochromat
  various interference filters
  → profiles and cross section
- **Camera:**
  Either Cooled CCD (ATIK KAF-8300)
  or emCCD (PI ProEm 512B+)
  or intensified CCD (one MCP Pi Max4)
- **Gas inlet**:
  $\boldsymbol{p}$ = 10^{-5} ... 10^{2} mbar
- **Vacuum separation:**
  $\boldsymbol{p}$ < 1mbar: differential pumping
  ⇒ S^{8+} collisions at 2.7 MeV/u
  $\boldsymbol{p}$ > 1mbar: Ti foil 1.3 mg/cm^2

⇒ stripping S^{8+} to ≈ S^{q+} q ≈ 12.5, 2.3 MeV/u



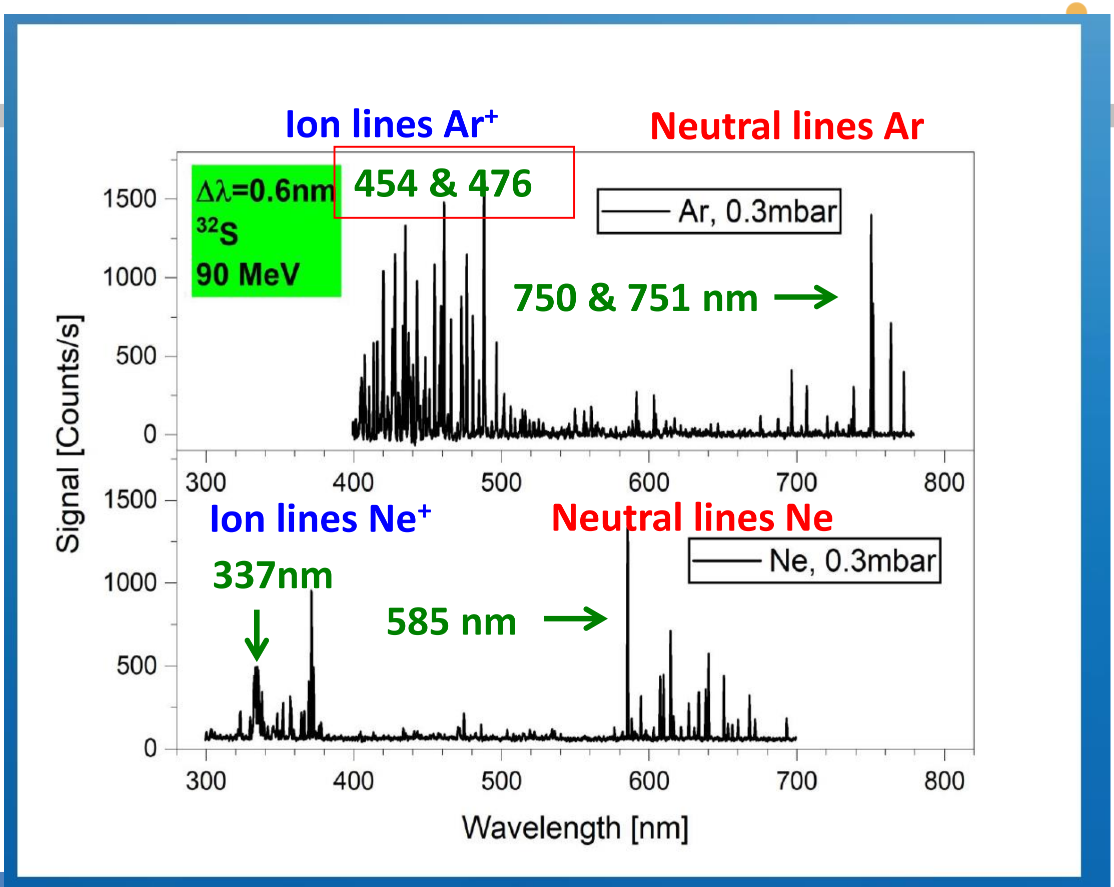
Setup at TANDEM TU München



Measurements have been performed:

- N_2, Ne and Ar as gas
- Spectrometer & camera for profile and cross section
- Depending on gas transition different interference filters
- Principle of equal velocities: 13.8 MeV p^+ should be equivalent to 7.5 keV e^-.

Overview Spectra by Ion Impact

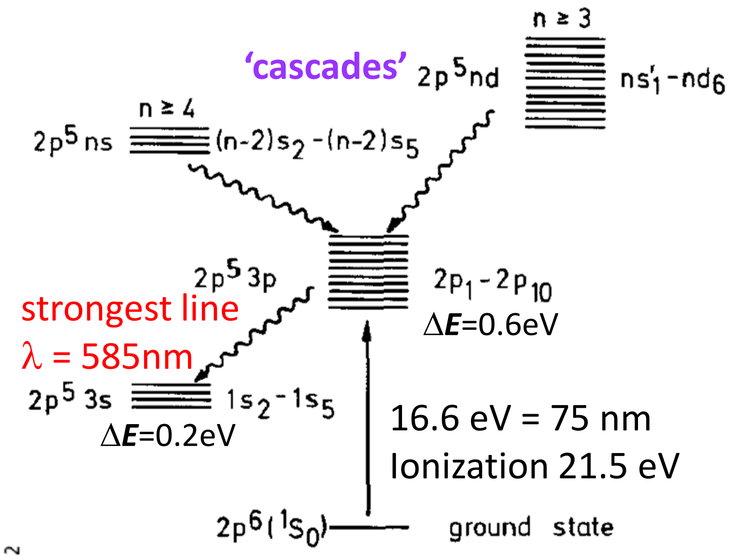


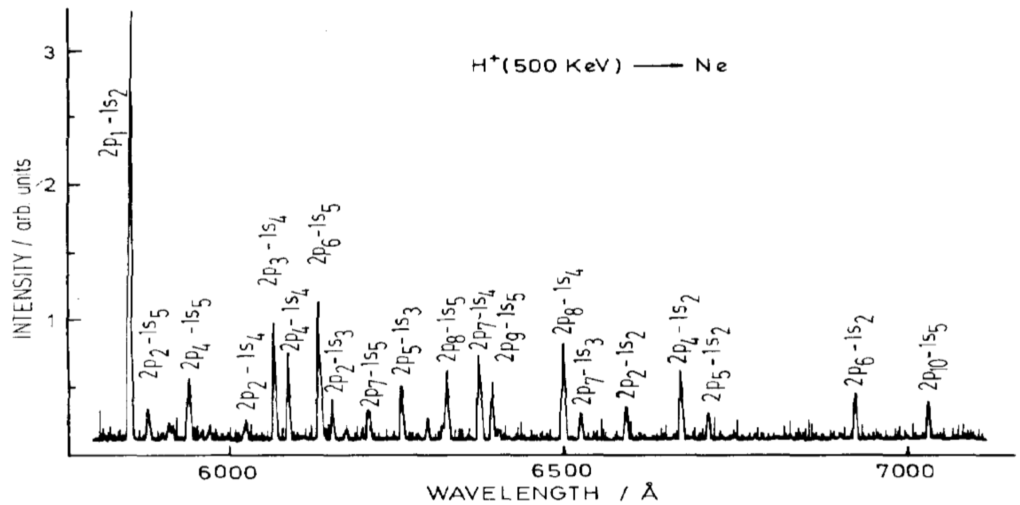
Seban's report:
Estimated cross section
for 7 TeV protons
at low pressure p << 10^{-3}mbar

Gas	Wavelength λ [nm]	Lifetime [ns]	σ [10^{-21} cm^2] (Serban, 7TeV)
Ne	585	15	0.5 (one line)
Ne^+	337	6	-----
Ar	750 & 751	30	3.3 (two lines)
Ar^+	454 & 476	10	1.7 (two lines)
N_2^+	391	60	37. (one line)

Atomic Physics for Proton Impact on Neon: Neutral Transitions

Paper: M. Eckhardt et al., Proton impact on Neon for 0.1 to 1 MeV, Z. Physik A 292, 337 (1979)





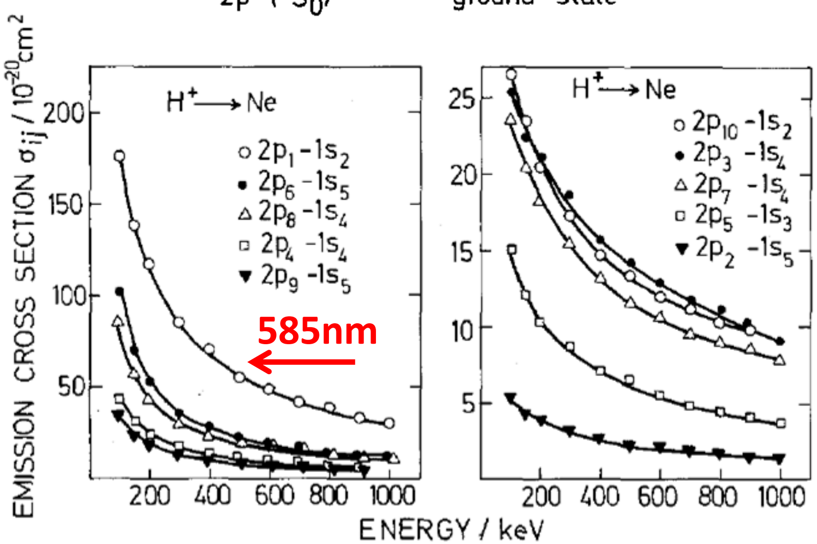
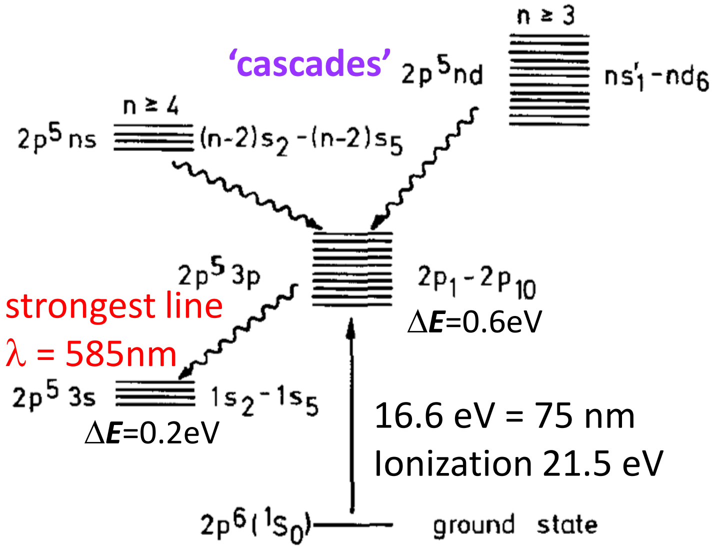


