university of groningen / faculty of science and engineering

Optimization of MR ToF MS ion beam optics for the NEXT project

Physics Bachelor project

Supervisor: J. Even

Author: Tudor Stefan (S4326091)

Daily supervisor: M. Brajković

2nd examiner: L. Willmann

Introduction

Nuclear mass measurements → **Nuclear structure**

W. N. Cottingham and D. A. Greenwood, An Introduction to Nuclear Physics, 2nd ed. Cambridge University Press, 2001

Introduction

Nuclear mass measurements → **Nuclear structure**

$$m_{nucleus}(Z,N)c^2 = Zm_pc^2 + Nm_nc^2 - B(Z,N)$$

$c =$ Speed of light in vacuum

$Z =$ Proton number

$N =$ Neutron number

$m_p =$ Proton mass

$m_n =$ Neutron mass

W. N. Cottingham and D. A. Greenwood, An Introduction to Nuclear Physics, 2nd ed. Cambridge University Press, 2001

Introduction

Nuclear mass measurements → **Nuclear structure**

$$\boxed{m_{nucleus}(Z,N)c^2} = Zm_pc^2 + Nm_nc^2 - B(Z,N)$$

$c =$ Speed of light in vacuum

$Z =$ Proton number

$N =$ Neutron number

$m_p =$ Proton mass

$m_n =$ Neutron mass

W. N. Cottingham and D. A. Greenwood, An Introduction to Nuclear Physics, 2nd ed. Cambridge University Press, 2001

Introduction

university of groningen / faculty of science and engineering

Nuclear mass measurements → **Nuclear structure**

$$m_{nucleus}(Z,N)c^2 = Zm_pc^2 + Nm_nc^2 - B(Z,N)$$

$B(Z,N)$ → **Binding energies**

$c =$ Speed of light in vacuum

$Z =$ Proton number

$N =$ Neutron number

$m_p =$ Proton mass

$m_n =$ Neutron mass

W. N. Cottingham and D. A. Greenwood, An Introduction to Nuclear Physics, 2nd ed. Cambridge University Press, 2001

Introduction

Nuclear mass measurements → **Nuclear structure**

$$m_{nucleus}(Z,N)c^2 = Zm_pc^2 + Nm_nc^2 - B(Z,N)$$

$B(Z,N)$ → **Binding energies** → **Nuclear structure**

$c =$ Speed of light in vacuum

$Z =$ Proton number

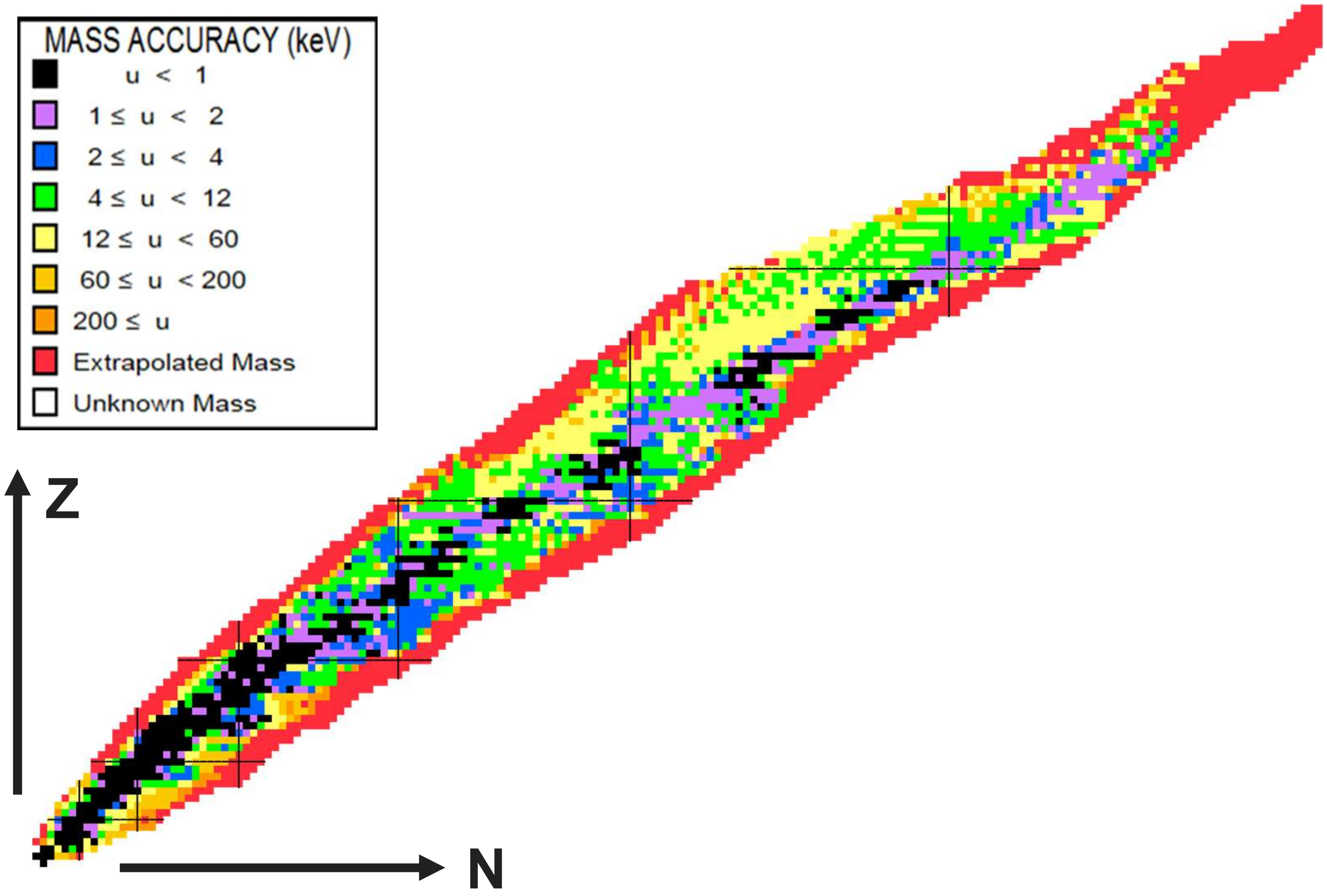
$N =$ Neutron number

$m_p =$ Proton mass

$m_n =$ Neutron mass

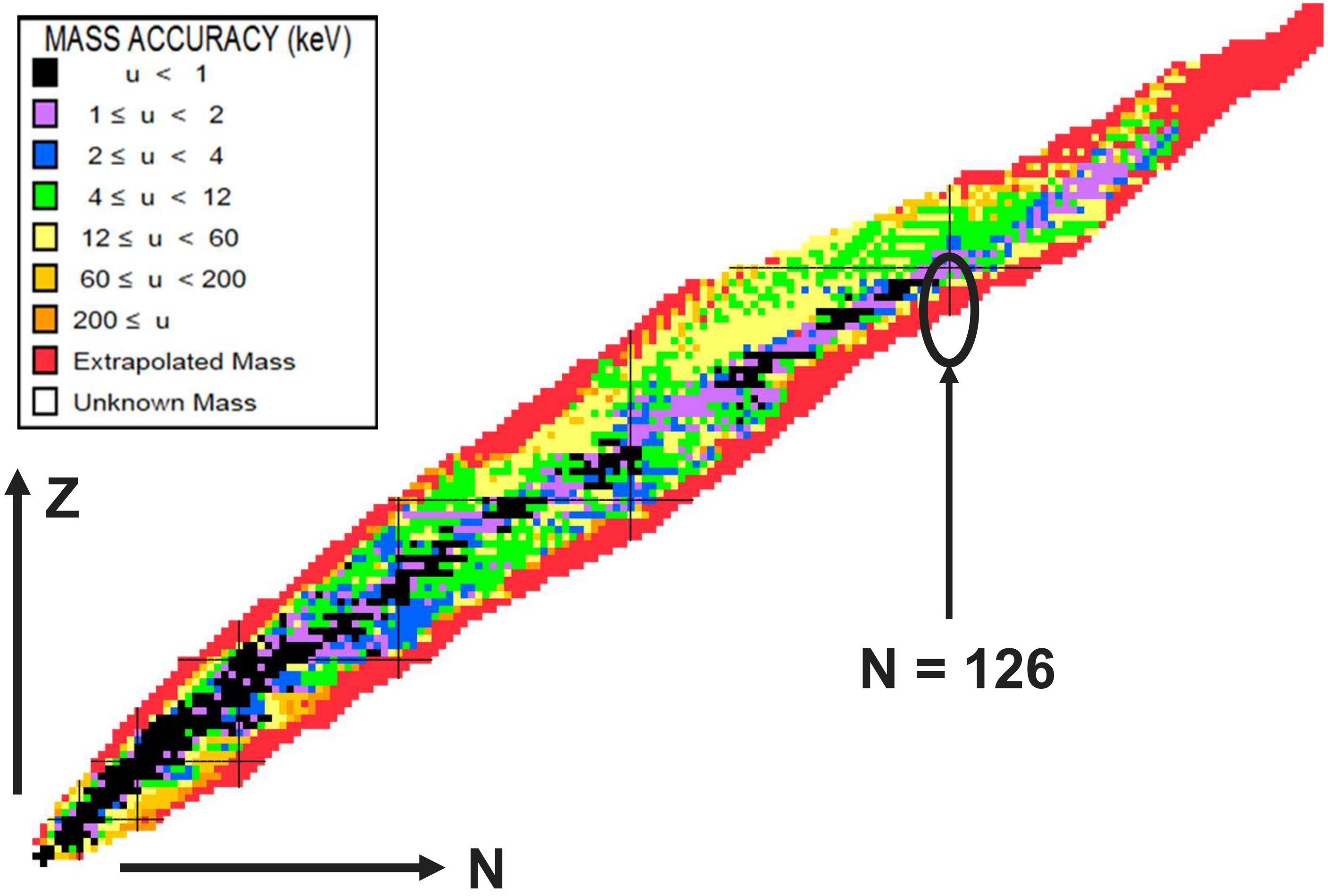
W. N. Cottingham and D. A. Greenwood, An Introduction to Nuclear Physics, 2nd ed. Cambridge University Press, 2001

Introduction



M. Wang, et al., “The ame 2020 atomic mass evaluation (ii). tables, graphs and references*,” Chinese Physics C, vol. 45, no. 3, p. 030 003, Mar. 2021.
J. Even, et al., “The next project: Towards production and investigation of neutron-rich heavy nuclides,” Atoms, vol. 10, no. 2, 2022.

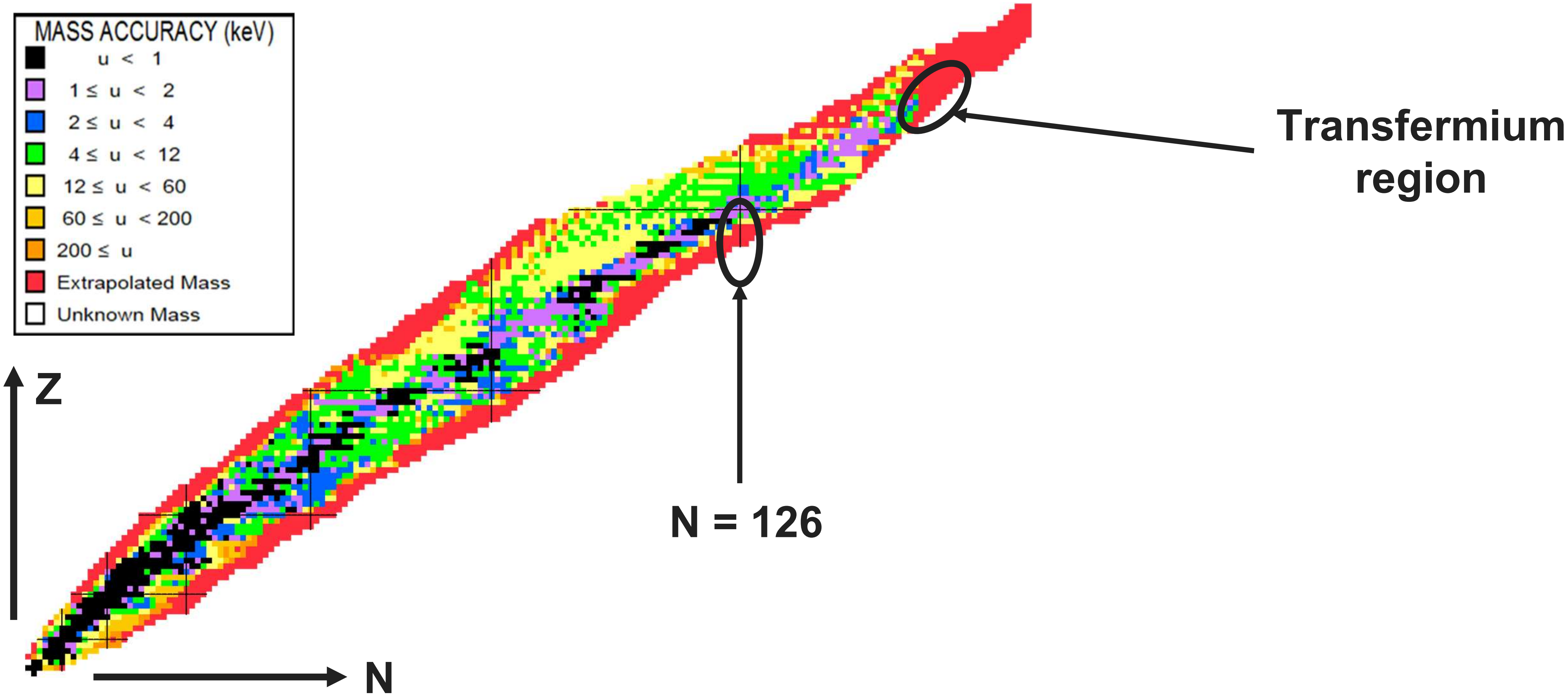
Introduction



M. Wang, et al., “The ame 2020 atomic mass evaluation (ii). tables, graphs and references*,” Chinese Physics C, vol. 45, no. 3, p. 030 003, Mar. 2021.
J. Even, et al., “The next project: Towards production and investigation of neutron-rich heavy nuclides,” Atoms, vol. 10, no. 2, 2022.

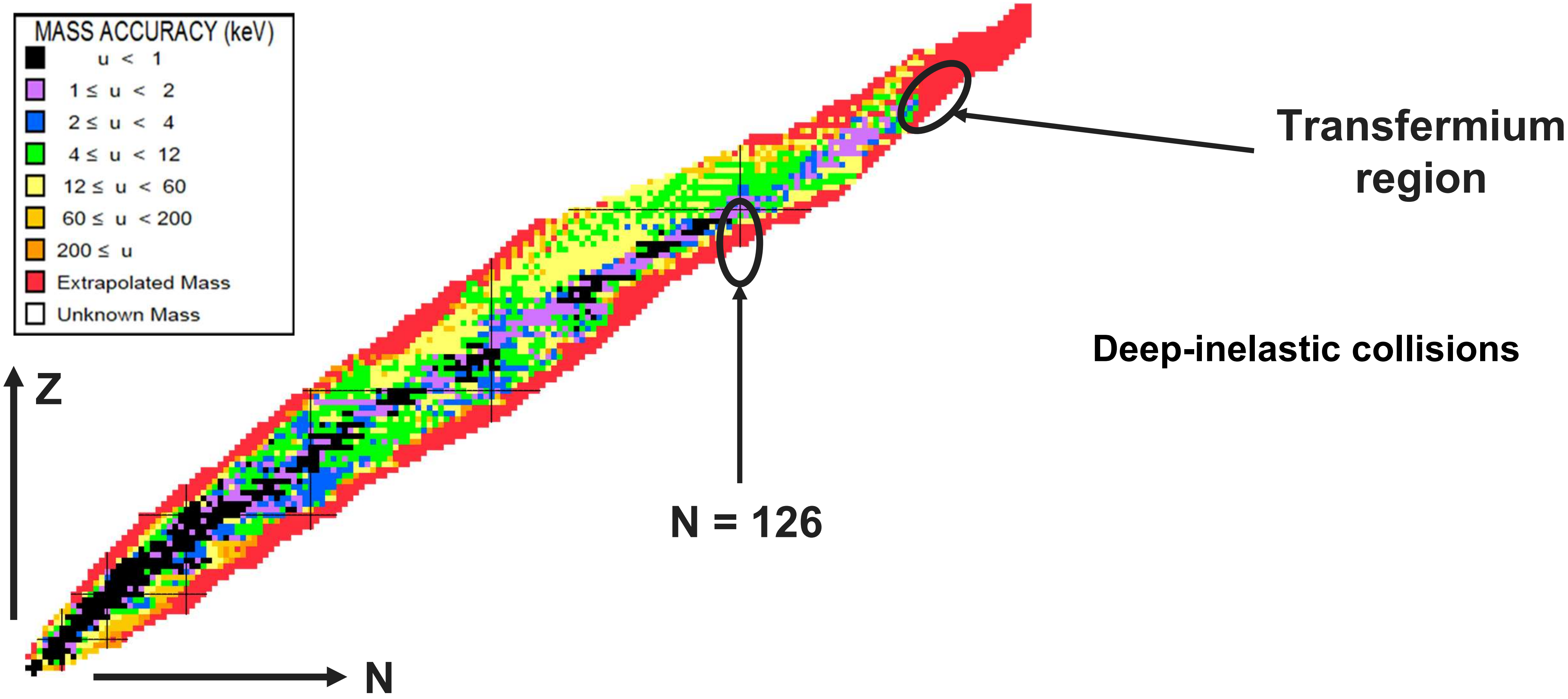
Introduction

university of groningen / faculty of science and engineering



M. Wang, et al., “The ame 2020 atomic mass evaluation (ii). tables, graphs and references*,” Chinese Physics C, vol. 45, no. 3, p. 030 003, Mar. 2021.
J. Even, et al., “The next project: Towards production and investigation of neutron-rich heavy nuclides,” Atoms, vol. 10, no. 2, 2022.

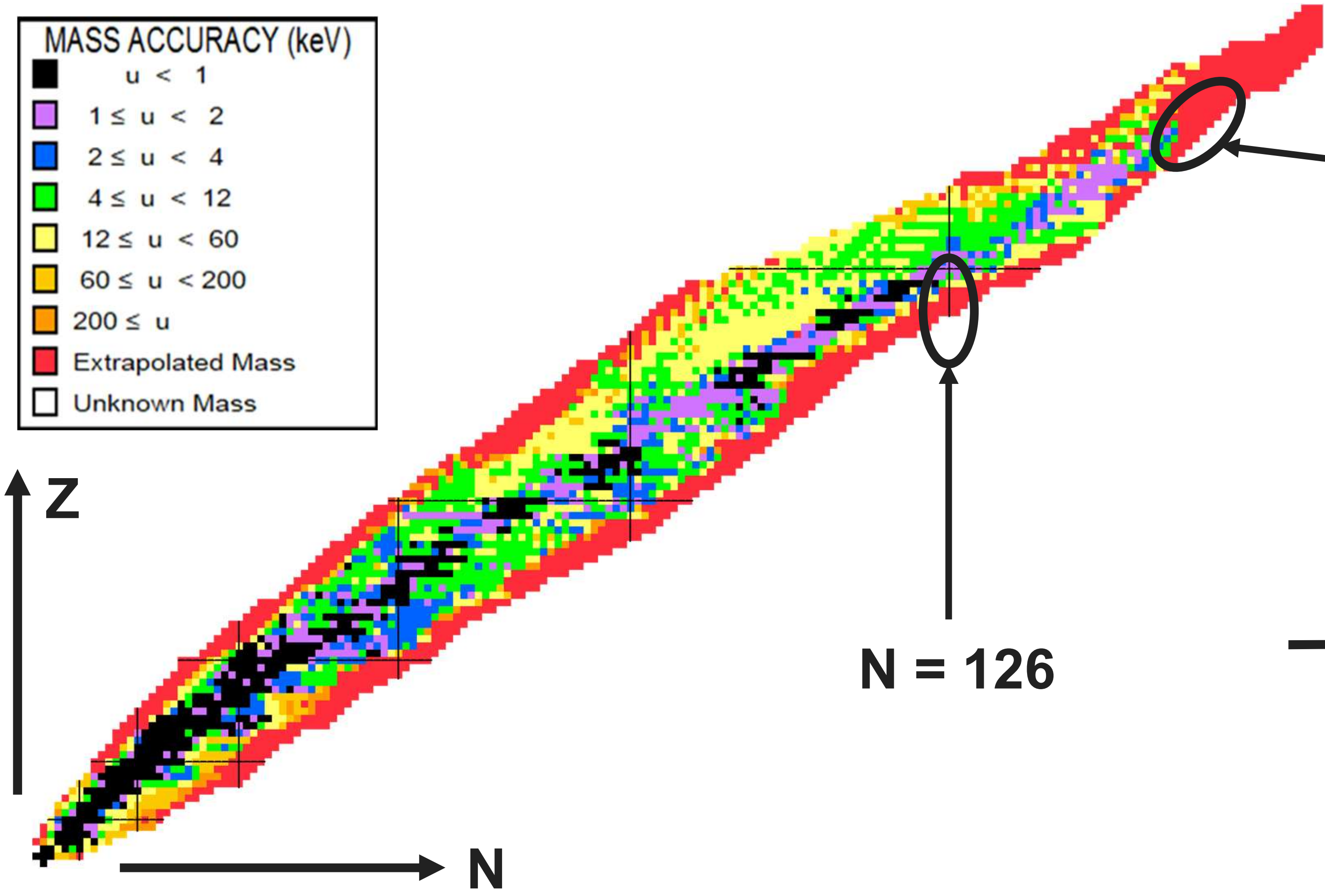
Introduction

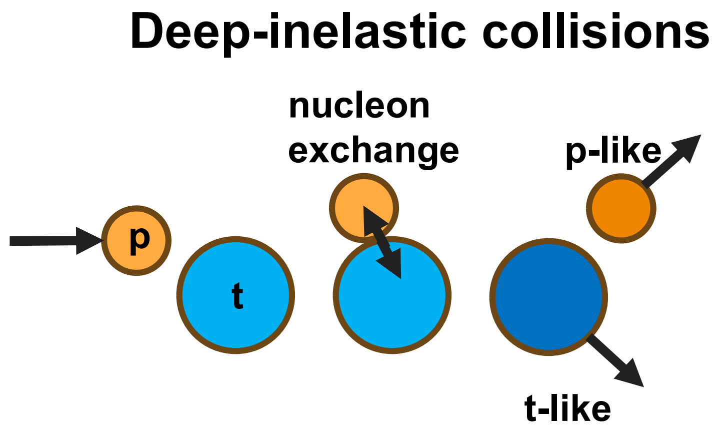


Deep-inelastic collisions

M. Wang, et al., “The ame 2020 atomic mass evaluation (ii). tables, graphs and references*,” Chinese Physics C, vol. 45, no. 3, p. 030 003, Mar. 2021.
J. Even, et al., “The next project: Towards production and investigation of neutron-rich heavy nuclides,” Atoms, vol. 10, no. 2, 2022.

Introduction

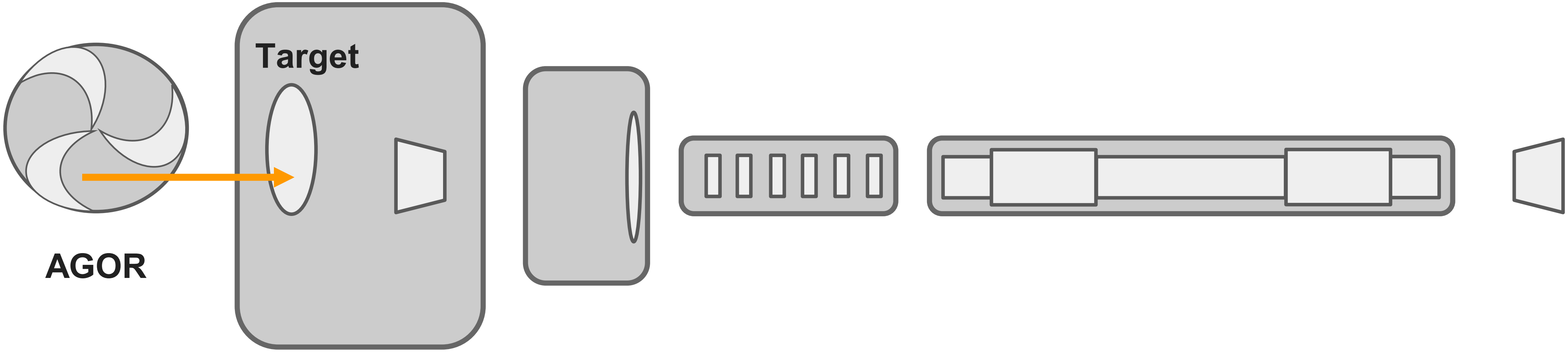




M. Wang, et al., “The ame 2020 atomic mass evaluation (ii). tables, graphs and references*,” Chinese Physics C, vol. 45, no. 3, p. 030 003, Mar. 2021.
J. Even, et al., “The next project: Towards production and investigation of neutron-rich heavy nuclides,” Atoms, vol. 10, no. 2, 2022.

Introduction

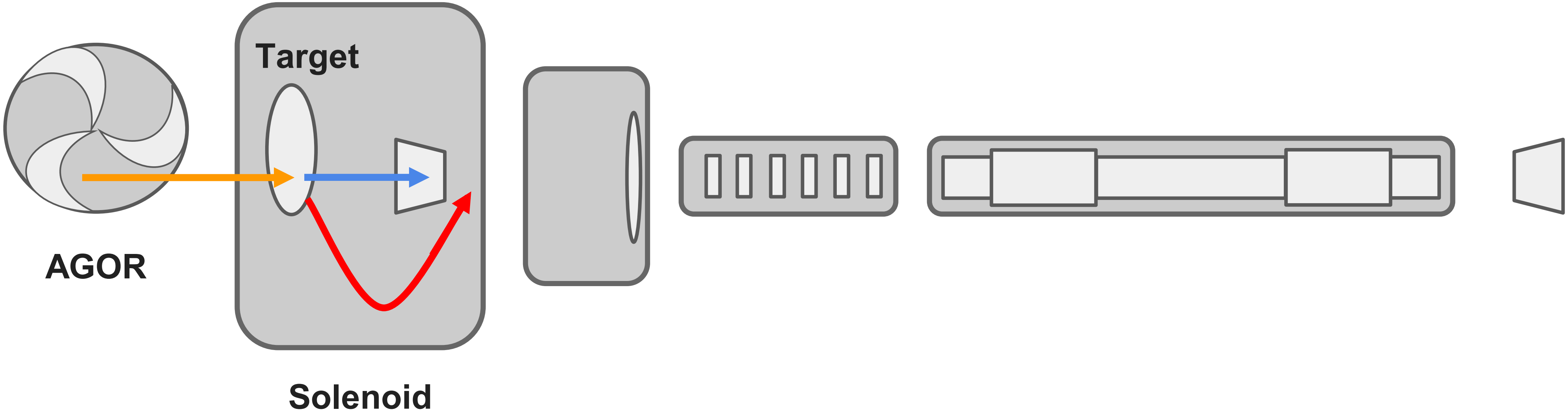
The Neutron-rich EXotic nuclei production in multi-nucleon Transfer reactions project - NEXT



J. Even, et al., “The next project: Towards production and investigation of neutron-rich heavy nuclides,” Atoms, vol. 10, no. 2, 2022.

Introduction

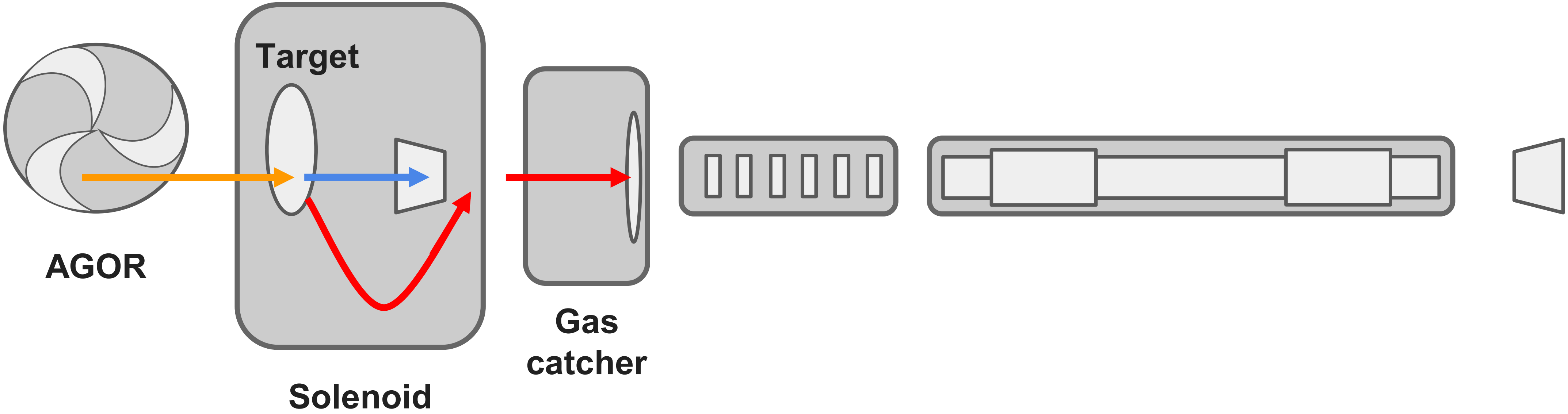
The Neutron-rich EXotic nuclei production in multi-nucleon Transfer reactions project - NEXT



J. Even, et al., “The next project: Towards production and investigation of neutron-rich heavy nuclides,” Atoms, vol. 10, no. 2, 2022.