Fig. 4. Absolute emission cross sections for the ten levels of the neon $3p$ configuration as a function of proton impact energy

Decrease of cross section following Born approximation

Paper: M. Eckhardt et al., Proton impact on Neon for 0.1 to 1 MeV, Z. Physik A 292, 337 (1979)



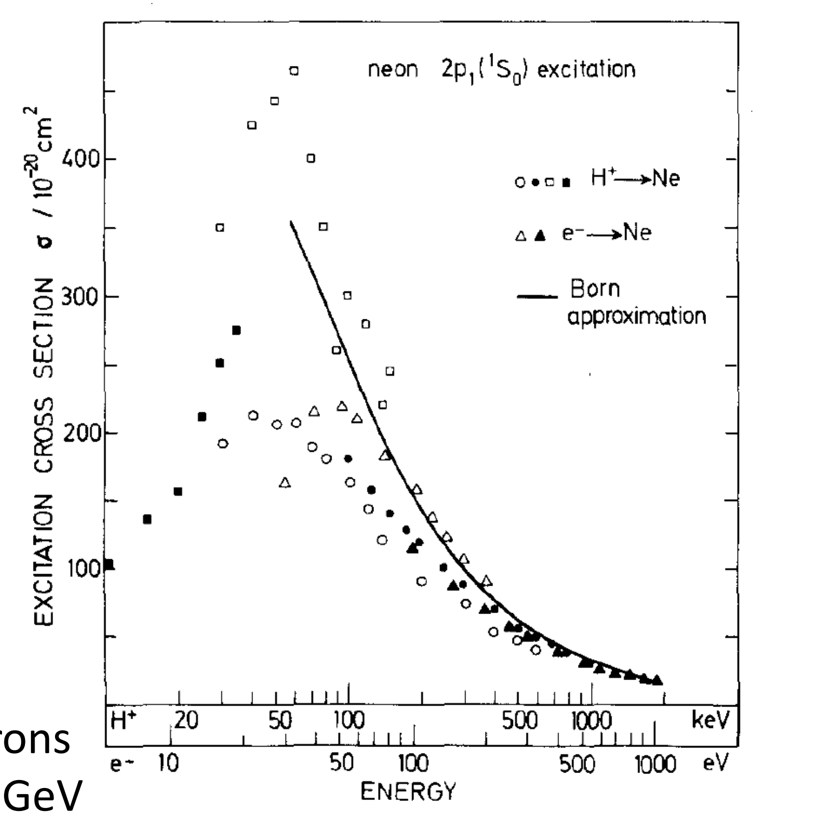


Fig. 6. Absolute excitation cross sections for the neon $2p_1(^1S_0)$ level. ●▲ present results, ○ Dufay et al. [3], △ Sharpton et al. [5], ■ de Heer et al. [1], □ York et al. [4] (sum of all ten $3p$ levels), —— Albat and Gruen [7]

Results for transition at λ = 585 nm:

- Experimental error $\Delta\sigma / \sigma$ = 35 %
- Pressure: $2x10^{-4}$ mbar ⇔ single collision
- High energies: Comparable σ for protons & electrons
  ⇒ 'principle of equal velocities': p@7TeV = e@3.8GeV
  ⇒ estimation by 'simple' Born approximation
  but extrapolation over 3 orders of magnitude
- Low cascade contributions, below 2 % (exp. error)
  ⇒ Lifetime of τ = 15 ns is relevant

Neon Spectra with Ion Impact

Result spectrum:

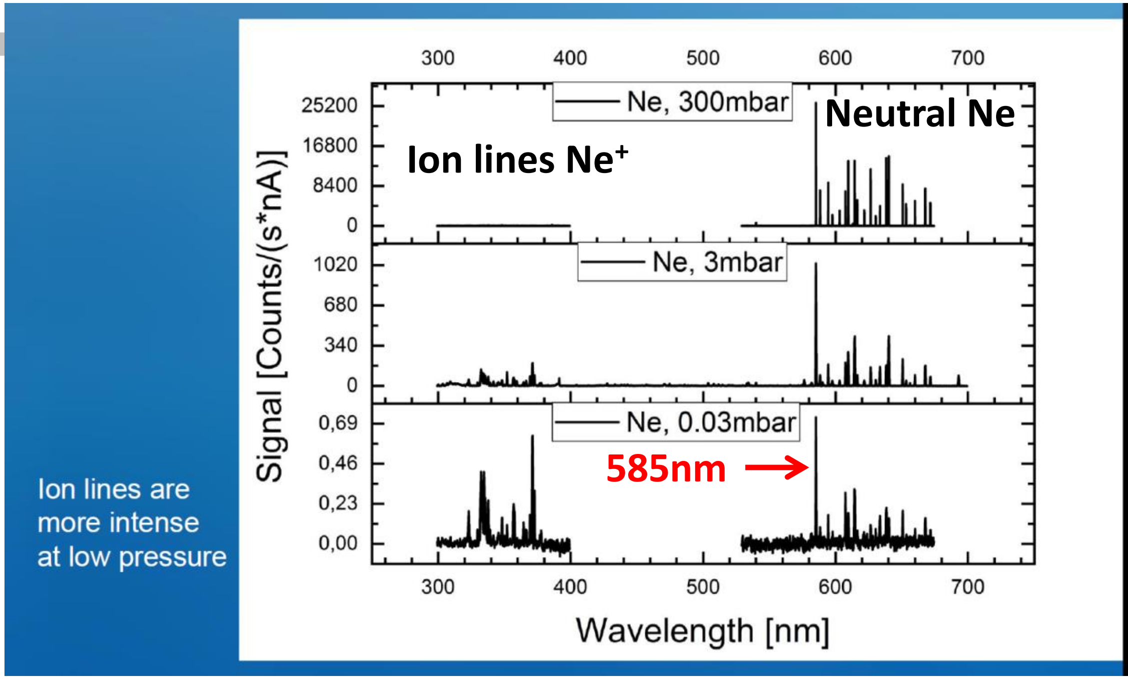
- Line position as expected from Serban's report
- Ratio ionic to neutral transitions depends on pressure (as expected)
- Ratio σ for ion-neutral changes
  Reason: Secondary electrons excite neutral atoms i.e.

$Ne + ion \rightarrow (Ne^{+})^{*} + e^{-} + ion$
$\rightarrow Ne^{+} + \gamma + e^{-} + ion$

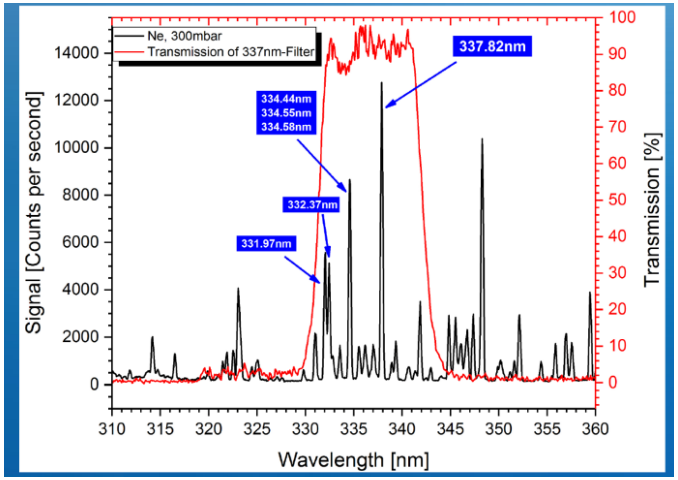
and

$Ne + e^{-} \rightarrow (Ne)^{*} + e^{-} \rightarrow Ne + \gamma + e^{-}$

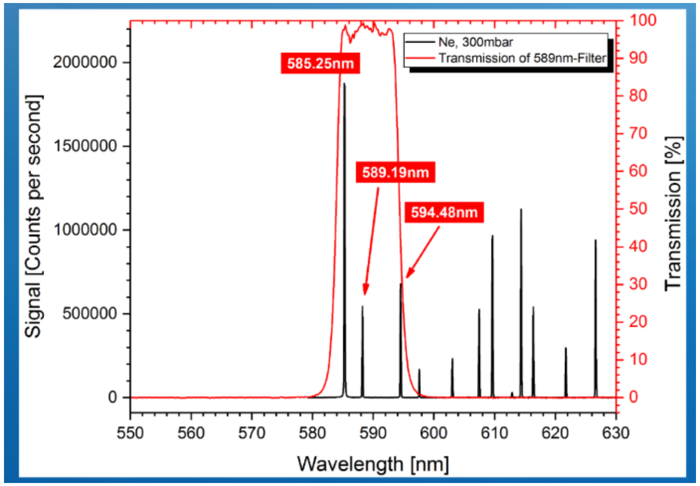
expected:
probability $\propto$ (pressure)^{2}
for high pressure