Introduction

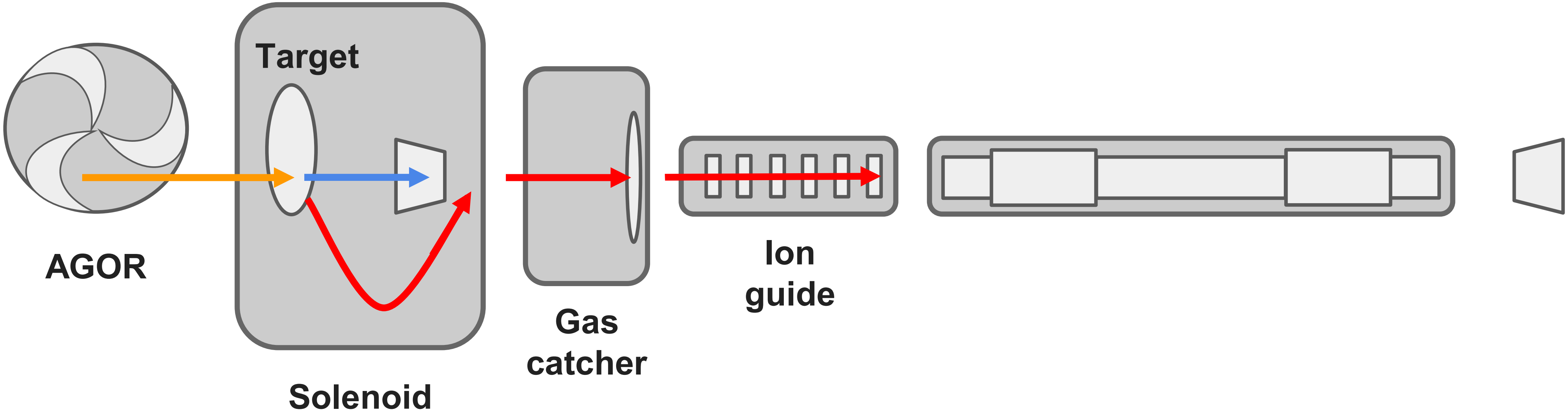
The **N**eutron-rich **EX**otic nuclei production in multi-nucleon **T**ransfer reactions project - NEXT



J. Even, et al., "The next project: Towards production and investigation of neutron-rich heavy nuclides," Atoms, vol. 10, no. 2, 2022.

Introduction

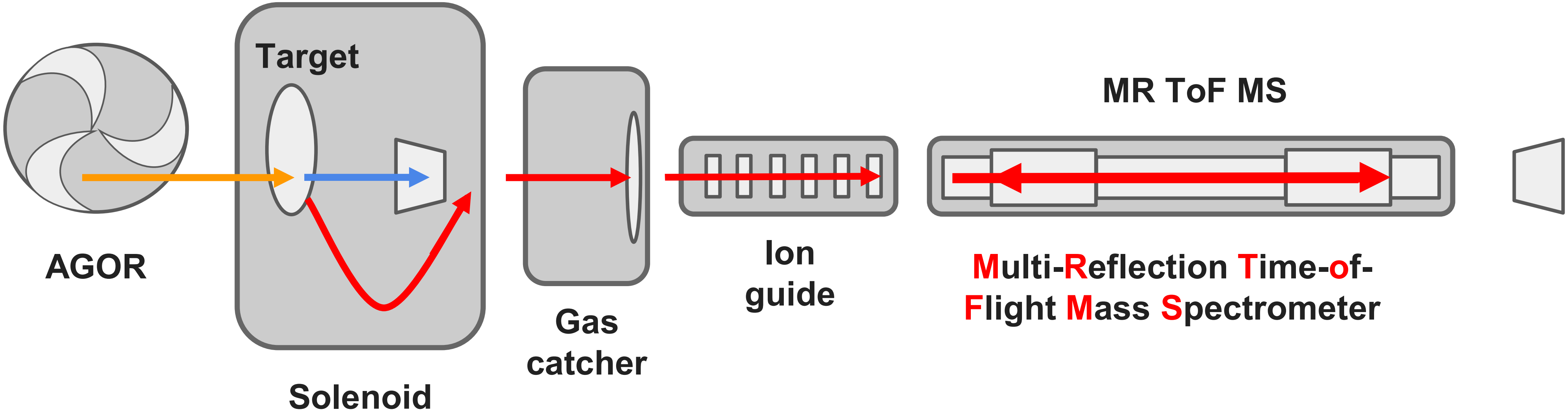
The Neutron-rich EXotic nuclei production in multi-nucleon Transfer reactions project - NEXT



J. Even, et al., "The next project: Towards production and investigation of neutron-rich heavy nuclides," Atoms, vol. 10, no. 2, 2022.

Introduction

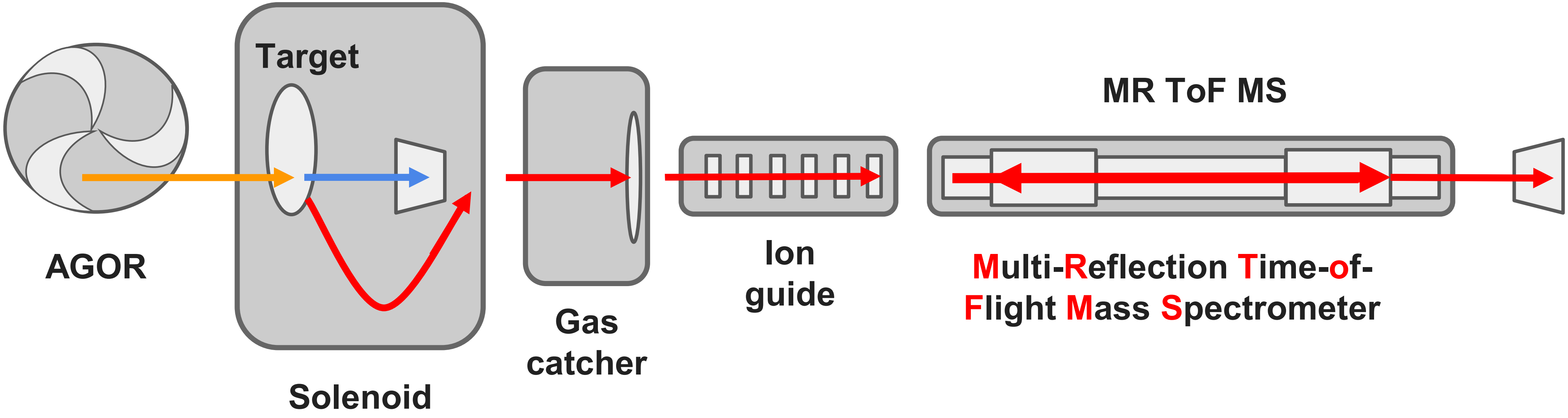
The Neutron-rich EXotic nuclei production in multi-nucleon Transfer reactions project - NEXT



J. Even, et al., “The next project: Towards production and investigation of neutron-rich heavy nuclides,” Atoms, vol. 10, no. 2, 2022.

Introduction

The Neutron-rich EXotic nuclei production in multi-nucleon Transfer reactions project - NEXT

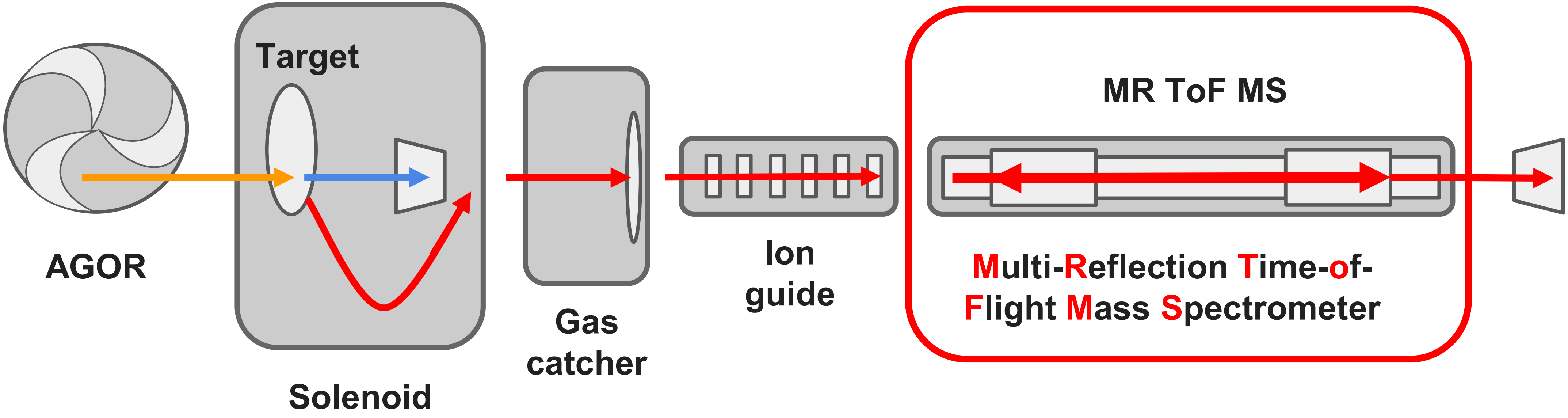


J. Even, et al., "The next project: Towards production and investigation of neutron-rich heavy nuclides," Atoms, vol. 10, no. 2, 2022.

Introduction

university of groningen / faculty of science and engineering

The Neutron-rich EXotic nuclei production in multi-nucleon Transfer reactions project - NEXT



J. Even, et al., “The next project: Towards production and investigation of neutron-rich heavy nuclides,” Atoms, vol. 10, no. 2, 2022.

Introduction

Experimental goals:

Off-line optimization of MR ToF MS ion beam optics

How & what:

Electrode voltage calibration

Setup configuration improvement

Theory

Theory

Acceleration region

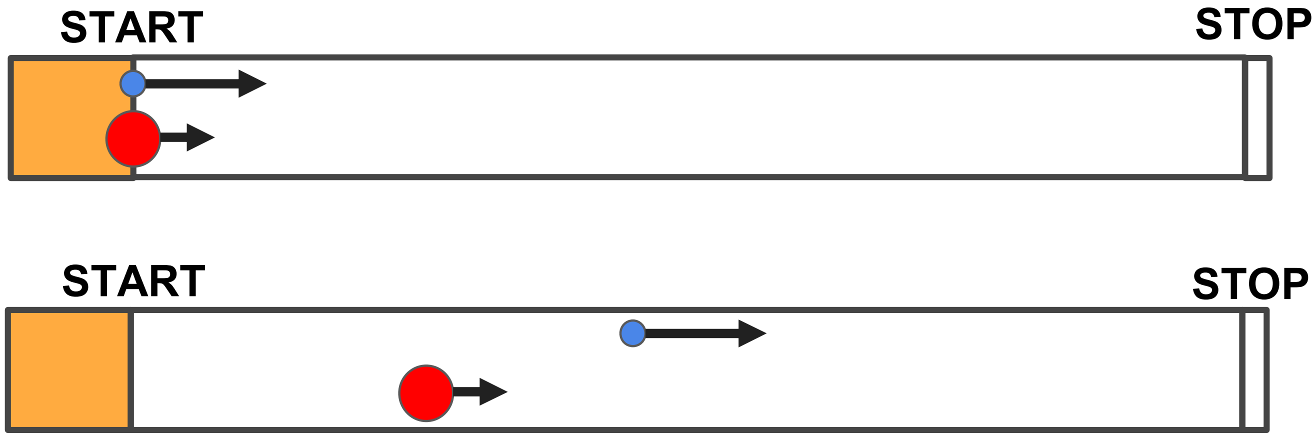
$$E = qU = \frac{mv^2}{2}$$

$q =$ Ion charge $\quad U =$ Accelerating potential

Theory

Acceleration region

$$E = qU = \frac{mv^2}{2}$$

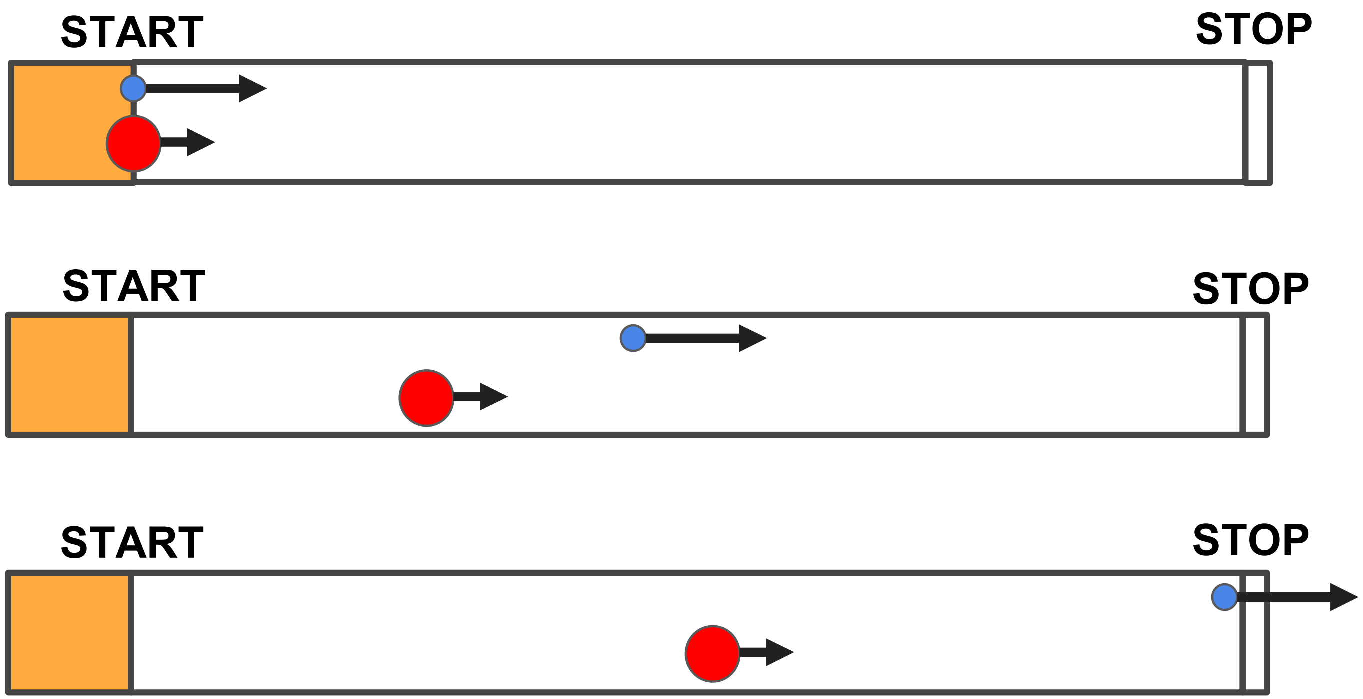


$q =$ Ion charge $\quad U =$ Accelerating potential

Theory

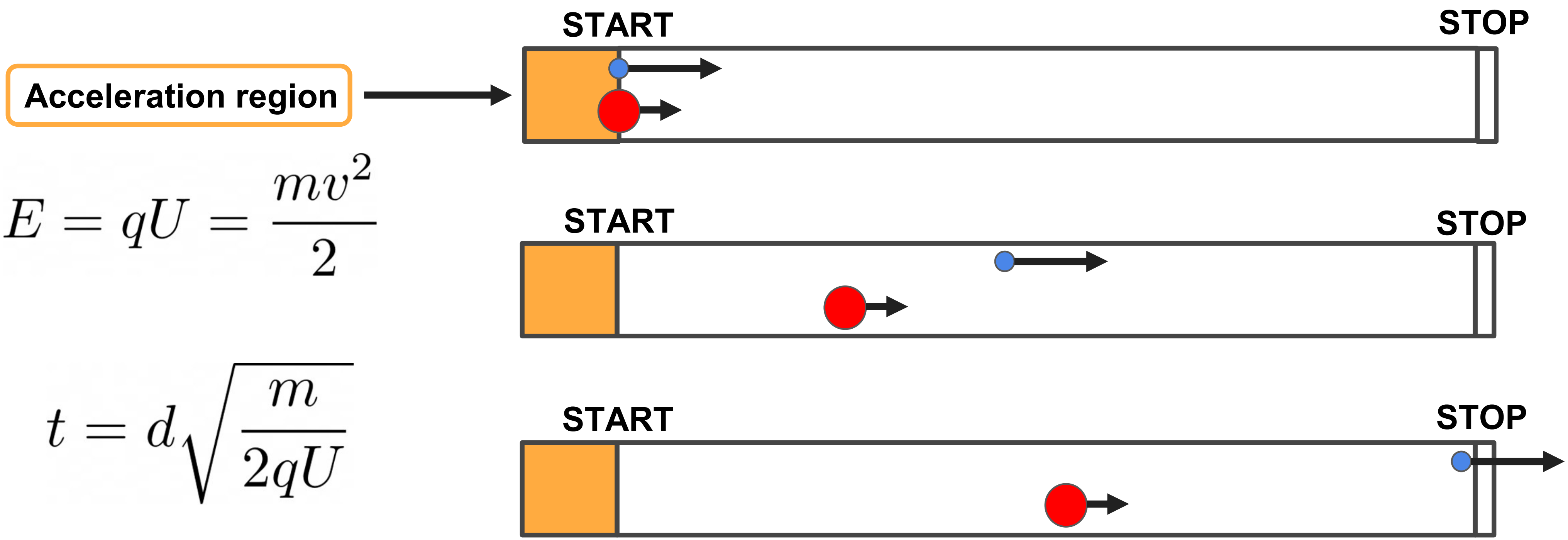
Acceleration region

$$E = qU = \frac{mv^2}{2}$$



$q =$ Ion charge $U =$ Accelerating potential

Theory



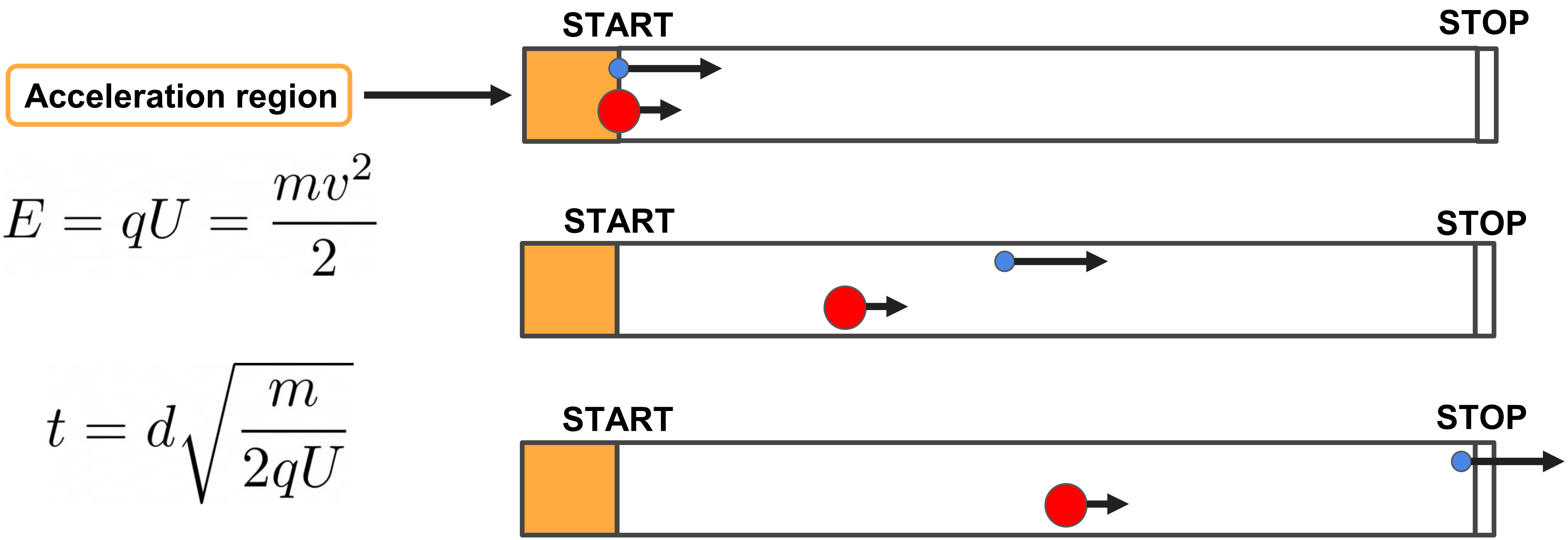
$$E = qU = \frac{mv^2}{2}$$

$$t = d\sqrt{\frac{m}{2qU}}$$

$q =$ Ion charge $U =$ Accelerating potential

$d =$ Flight path

Theory



$$E = qU = \frac{mv^2}{2}$$

$$t = d\sqrt{\frac{m}{2qU}}$$

$$R = \frac{m}{\Delta m} = \frac{t}{2\Delta t}$$

$q =$ Ion charge

$U =$ Accelerating potential

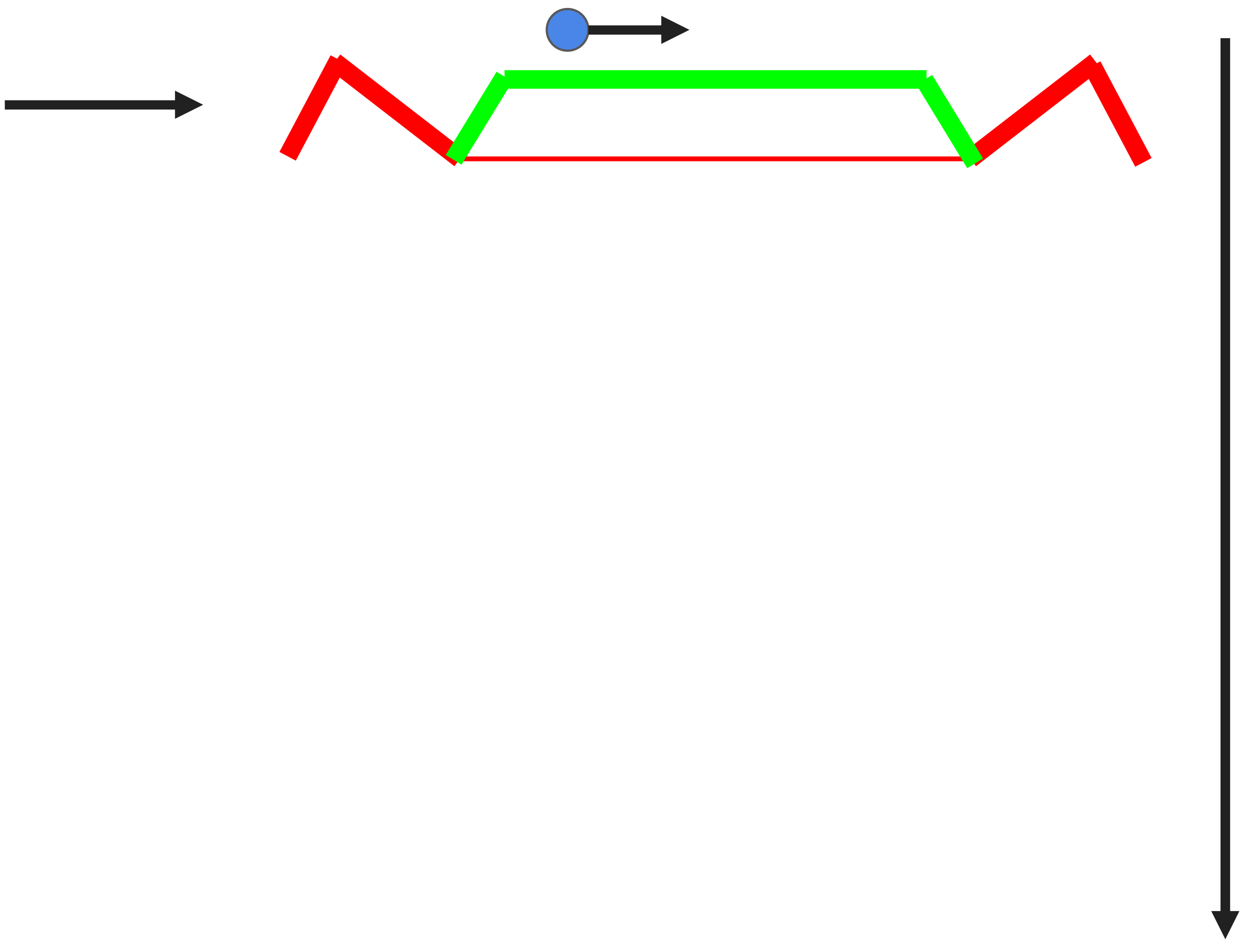
$d =$ Flight path

$\Delta t =$ Time-of-flight uncertainty

$\Delta m =$ Mass uncertainty

Theory

Ion injection into MR ToF MS

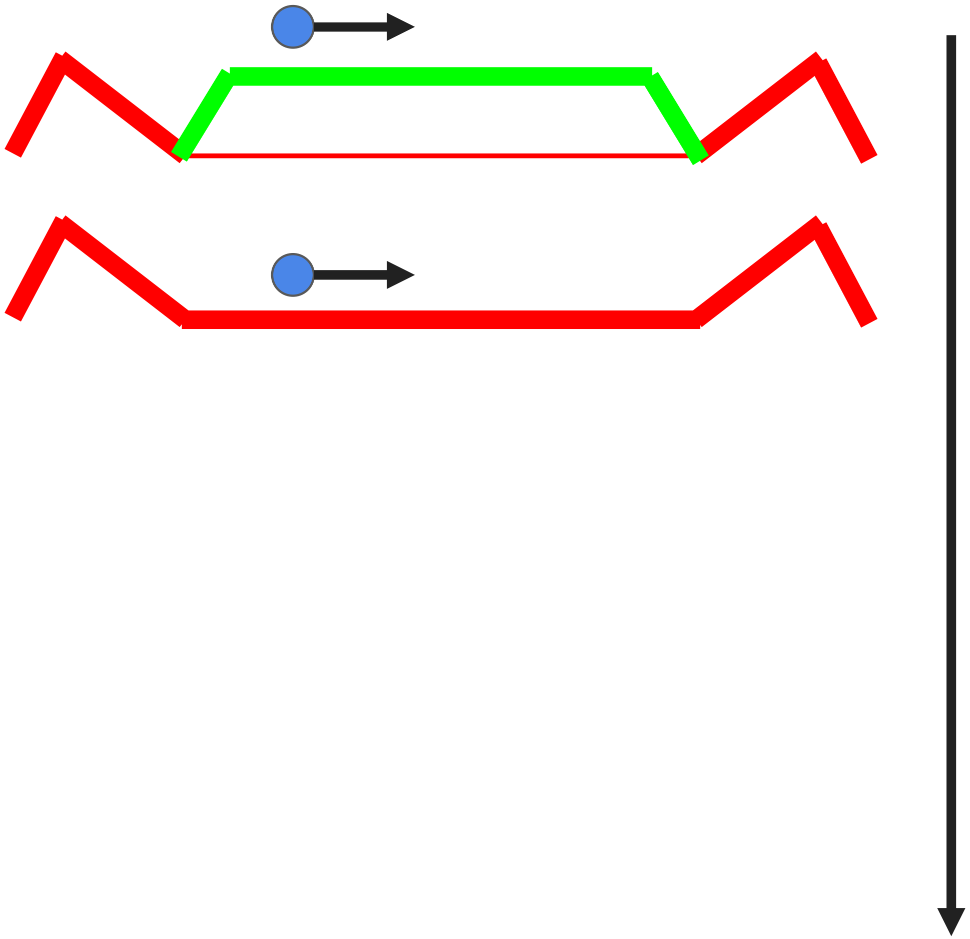


R. N. Wolf, et al., “Static-mirror ion capture and time focusing for electrostatic ion-beam traps and multi-reflection time-of-flight mass analyzers by use of an in-trap potential lift,” International Journal of Mass Spectrometry, vol. 313, pp. 8–14,2012

Theory

Ion injection into MR ToF MS

Ion capture by lift drop



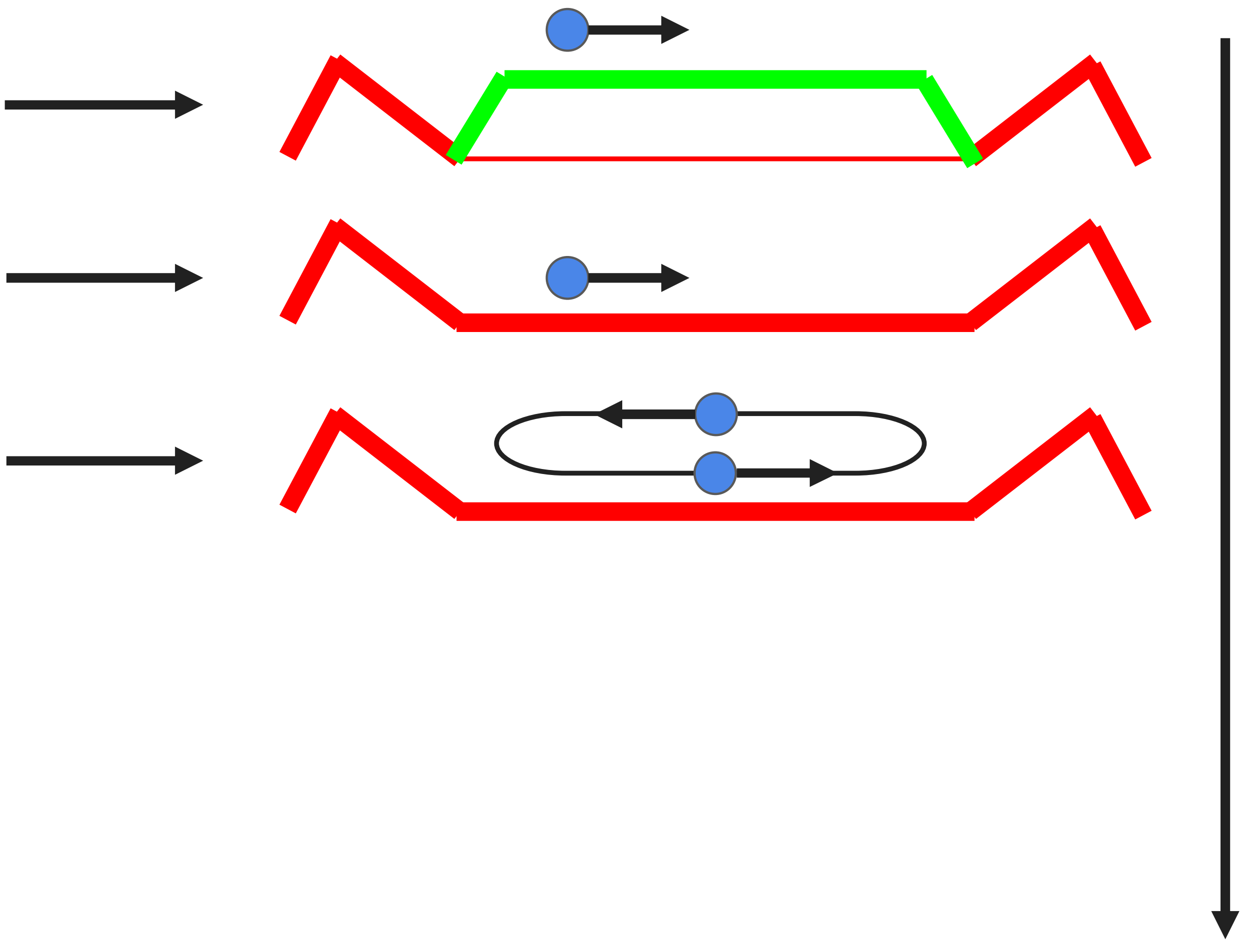
R. N. Wolf, et al., “Static-mirror ion capture and time focusing for electrostatic ion-beam traps and multi-reflection time-of-flight mass analyzers by use of an in-trap potential lift,” International Journal of Mass Spectrometry, vol. 313, pp. 8–14,2012