Ion lines Ne+



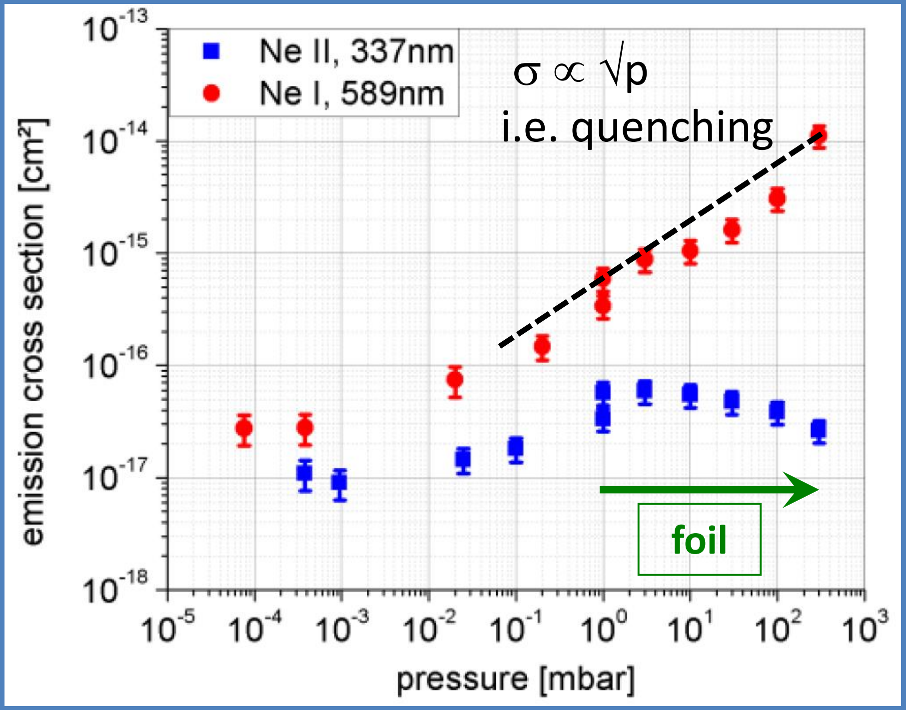
Neutral lines Ne



Neon Spectra with Sulfur Ion Impact at 3.1 MeV/u

Result for cross section:

- $\mathbf{Ne^+}$ **:** 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 $\Delta\sigma_{sys} = 50\ \%$



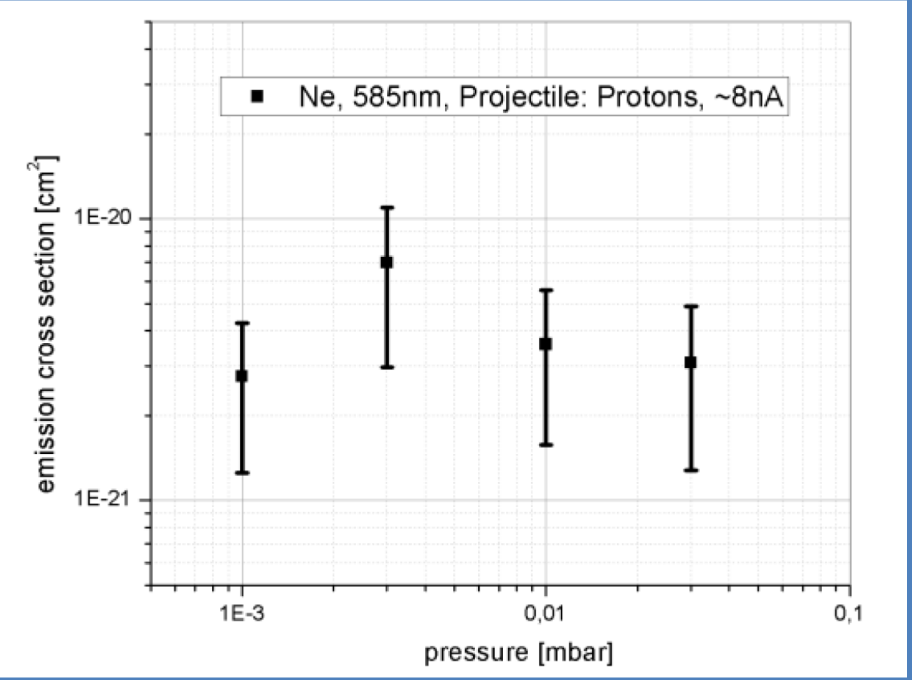
Estimation of cross section for neutral Ne:

- Sulfur $_{16}S^{8+}$ **no** Titanium foil
  $\sigma_S(2.7\text{MeV/u}) = 2.5 \cdot 10^{-17}\ \text{cm}^2$
- $dE/dx \propto q^2$ scaling with charge state $q = 8$ (Bethe-Bloch scaling)
  $\Rightarrow$ Proton $\sigma_p(2.7\text{MeV}) = \sigma_S(2.7\text{MeV/u}) / q^2 = 3.9 \cdot 10^{-19}\ \text{cm}^2$
- Energy loss from 2.7 MeV to 7 TeV by factor 0.03, but non Bethe-Bloch scaling for neutrals
  $\Rightarrow$ Bethe-Bloch scaling $\sigma_p(7\text{TeV}) = 0.03 \cdot \sigma_p(2.7\text{MeV}) = 1.2 \cdot 10^{-20}\ \text{cm}^2$
  $\Rightarrow$ Bethe-Born scaling $\sigma_p(7\text{TeV}) = 0.007 \cdot \sigma_p(2.7\text{MeV}) = 2.8 \cdot 10^{-21}\ \text{cm}^2$
- Serban's estimation: $\sigma_p(7\text{TeV}) = 4.7 \cdot 10^{-22}\ \text{cm}^2 \Rightarrow$ factor **6** too large (25 for B-Bloch)

Neon Spectra with Proton Impact at 14 MeV

Result for cross section:

- Ne & low pressure $\boldsymbol{p} < 10^{-3}$ mbar:
  $\boldsymbol{\sigma}$ is constant
  i.e. reflects beam profile
- Absolute systematic error $\Delta\boldsymbol{\sigma}_{sys} = 50\ \%$



Estimation of cross section for neutral Ne:

- Proton $\boldsymbol{\sigma}_p(14\text{MeV}) = 4 \cdot 10^{-21}$ cm²
- Energy loss from 14 MeV to 7 TeV by factor 0.1

  ⇒ Bethe-Bloch scaling $\boldsymbol{\sigma}_p(7\text{TeV}) = 0.1 \cdot \boldsymbol{\sigma}_p(14\text{MeV}) = 4.0 \cdot 10^{-22}$ cm²

  ⇒ Bethe-Born scaling $\boldsymbol{\sigma}_p(7\text{TeV}) = 0.06 \cdot \boldsymbol{\sigma}_p(14\text{MeV}) = 2.3 \cdot 10^{-22}$ cm²
- Serban's estimation $\sigma_p(7\text{TeV}) = 4.7 \cdot 10^{-22}$ cm² ⇒ factor 2 too small (1.1 for B-Bloch)
  (scaling from S^{8+} factor 6 too large)

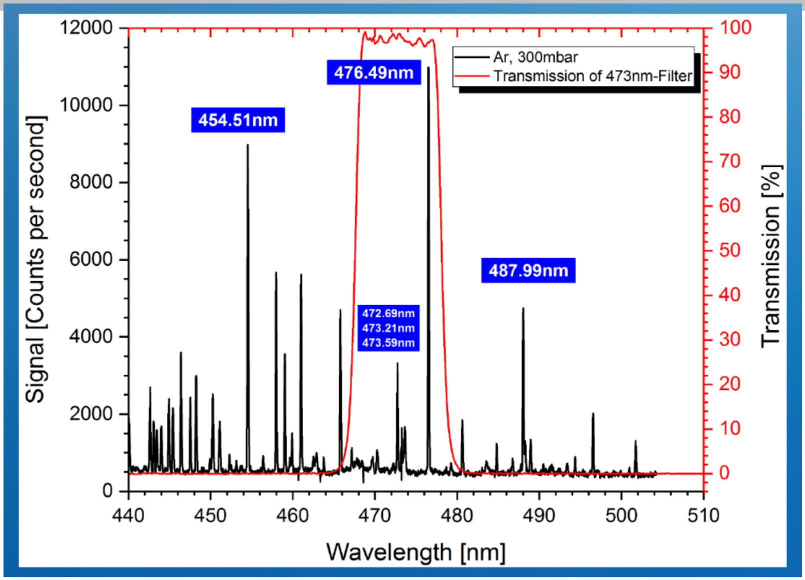
Argon Spectra with Ion Impact: Ionic Lines

Ionic transition:

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

- Wavelength λ = 400 ... 500 nm, lifetime $\tau \approx$ 10 ... 20 ns
- Cross section available up to 1 keV for e^- impact
- Might be populated by cascades, contribution ≈ 5%.
- Same upper level ⇒ shorter eff. lifetime, double σ

Initial $[3s^2 3p^4(^3P)]4p$	Final $[2s^2 2p^4(^3P)]4s$	λ [nm]	τ [ns]
$^2P^o_{3/2}$	$^2P_{3/2}$	454.5	21
$^2P^o_{3/2}$	**$^2P_{1/2}$**	**476.5**	**16**



Further remarks:

- Good wavelength range for image intensifier
- Larger signal for band λ = 440 .... 480 nm
- Low space charge influence due to short lifetime and large mass A = 40
- **But:** Cluster formation within jet **?**

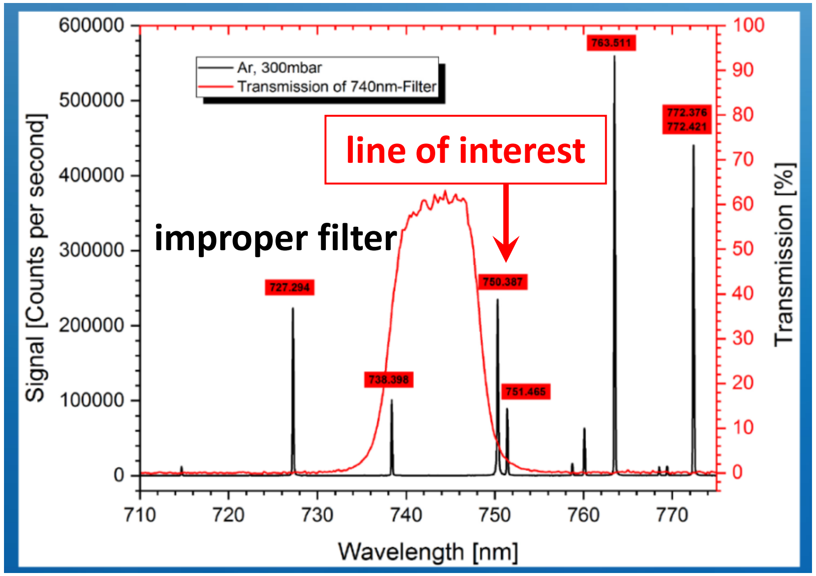
⇒ Could be good candidate if no clusters!