Theory

Ion injection into MR ToF MS

Ion capture by lift drop

Ions stored for multiple revolutions



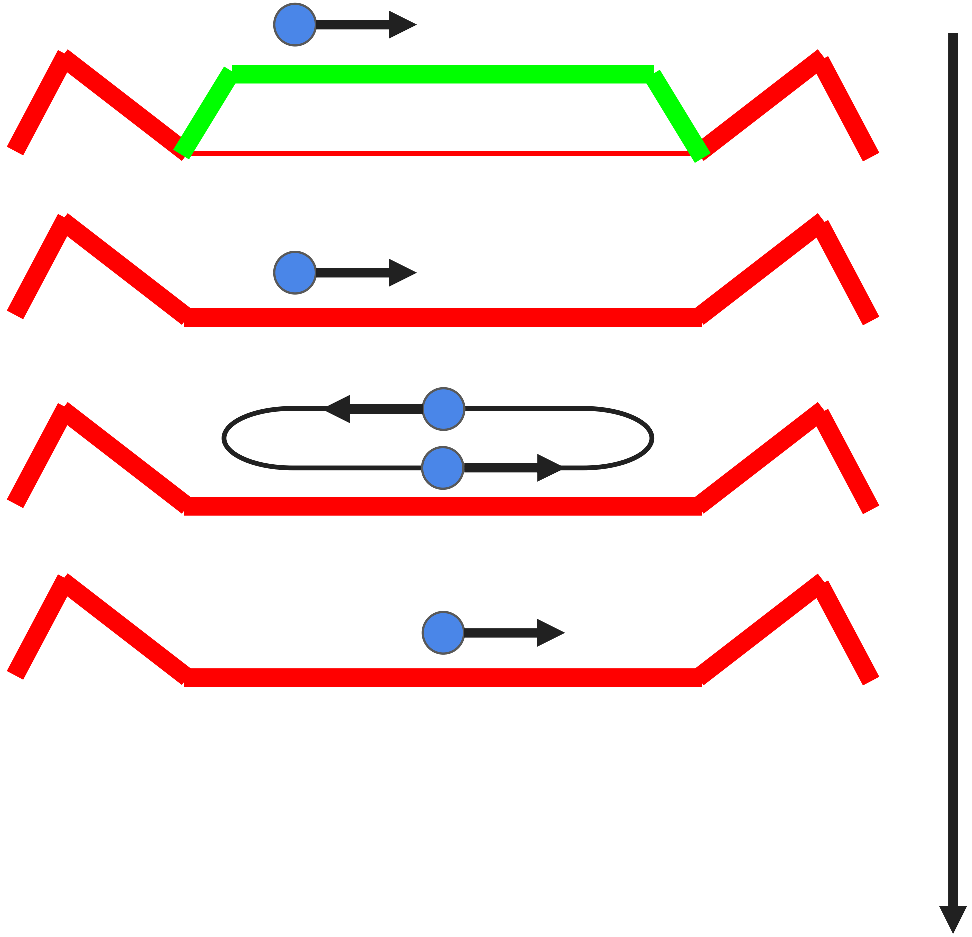
R. N. Wolf, et al., “Static-mirror ion capture and time focusing for electrostatic ion-beam traps and multi-reflection time-of-flight mass analyzers by use of an in-trap potential lift,” International Journal of Mass Spectrometry, vol. 313, pp. 8–14,2012

Theory

Ion injection into MR ToF MS →

Ion capture by lift drop →

Ions stored for multiple revolutions →



R. N. Wolf, et al., "Static-mirror ion capture and time focusing for electrostatic ion-beam traps and multi-reflection time-of-flight mass analyzers by use of an in-trap potential lift," International Journal of Mass Spectrometry, vol. 313, pp. 8–14,2012

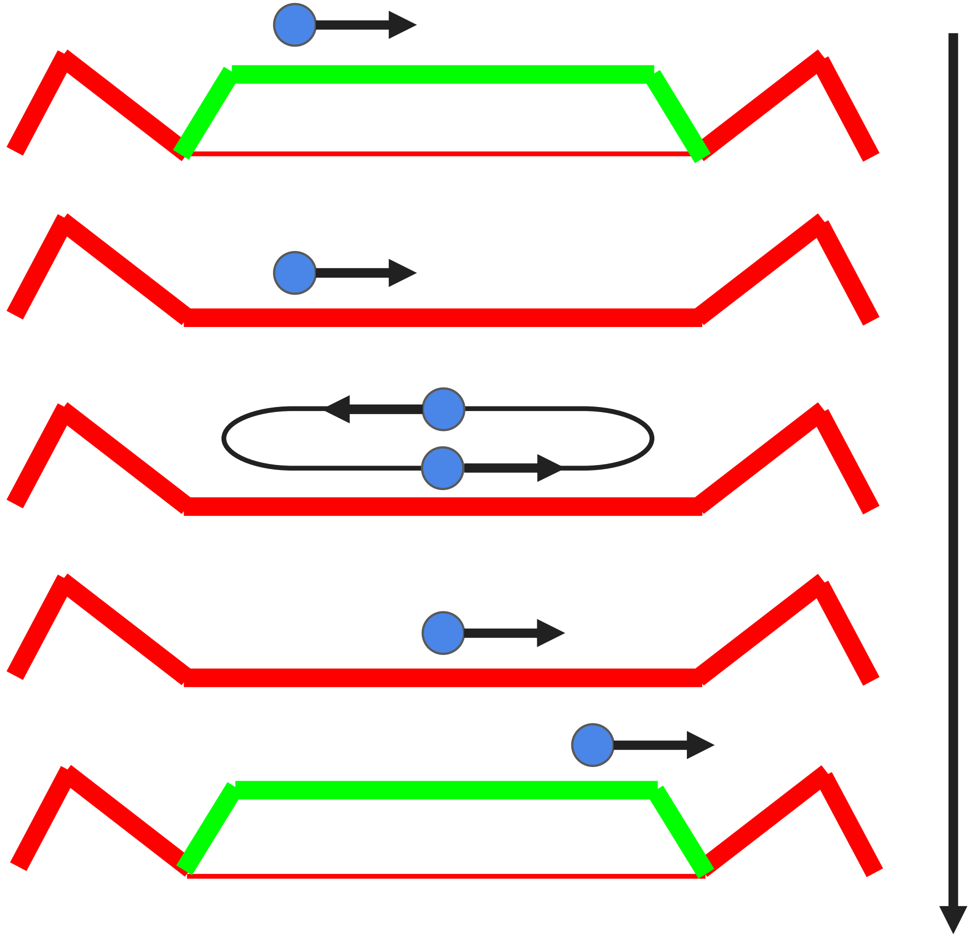
Theory

Ion injection into MR ToF MS

Ion capture by lift drop

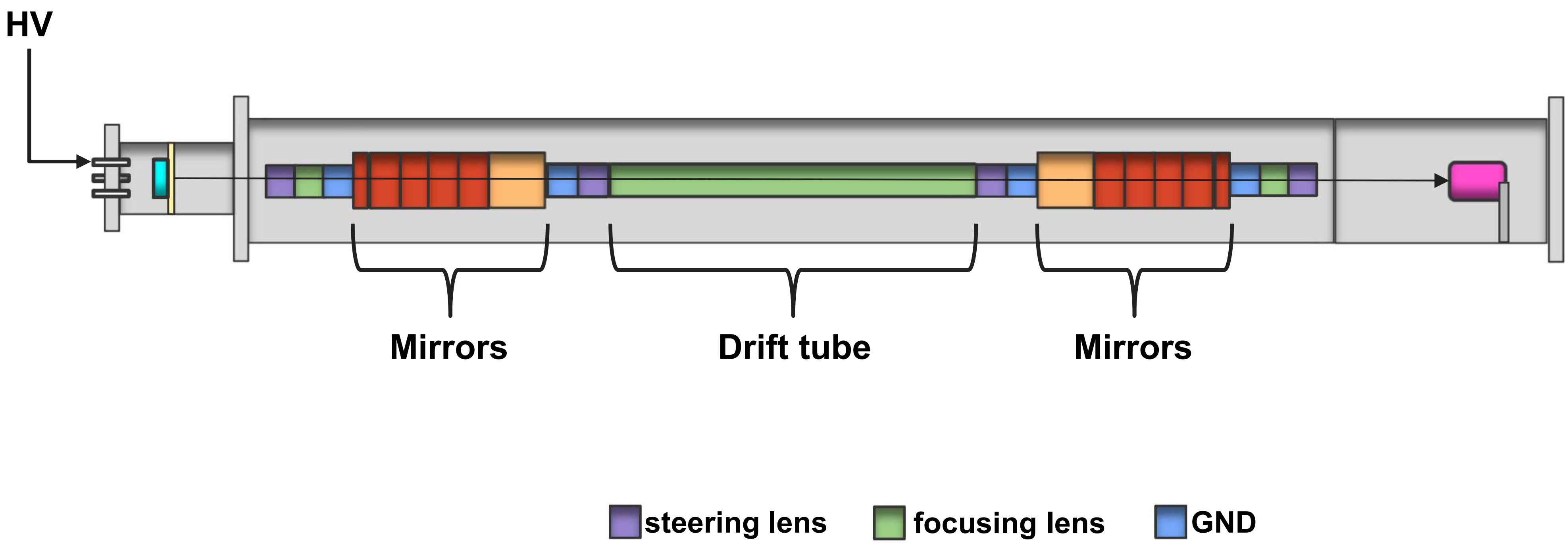
Ions stored for multiple revolutions

Ion ejection by lift rise



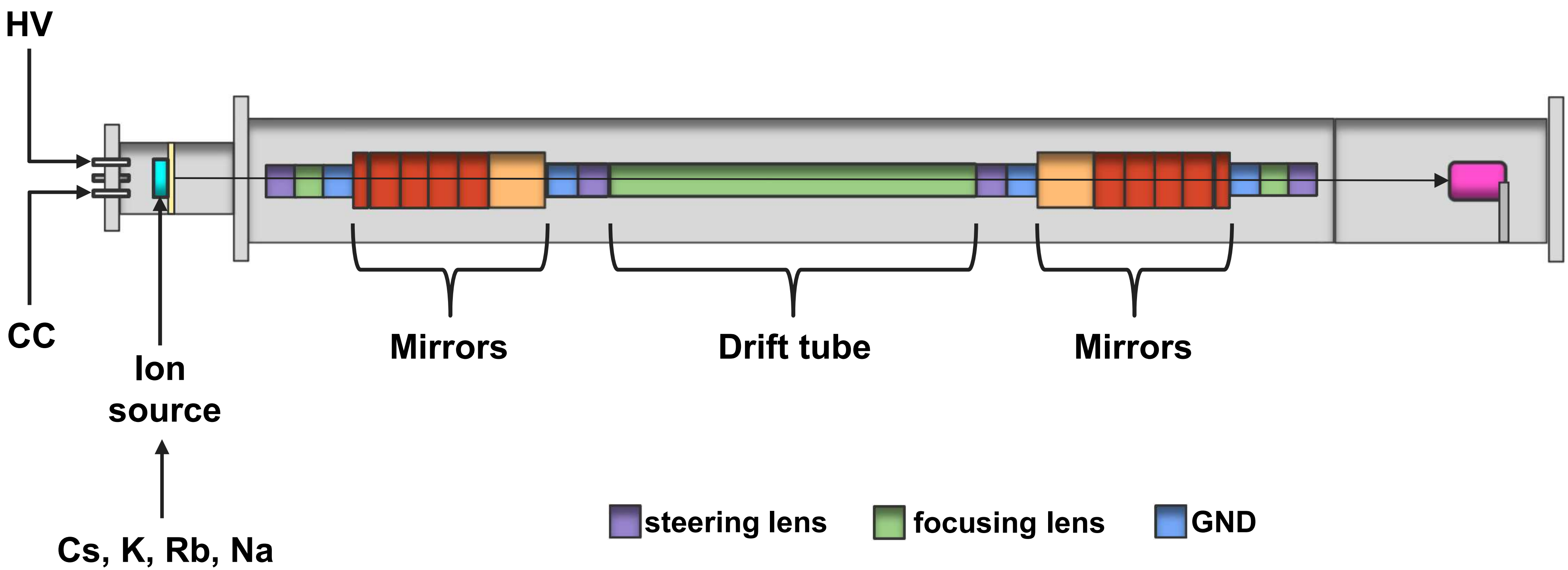
R. N. Wolf, et al., "Static-mirror ion capture and time focusing for electrostatic ion-beam traps and multi-reflection time-of-flight mass analyzers by use of an in-trap potential lift," International Journal of Mass Spectrometry, vol. 313, pp. 8–14,2012