Argon Spectra with Ion Impact: Neutral Lines

Neutral transition:

Ar + p/e$^-$ → (Ar)* + p/e$^-$ → Ar + γ +p/e$^-$

- **Care**: Intensifier's photo cath. 2% sensitive, emCCD or sCMOS is better
- Cross section data available up to 1keV for e$^-$ impact
- Significant ≈ 25 % cascades



Initial $[3s^2 3p^5(^2P)]4p$	Final $[3s^2 3p^5(^2P)]4s$	λ [nm]	τ [ns]
$2p_1$	$1s_2$	750.4	22
$2p_5$	$1s_4$	751.5	25

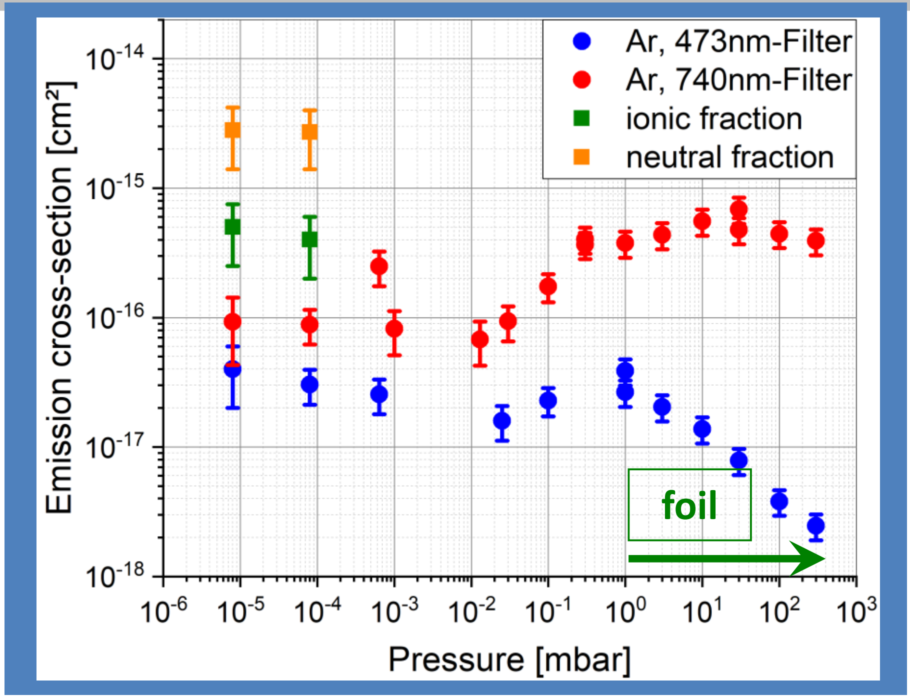
Further remarks:

- Used filter: Mainly transmitting line at λ = 738.4 nm
- Line λ = 738.4 nm, τ ≈ 118 ns: **no** estimation by Serban (concerning cross section, cascades)
- **But:** Bad wavelength range for image intensifier
- **But:** Cluster formation within jet **?**

Argon Spectra with Ion Impact: Cross Section

Result for cross section:

- More complex scaling as for Ne
- Ar & low pressure p < 10^{-3} mbar:
  constant cross section for Ar^+ and Ar



Estimation of cross section:

- **Neutral**: σ_S(2.7 MeV/u) = $9 \cdot 10^{-17}$ cm^2

  ⇒ Proton σ_p(2.7MeV/u) = σ_S(2.7MeV/u) / q^2 = $1.4 \cdot 10^{-18}$ cm^2

  ⇒ Bethe-Born scaling σ_p(7TeV) = 0.007 · σ_p(2.7MeV) = $1.0 \cdot 10^{-20}$ cm^2

  Serban's estimation: σ_p(7TeV) = $3.3 \cdot 10^{-22}$ cm^2 ⇒ factor 30 too large (but improper filter)

- **Ionic**: σ_S(3.1 MeV/u) = $2.2 \cdot 10^{-17}$ cm^2

  ⇒ Proton σ_p(3.1MeV) = σ_S(2.7MeV/u) / q^2 = $3.4 \cdot 10^{-19}$ cm^2

  ⇒ Bethe-Bloch scaling: σ_p(7TeV) = 0.03 · σ_p(2.7MeV/u) = $1.0 \cdot 10^{-20}$ cm^2

  Serban's estimation λ=476nm: σ_p(7TeV) = $1.0 \cdot 10^{-21}$ cm^2 ⇒ factor 10 too large

Nitrogen Molecule Spectra with Ion Impact: Cross Section

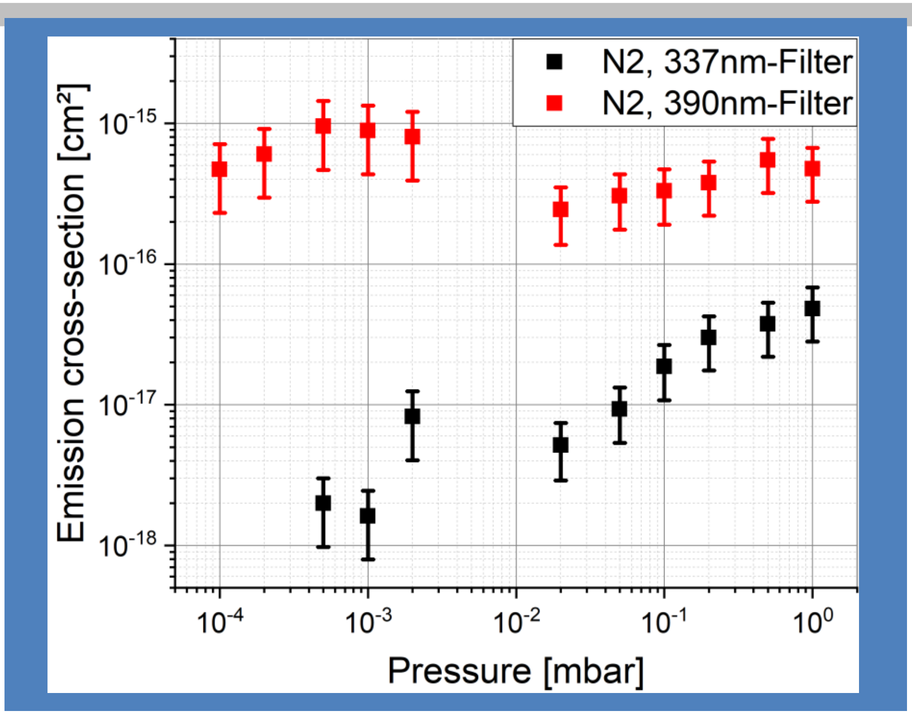
N_2 as working gas for process:

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)



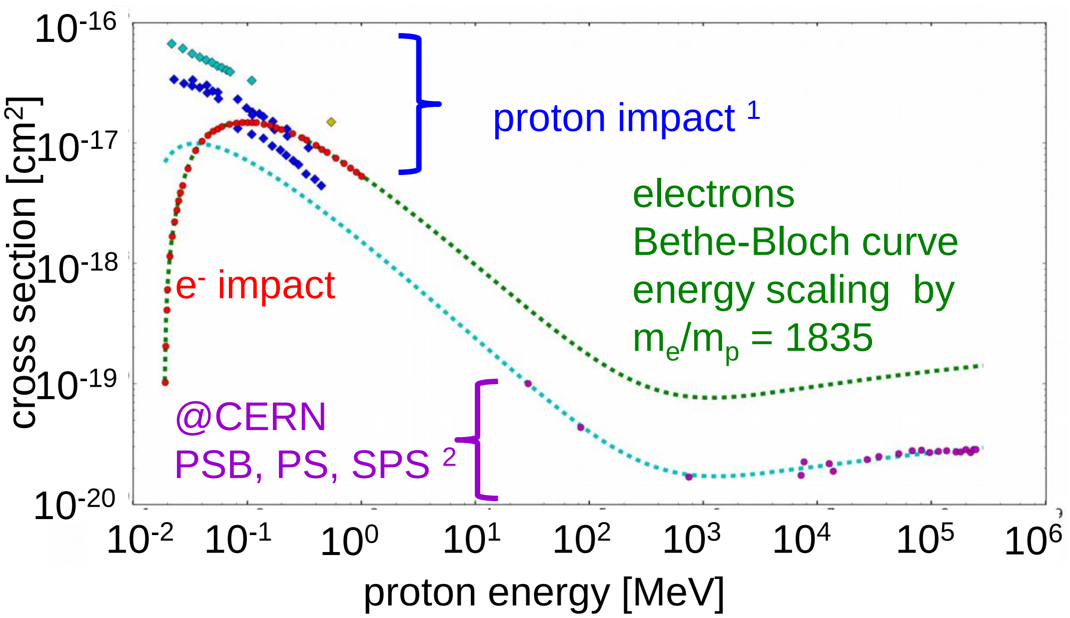
Estimation of cross section:

- **Ionic**: σ_S(2.7 MeV/u) = 4 · 10^{-16} cm²
  $\Rightarrow$ Proton σ_p(2.7MeV/u) = σ_S(2.7MeV/u) / q^2 = 6.3 · 10^{-18} cm²
  $\Rightarrow$ Bethe-Bloch scaling σ_p(7TeV) = 0.03 · σ_p(2.7MeV) = 1.8 · 10^{-19} cm²
  Serban's estimation: σ_p(7TeV) = 3.7·10^{-20} cm² $\Rightarrow$ factor 5 too large
- **Neutral**: Can't be excited by proton & ion impact!