Setup & Methods



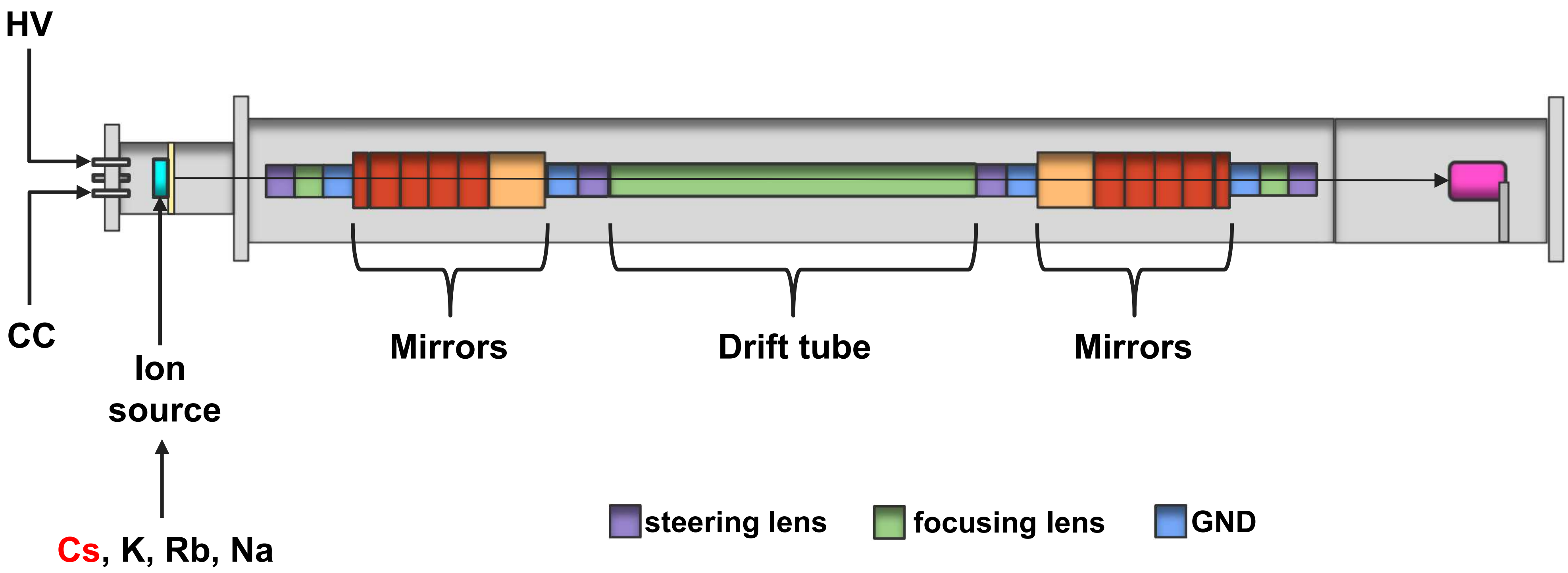
Setup & Methods

university of groningen
faculty of science and engineering

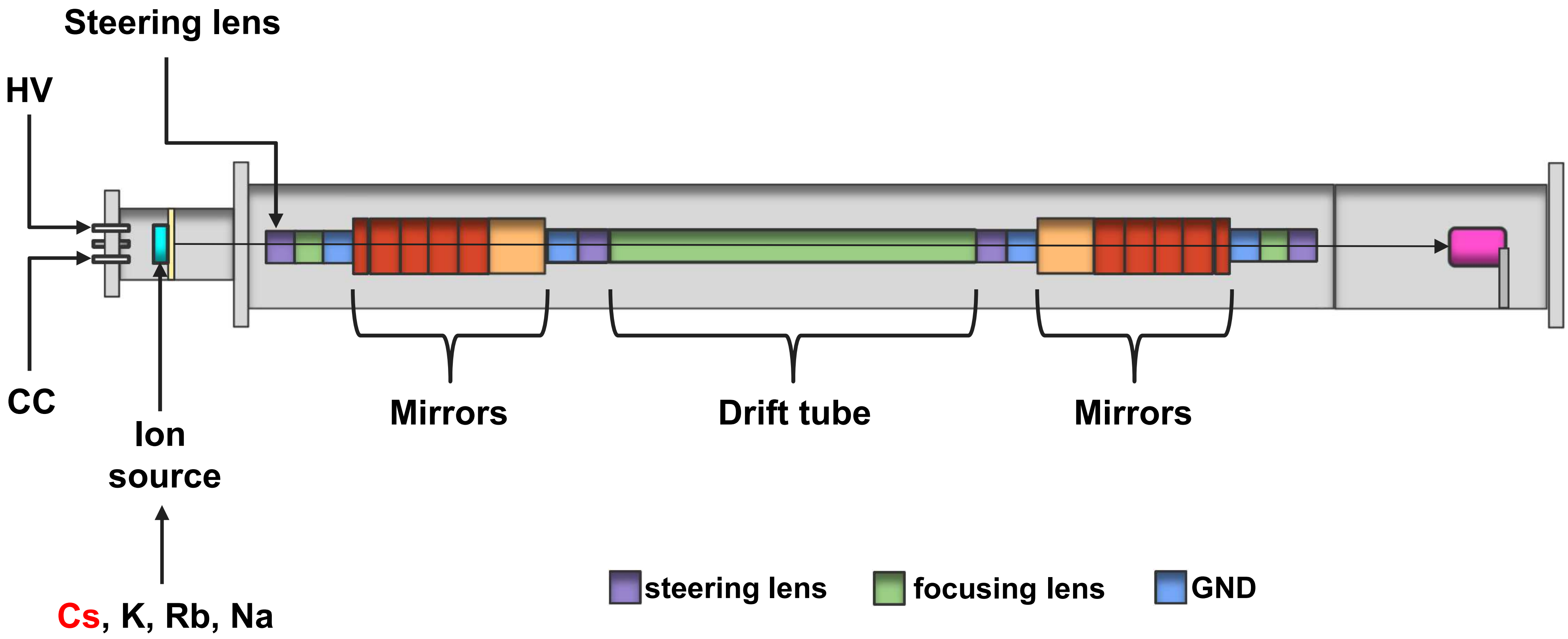


Setup & Methods

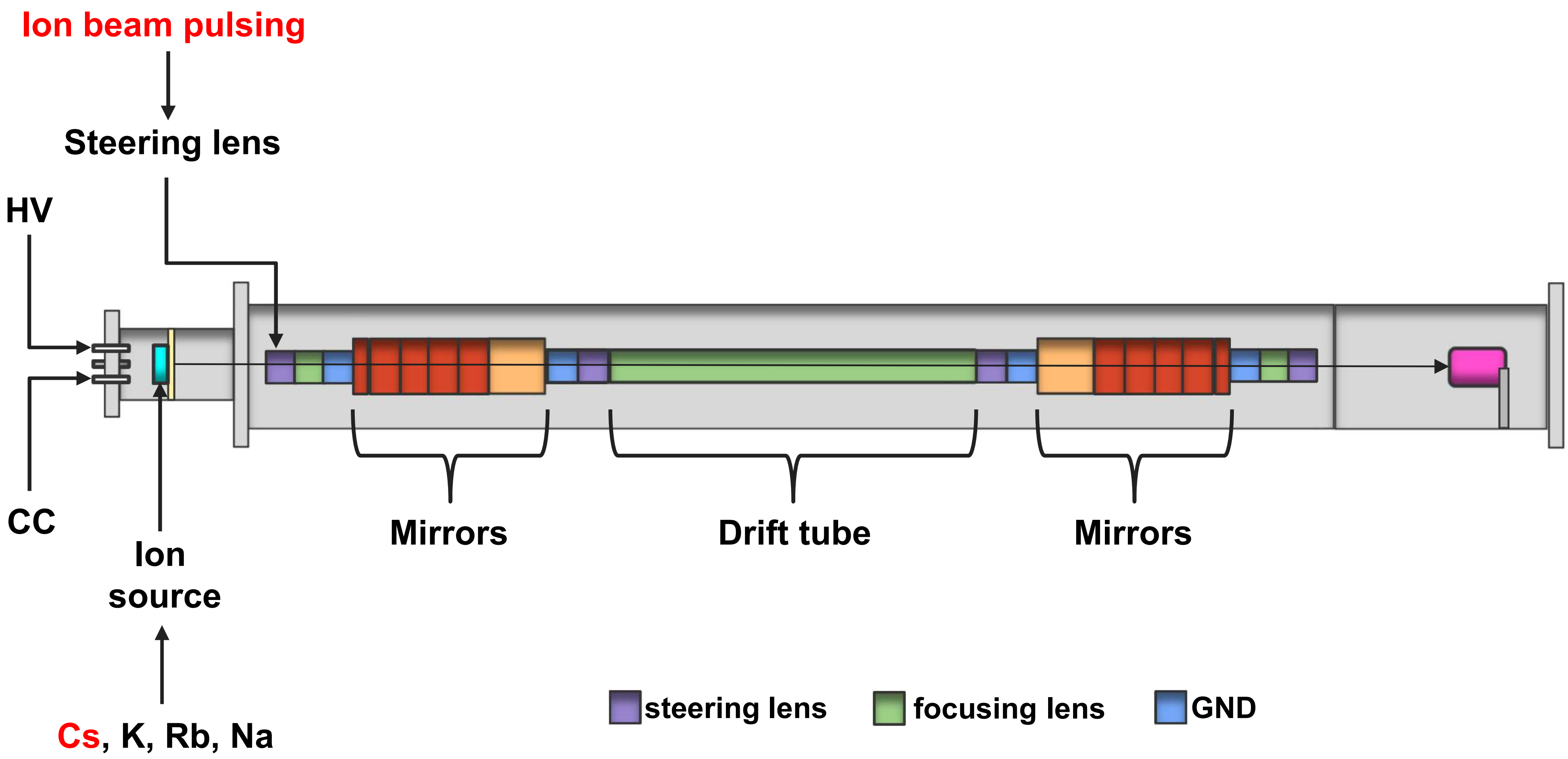
university of groningen / faculty of science and engineering