Nitrogen: Energy Scaling for ionic Transition

N_2 as working gas for process:

- Cross section scaling according to Bethe-Bloch equation
- Good correspondence between electron and proton impact ⇔ principle of equal velocities
- Systematic deviation between low and high energy proton σ



[1] R.H. Hughes et al., Phys.Rev. 123, 1961
J.L. Philpot et al., Phys.Rev. 133, 1964
P..C. Sercal et al., NIMB 31, 1988
Y. Itikawa, J. Phys. Cem. Ref Data 6, 1997
R.F. Holland et al., Phys.Rev. 41, 1990

[2] M. Plum et al., NIMA 492, 2002
A. Variola et al.,
Phys.Rev Accel. Beams 11, 2007

Profile Distortions by secondary Electrons

First step: Ion beam generates residual gas ions & electrons:

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

$\rightarrow$ Ne^+ + γ + e^- + ion

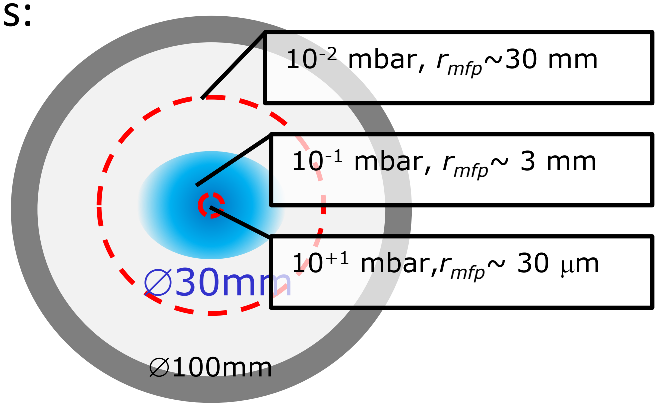
Second step: Electron excite gas followed by

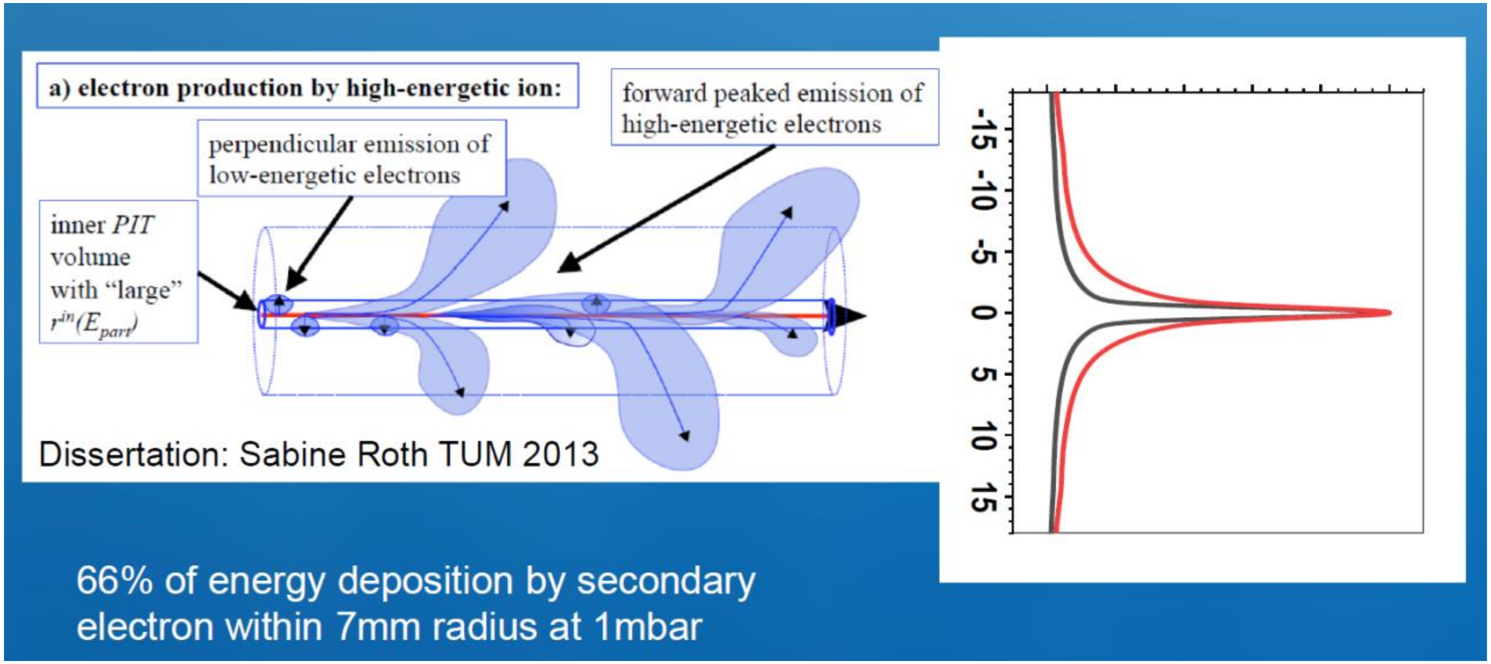
Ne + e^- $\rightarrow$ $(Ne)^*$ + e^- $\rightarrow$ Ne + γ + e^-

Expectation: Probability $\propto$ $(\text{pressure})^2$ for high pressure

Other parameterization: Mean free path

Large effect if $\boldsymbol{r_{mfp} \approx r_{chamber}}$ $\Leftrightarrow$ $\boldsymbol{p} \approx 10^{-2}$ mbar

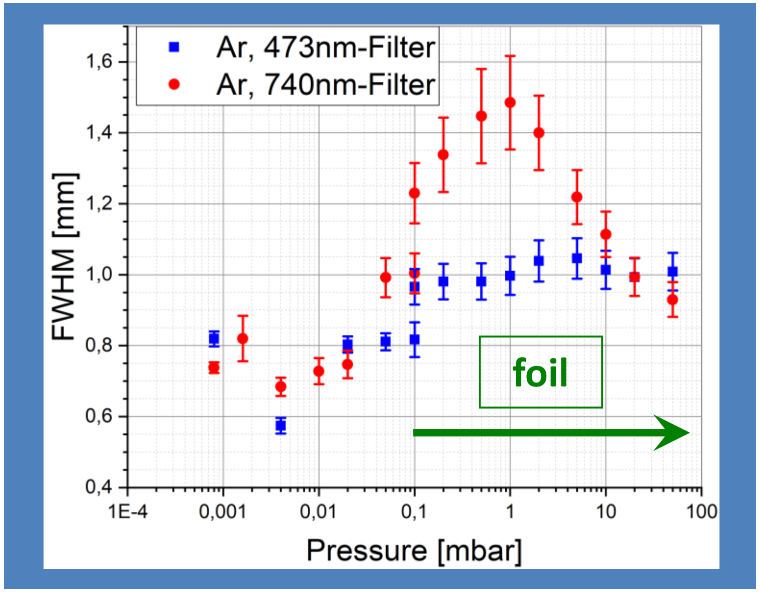


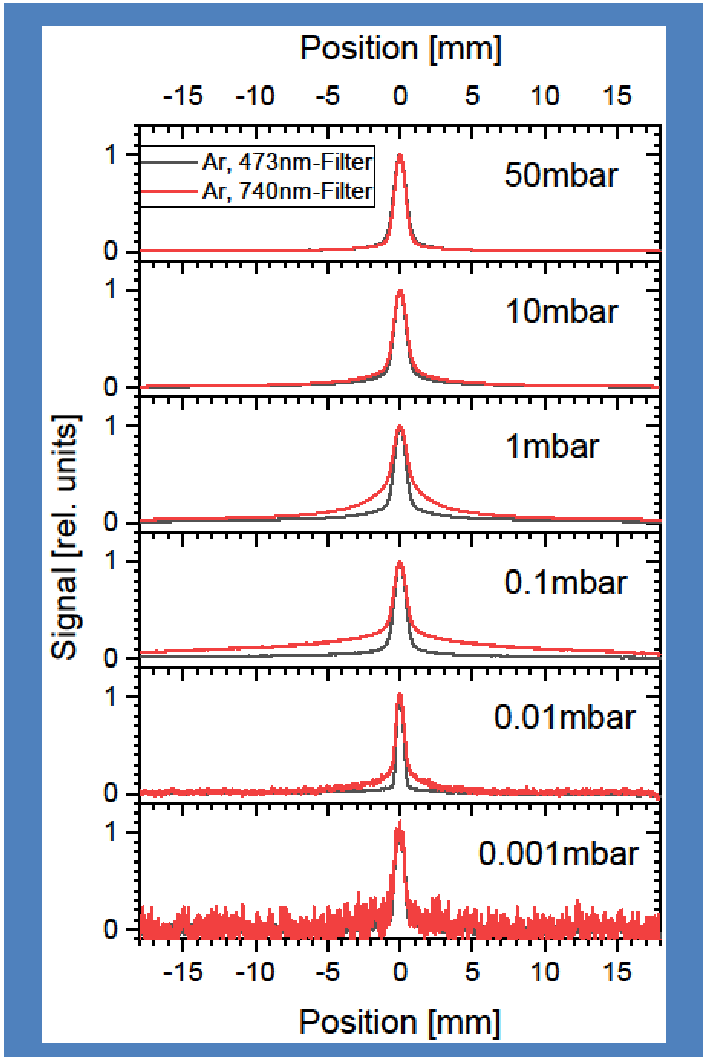


Profile Measurement with Argon

Results for profile reading:

- High pressure $\boldsymbol{p}$ > 10 mbar:
  Same profile for **Ar** & **Ar⁺** due to $r_{mfp} \ll r_{beam}$
- Medium pressure $\boldsymbol{p} \approx$ 10 mbar:
  Wider profile for Ne caused by sec. e^-
  due to $r_{mfp} \approx r_{beam}$
- Low pressure $\boldsymbol{p} < 10^{-3}$ mbar:
  Same profile for **Ar** & **Ar⁺** due to $r_{mfp} \ll r_{beam}$
- **Gas jet**: pressure $\boldsymbol{p} \ll 10^{-3}$ mbar $\Rightarrow$ correct reading





Profile Measurement with Neon and Nitrogen

Results for Neon:

- Same as for Argon: correct reading for $p < 10^{-3}$ mbar
- **Gas jet**: pressure $\boldsymbol{p} \ll 10^{-3}$ mbar $\Rightarrow$ correct reading

Older measurements for N_2 (executed by GSI):

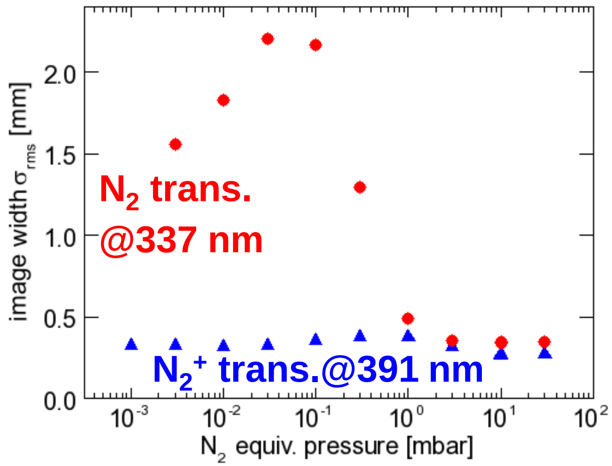
- **Ionic transitions λ=391 nm:**

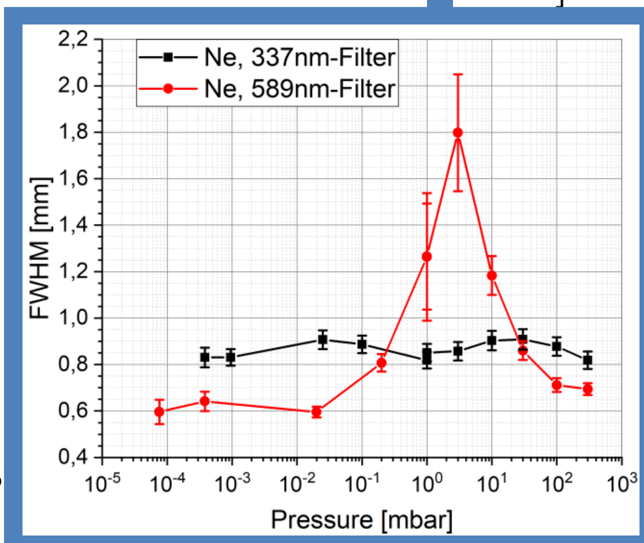
N_2 + ion$\rightarrow(N_2^+)^*$ +e^-+ ion$\rightarrow N_2^+$+ γ+e^- + ion

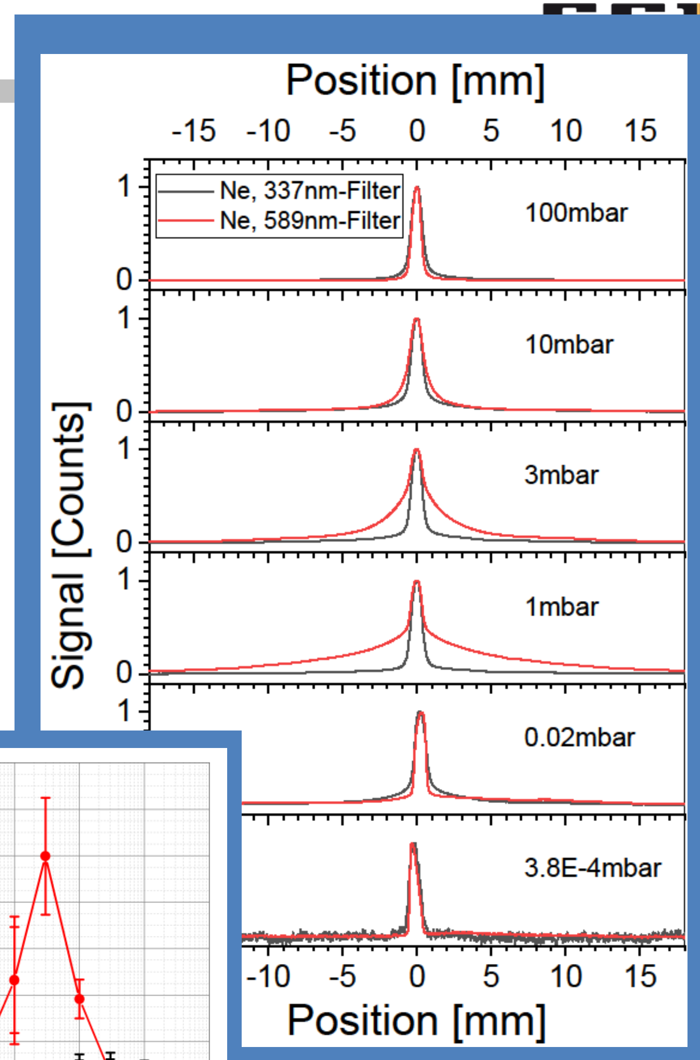
- **Neutral transitions λ=337 nm:**

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

large $\boldsymbol{\sigma}$ of e^- excitation, for ions spin forbidden







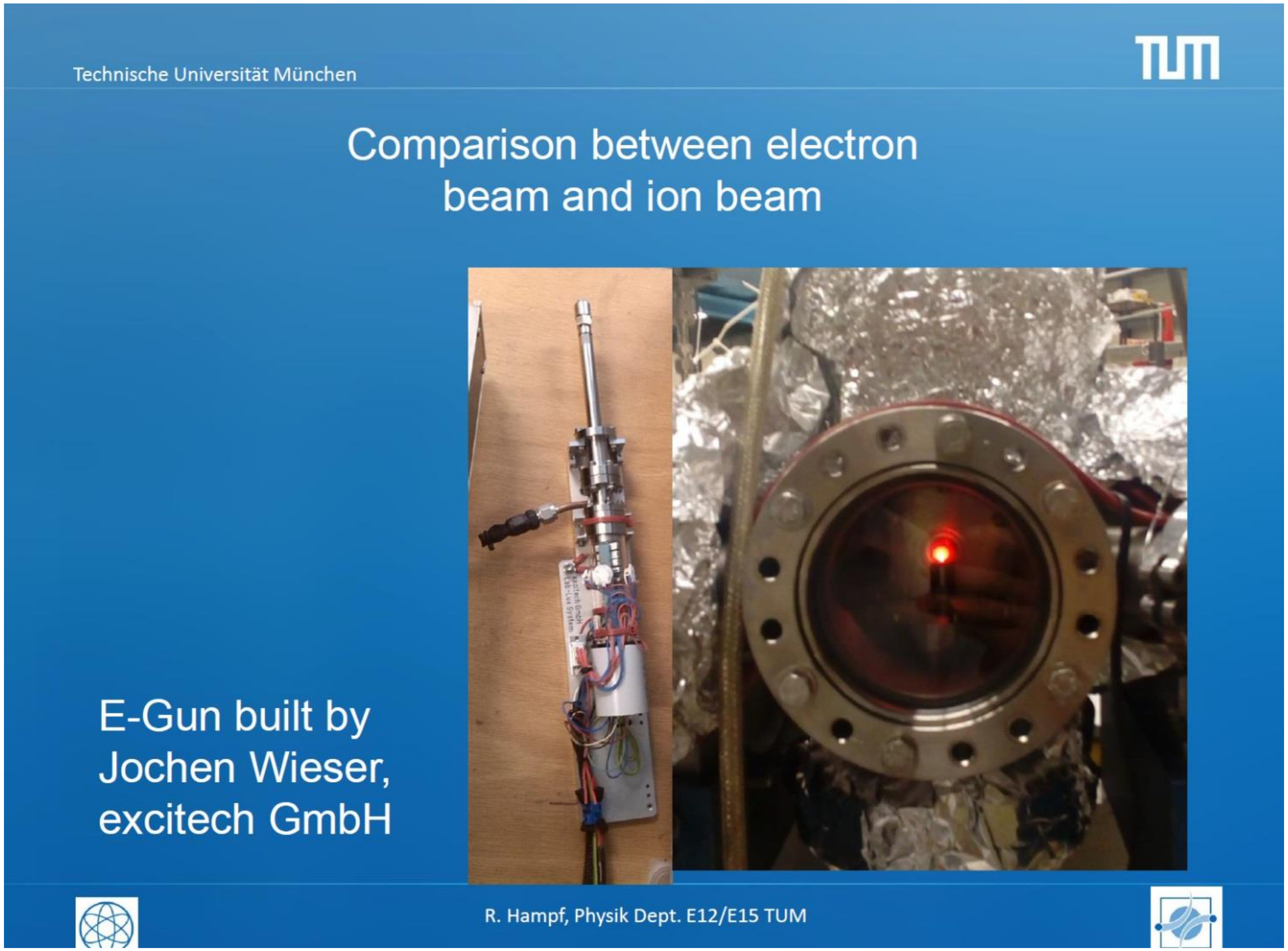
$\Rightarrow$ **Comparable for investigated gases**
maximum at $\boldsymbol{p} \approx$ 0.1...1 mbar

$\Rightarrow$ Concept of mean free path can be applied

Comparison of Electron and Ion Spectra

An electron gun installed in same chamber using the same spectrometer

Current measurement was not possible $\Rightarrow$ no absolute σ determined



Comparison Electrons to Ions for Neon

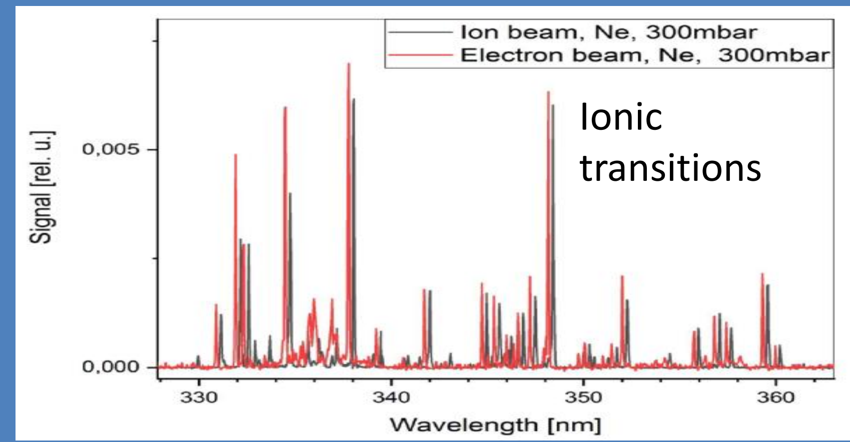
Neon spectra for electron – ion comparison:

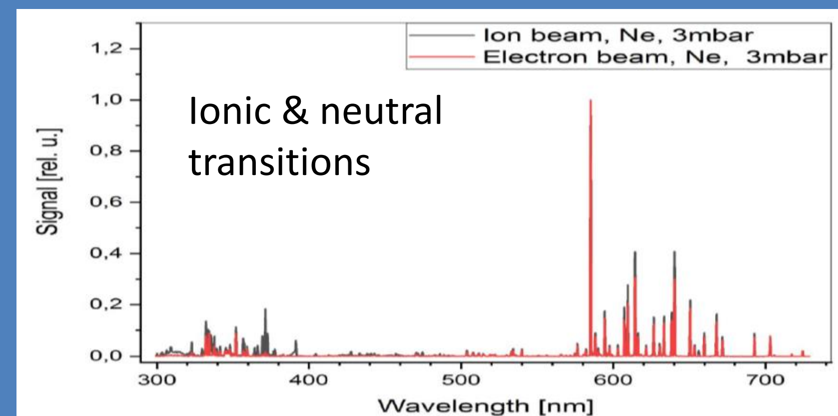
- **High pressure *p*** = 300 mbar
  comparable lines and relative strength
  explanation: Dominated by secondary electron excitation
- **Medium pressure *p*** = 3 mbar
  comparable for neutral lines
  some correspondence for ionic lines
- **Low pressure *p*** = 0.03 mbar
  comparable for neutral lines
  some correspondence for ionic lines

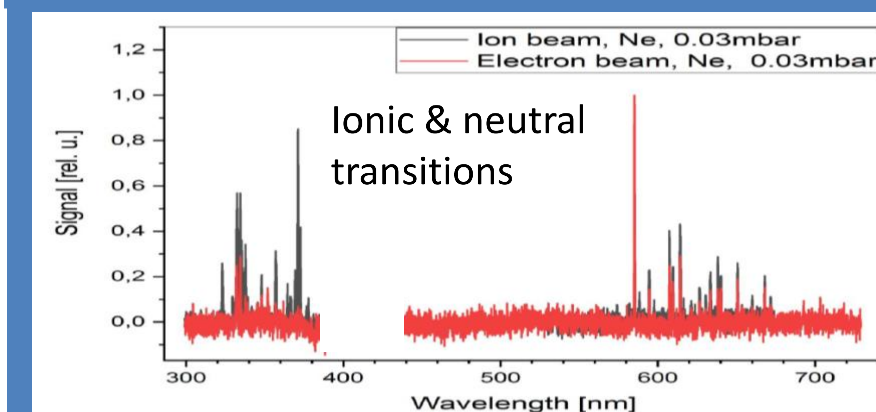
Result:

Neutral line: equally excited

Ionic lines: λ = 337 nm equally excited
λ = 371 nm not excited by electrons







Comparison Electrons to Ions for Neon

Neon spectra for electron – ion comparison:

Ionic lines:

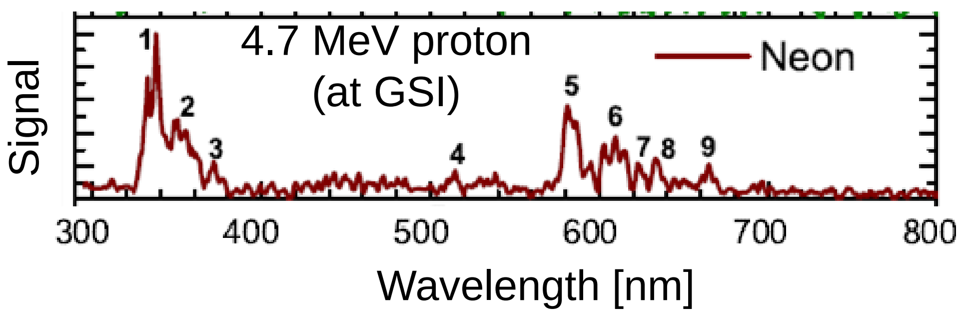
- Comparable for $\lambda = 337$ nm
- Excitation of $\lambda = 371.3$ nm

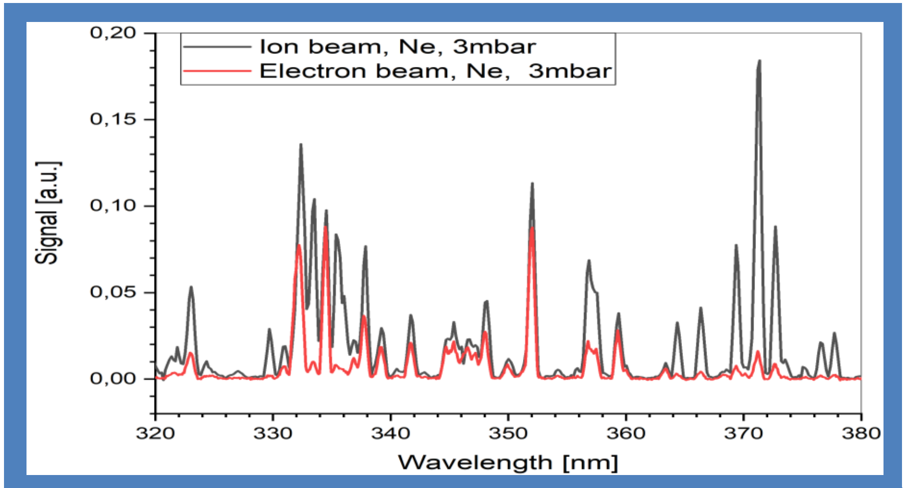
  only by Sulfur impact

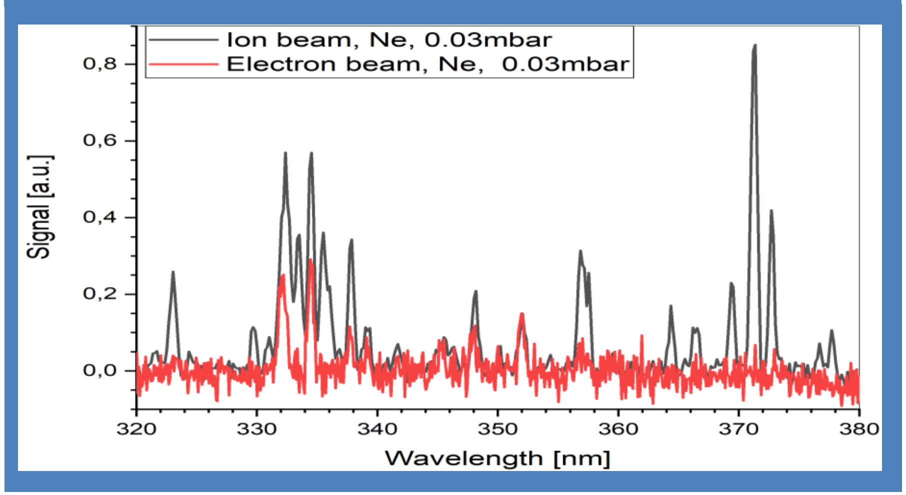
  (heavy ion due to inner shell electrons?)

  Less pronounced by proton impact

Reason unknown!







Remark:

Line $\lambda = 371.3$ nm, $\tau = 8$ ns

$2s^2 2p^4(^3P)3p\ ^2D^\circ\ ^5/_2 \rightarrow 2s^2 2p^4(^3P)3s\ ^2P\ ^3/_2$

i.e. not an exotic configuration

Summary

Relevant measurements at TU-München performed; results for **ion impact and low pressure**:

- For $p < 10^{-3}$ mbar correct beam profile measured i.e. no excitation by secondary electrons
- **Neutral transition** for **Ne** at 585 nm: cross section σ same order of magnitude as estimation
- **Ionic transition** for **Ne^+** at 337 nm: σ same order of magnitude as neutral, no estimation
- **Neutral transition** for **Ar** at 750 nm: significant different σ, but improper filter
- **Ionic transition** for **Ar^+** at 476 nm: σ factor of 6 too large
- **Ionic transition N_2^+** at 391 nm: σ factor of 5 too large

Electron impact: Same spectral lines for Ne excited, some differences for Ne^+, analysis ongoing

Gas	λ [nm]	τ [ns]	σ_p [10^{-21}cm^2] (estimated)	σ_p [10^{-21}cm^2] (TU München)	Factor	Remark
Ne	585	15	0.47	2.8 (S^{8+}) & 0.23 (p)	6 (S^{++}) & 0.5 (p)	
Ne^+	337	6	---	4.8	---	
Ar	750 & 751	30	0.33	10.	30	Improper filter
Ar^+	454 & 476	10	1.7	10.	6	
N_2^+	391	60	37.	180.	5	