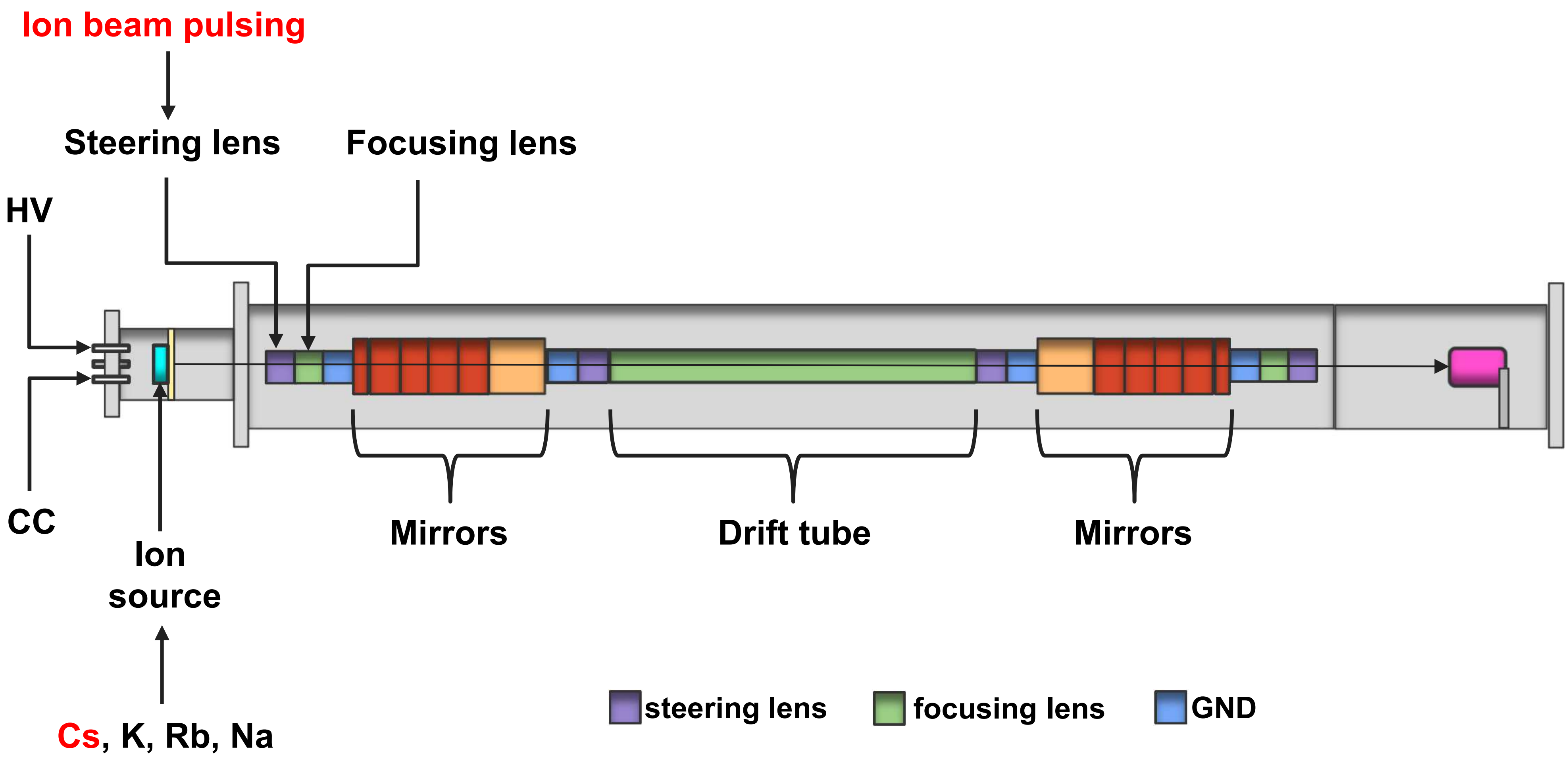
Setup & Methods



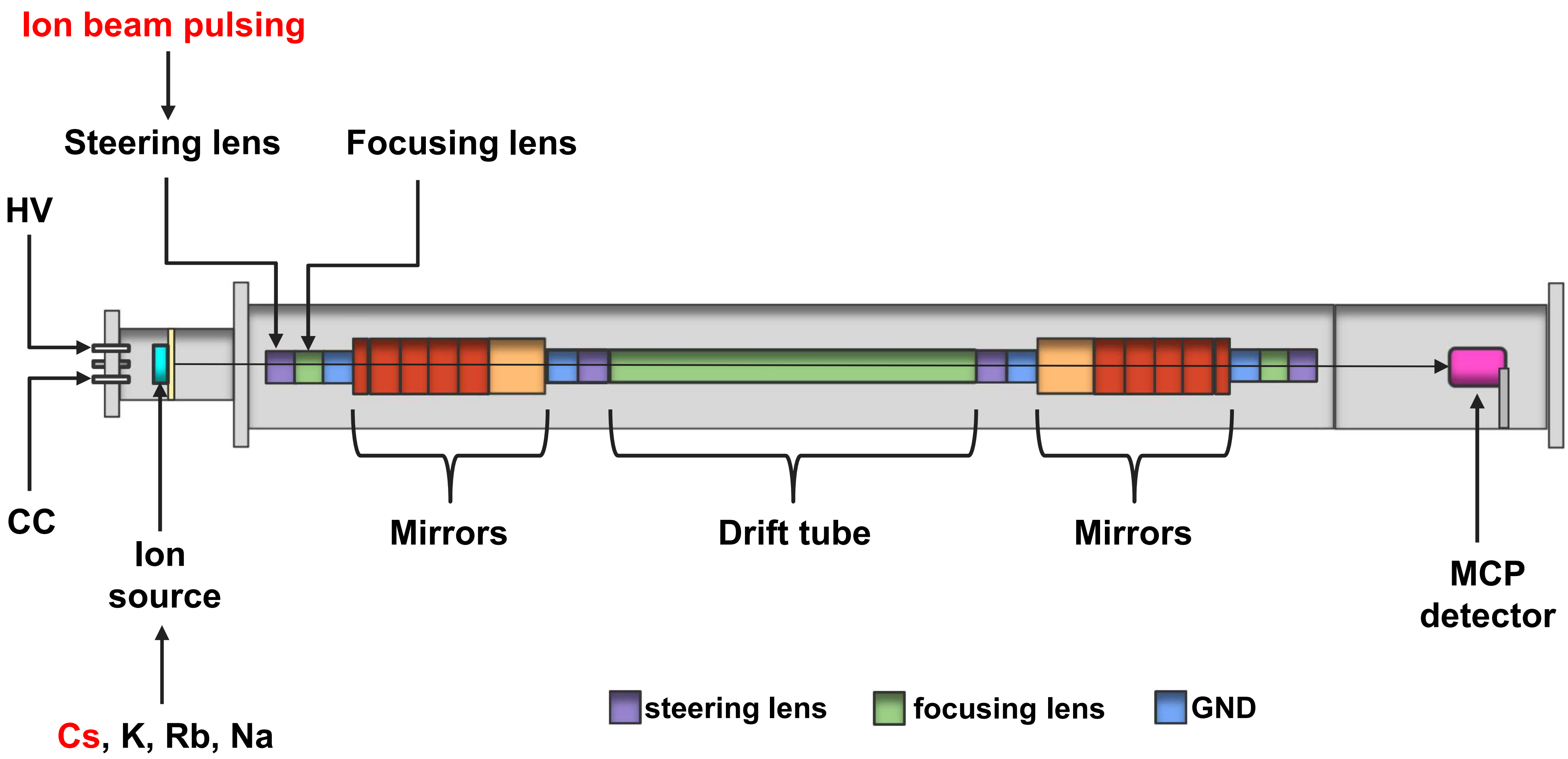
Setup & Methods



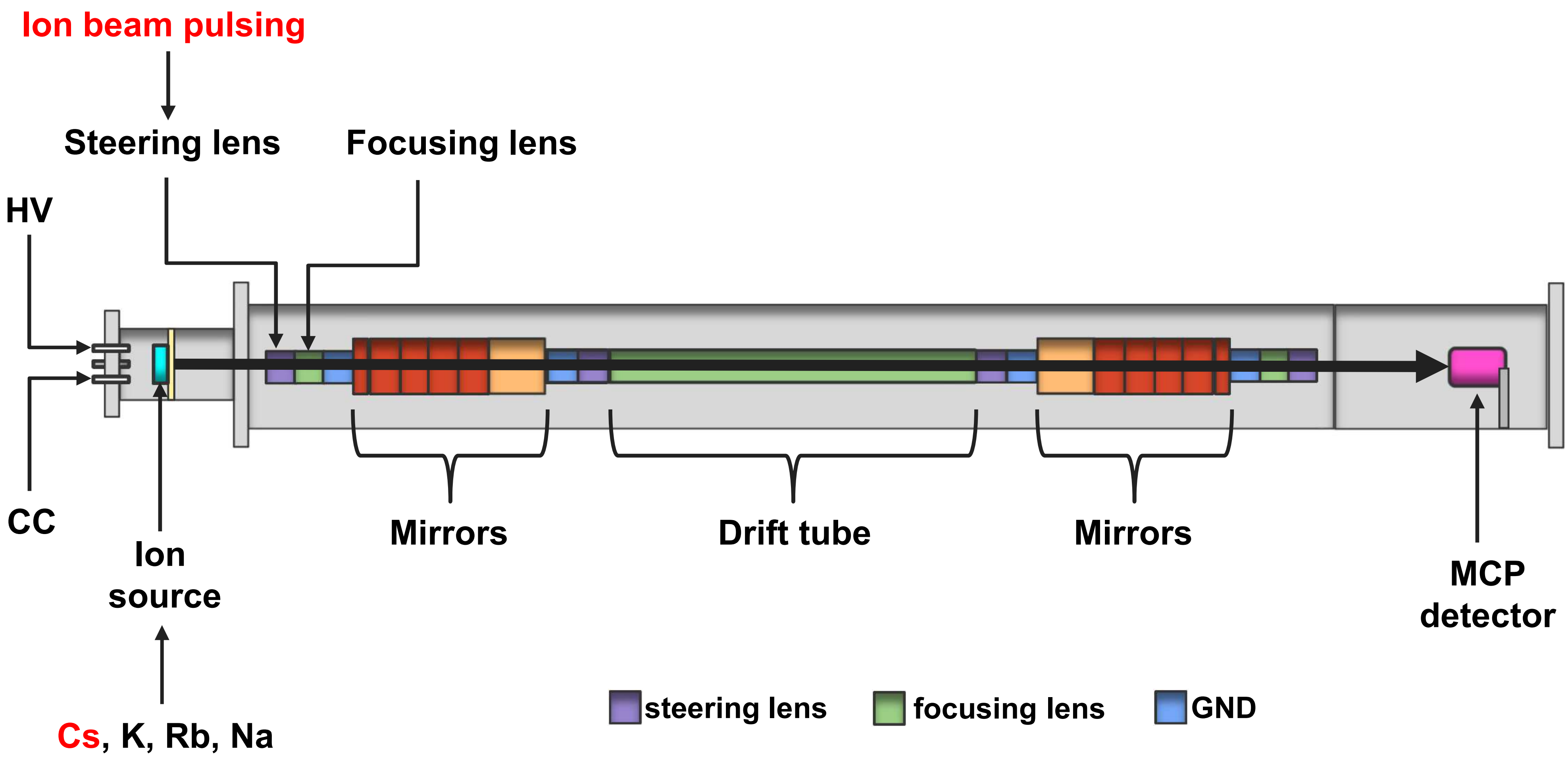
Setup & Methods



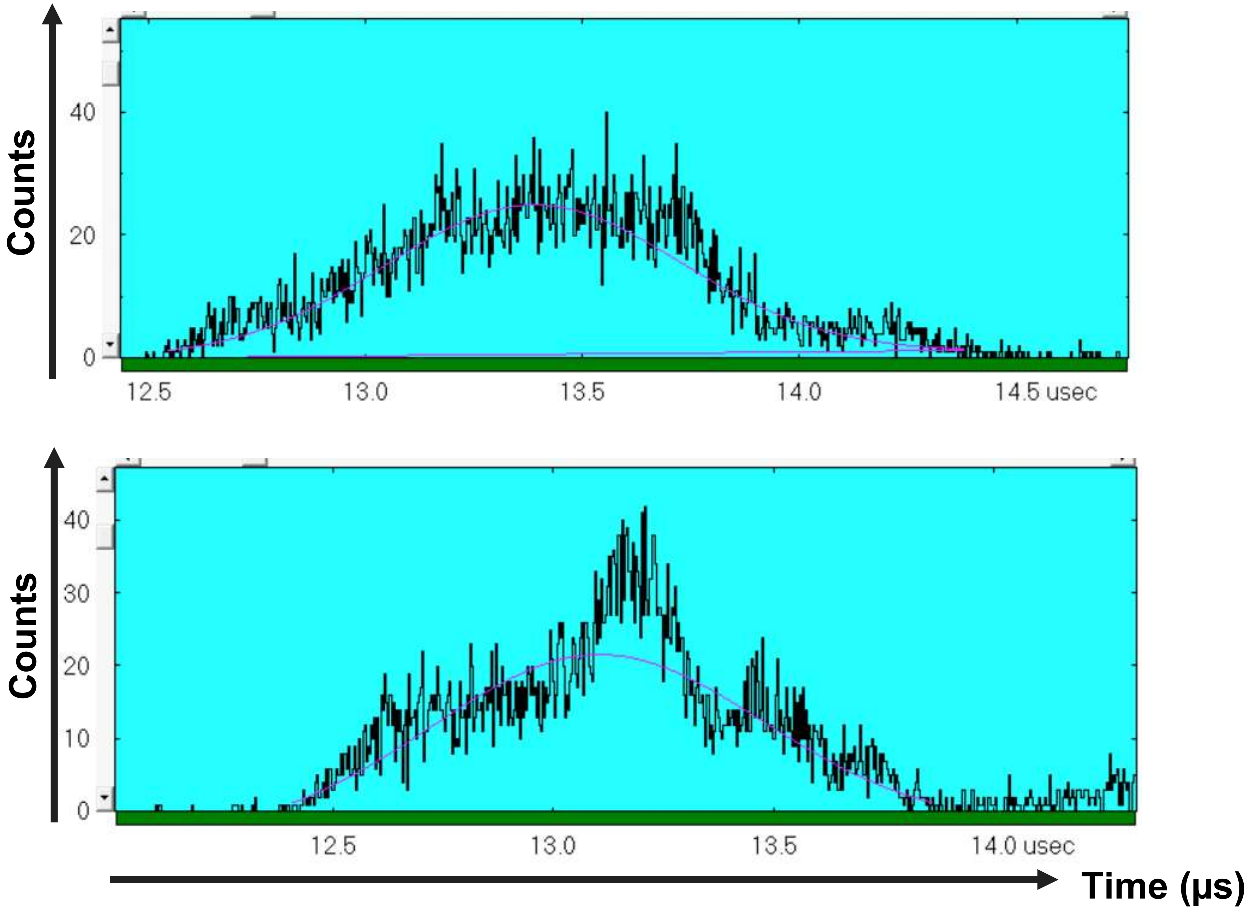
Setup & Methods



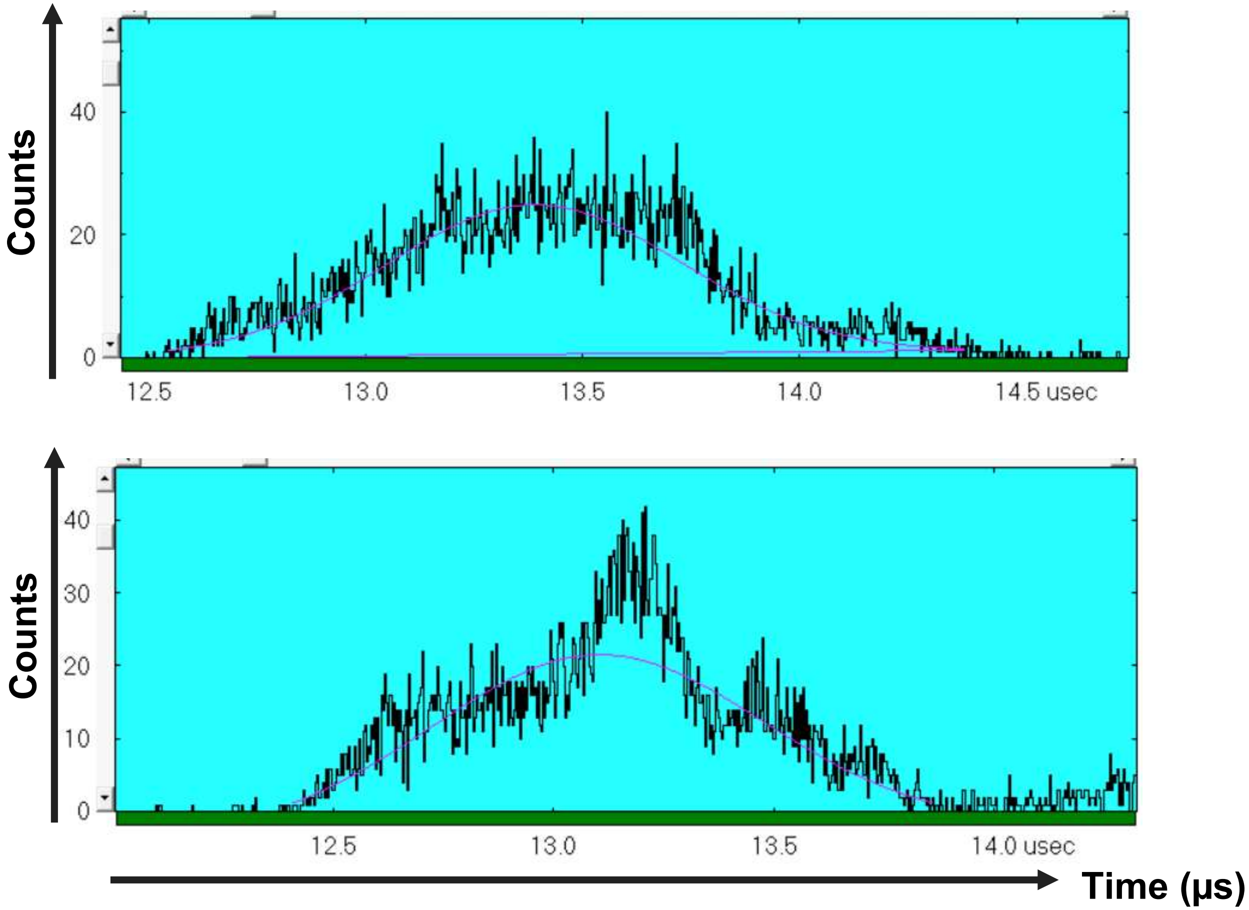
Setup & Methods

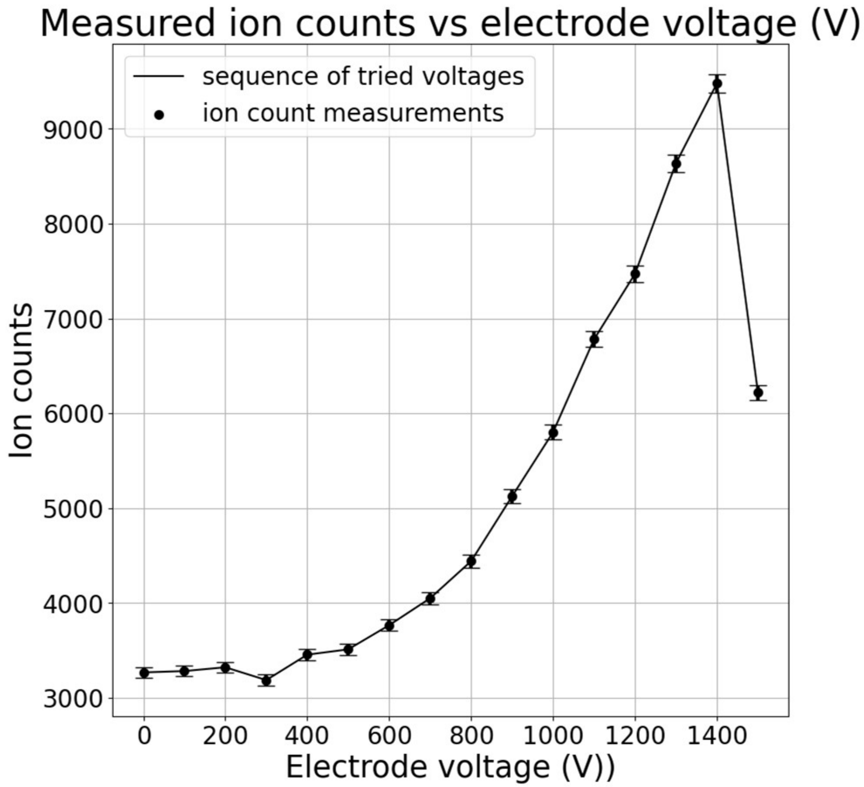


Setup & Methods

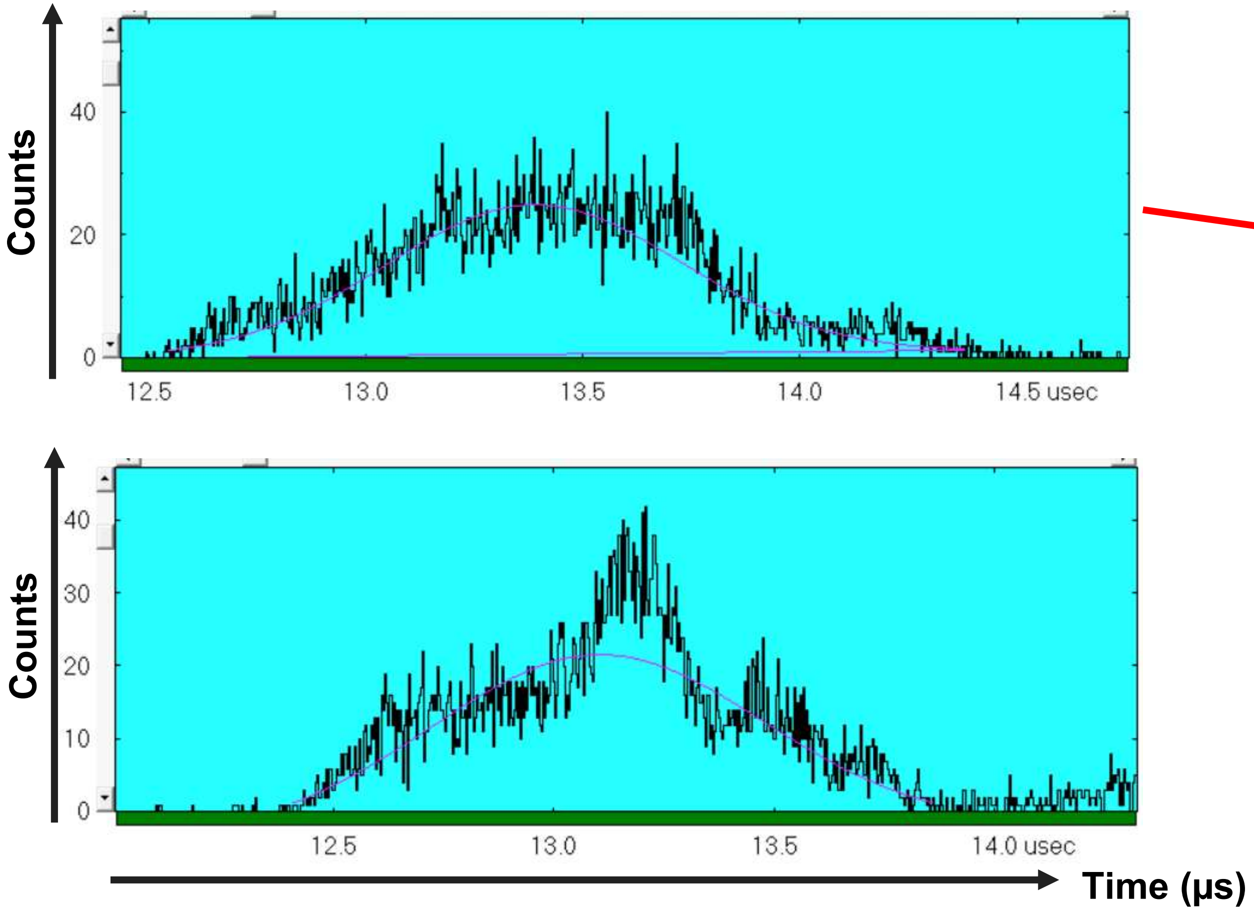