Conclusion & Outlook

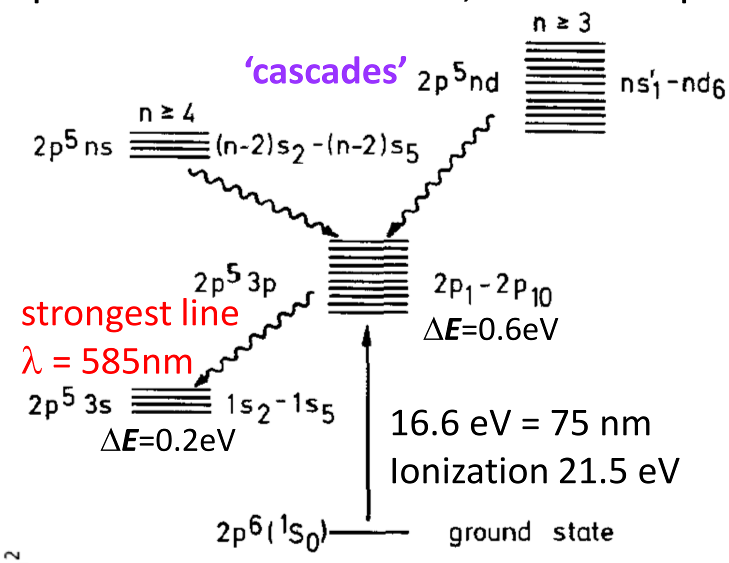
- **Neutral transition Ne** at 585 nm: low σ, no space charge (SC) effects
  $\Rightarrow$ gas jet density optimization required
- **Ionic transition Ne^+** at 337 nm: medium **,** good for image intensifier, medium SC effects ?
- **Neutral transition Ar** at 750 nm, medium σ, bad for image intensifier, emCCD required
  But: ≈ ≈ 25 % cascade transitions, **cluster build-up in gas jet** $\Rightarrow$ questionable
- **Ionic transition** for **Ar^+** at 476 nm: medium σ, good for image intensifier, low SC effects ?
  But: 5 % cascade transitions i.e. enlarged lifetime, clusters
- **Ionic transition N_2^+** at 391 nm: high σ, larger SC effects, bad for vacuum pumping
- **Electron impact**: comparable spectral lines (as expected)

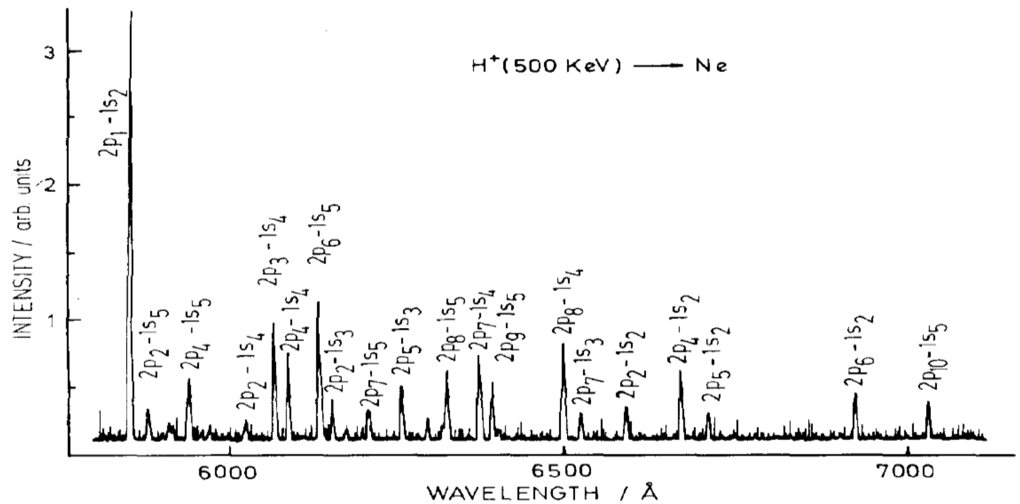
Gas	λ [nm]	τ [ns]	σ_p [10^{-21}cm^2] (estimated)	σ_p [10^{-21}cm^2] (TU München)	Pros	Cons
Ne	585	15	0.47	2.8 (S^{8+}) & 0.23 (p)	No SC	Low σ
Ne^+	337	6	---	4.8	Low SC (?)	Medium σ
Ar	750 & 751	30	0.33	10.	No SC	Casc., cluster, only emCCD
Ar^+	454 & 476	10	1.7	10.	Low SC	Cluster
N_2^+	391	60	37.	180.	Large σ	Vacuum, large SC

Backup slides

Atomic Physics for Proton Impact on Neon: Neutral Transition xxxx

Paper: M. Eckhardt et al., Proton impact on Neon for 0.1 to 1 MeV, Z. Physik A 292, 337 (1979)





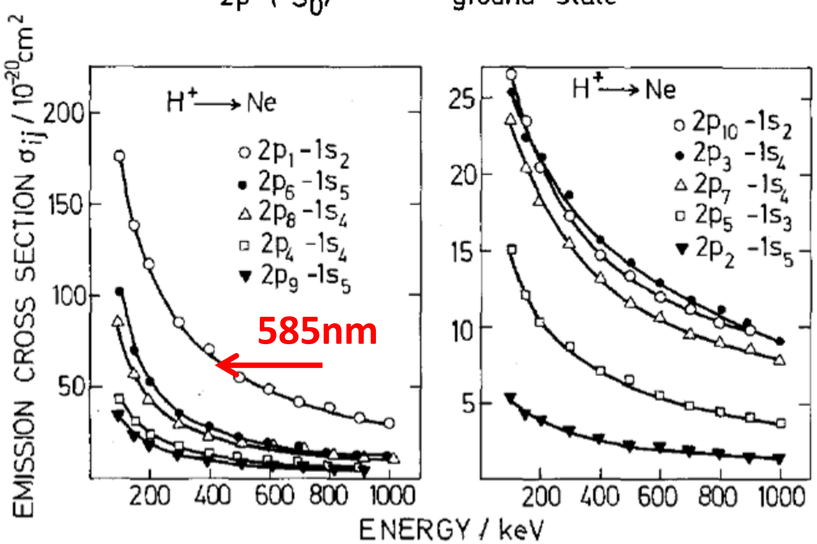


Fig. 4. Absolute emission cross sections for the ten levels of the neon $3p$ configuration as a function of proton impact energy

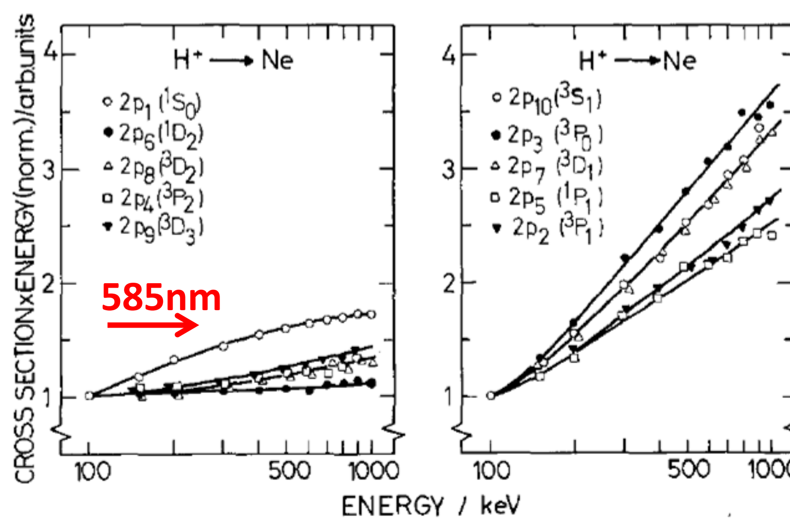
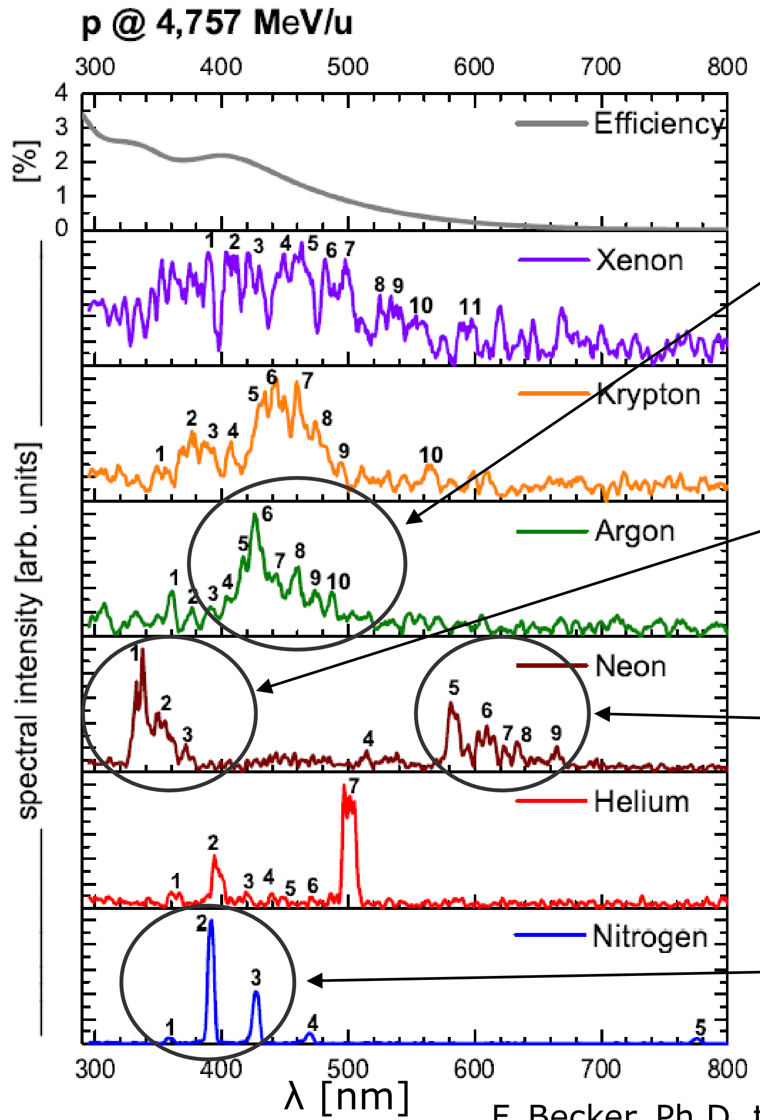


Fig. 5. Normalized Bethe-Fano-plots ($\sigma \times E = f(\ln E)$) for the dipole forbidden excitation of the ten neon $3p$ levels by proton impact

Fluorescence of different gases



Strongest emission from Ar^+ blue/green lines mainly corresponding to different $[3s^2 3p^4(^3P)]4p \rightarrow 4s$ transitions with life times of 10-20 ns.

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

Several Ne yellow/red lines mainly corresponding to different $[2s^2 2p^5(^2P)]3p \rightarrow 3s$ transitions with life times of about 20 ns.

The strong UV/blue 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.

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