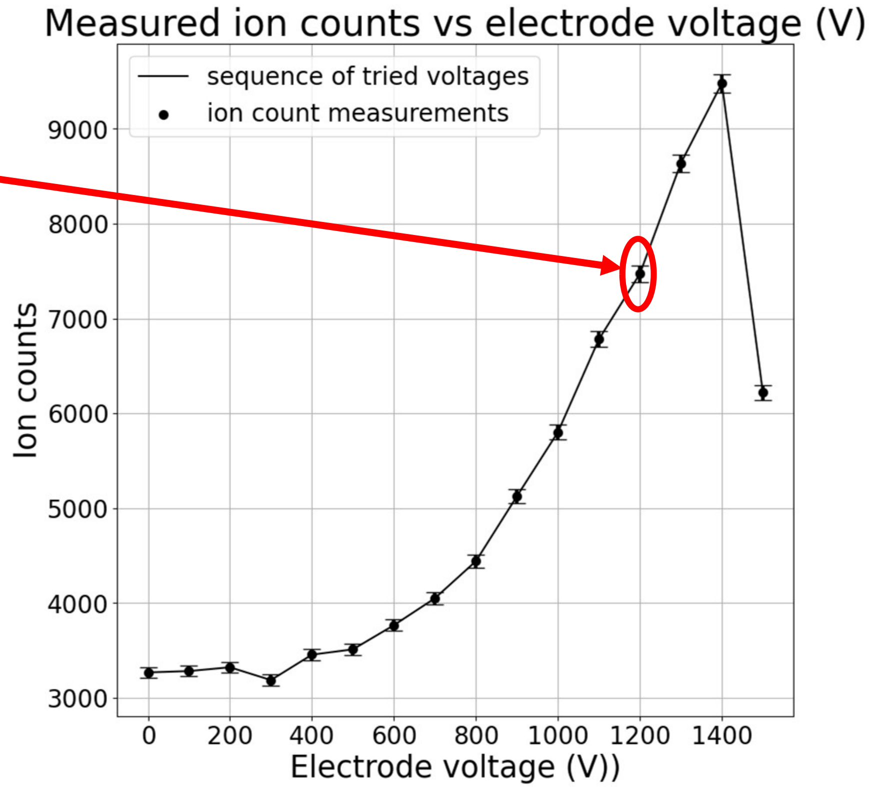
Setup & Methods



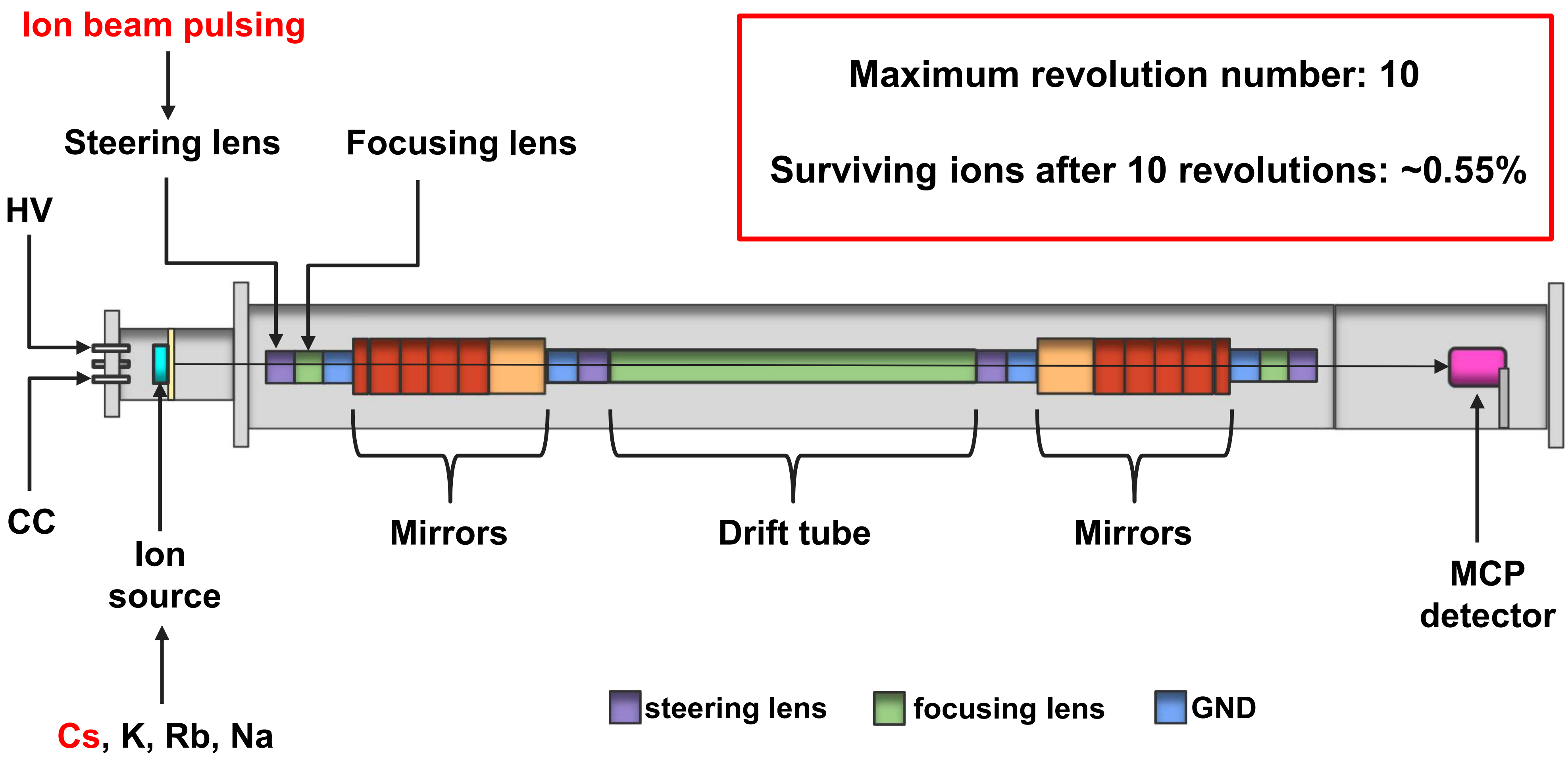


Setup & Methods





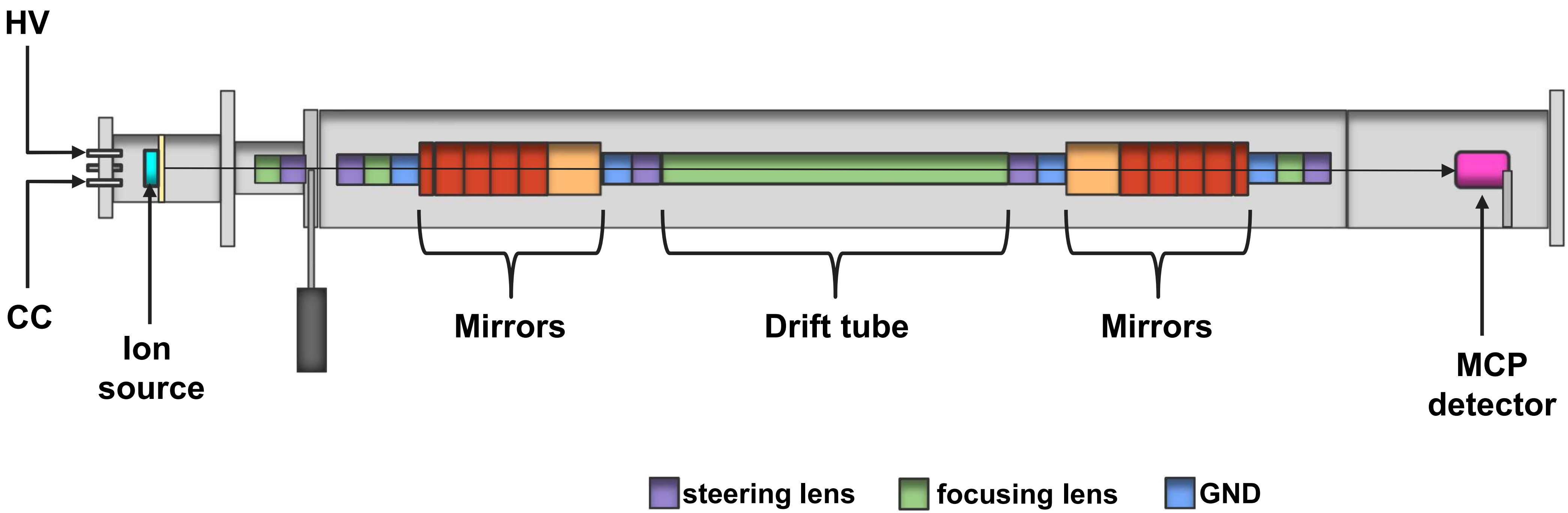
Setup & Methods



Maximum revolution number: 10

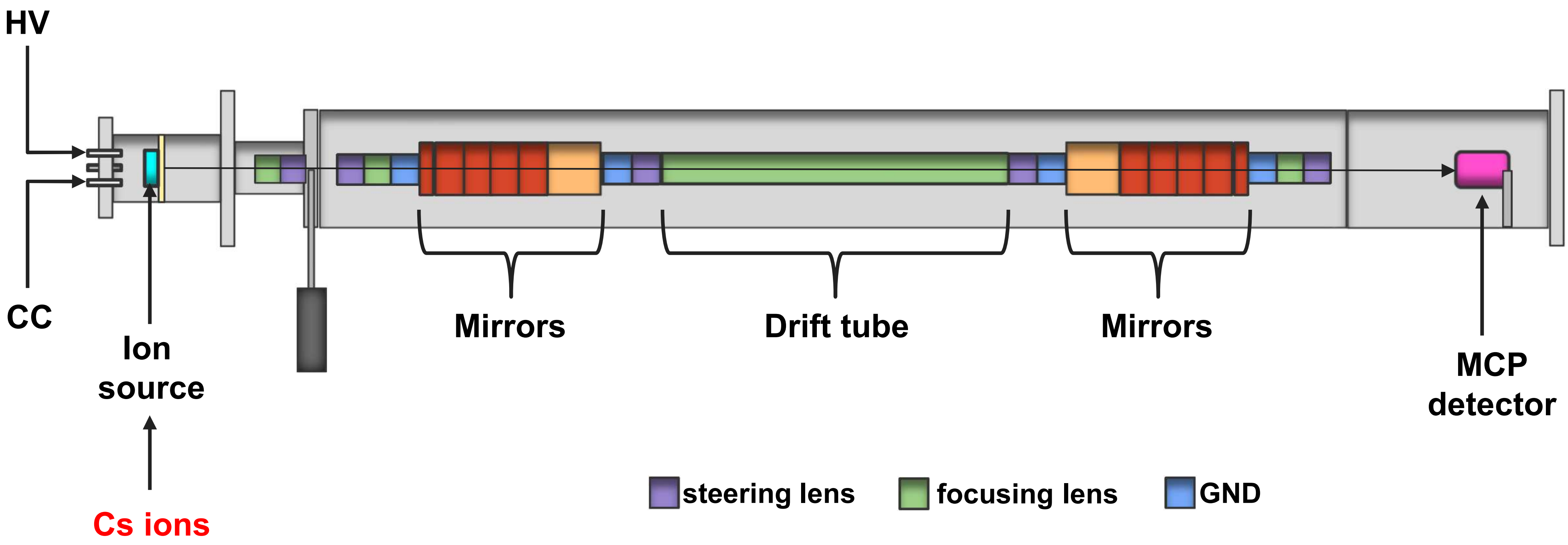
Surviving ions after 10 revolutions: ~0.55%

Setup & Methods



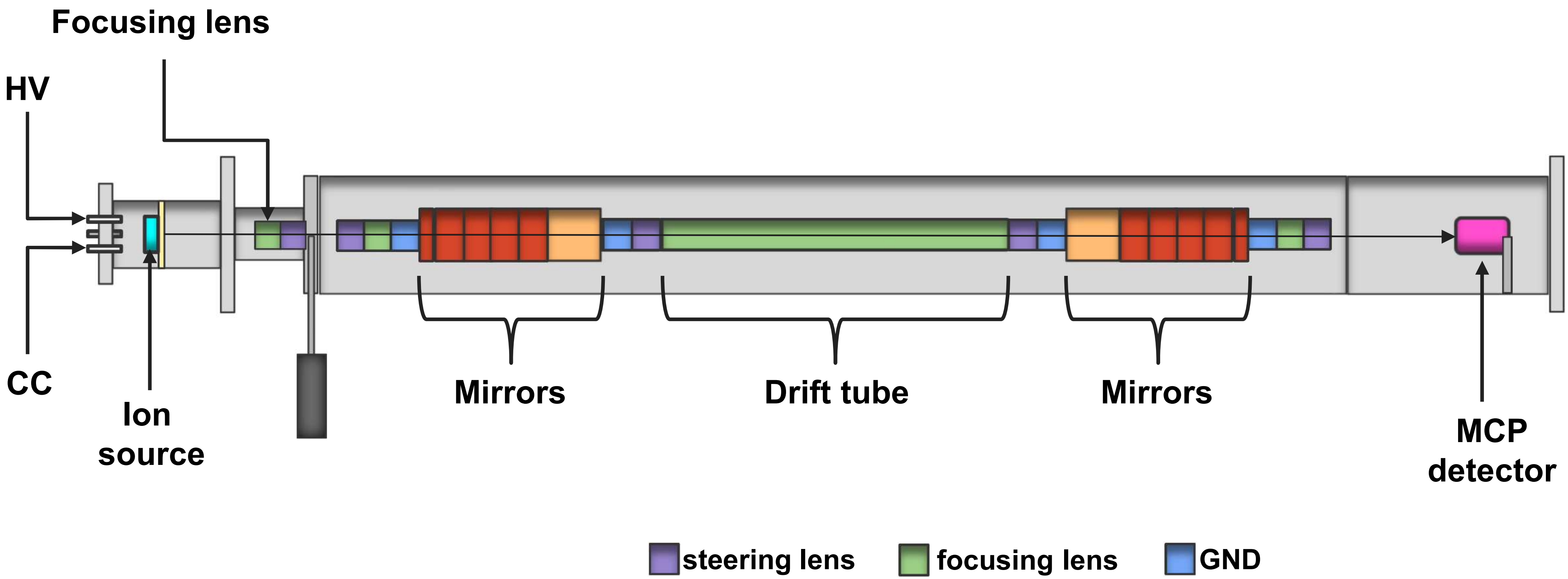
Setup & Methods

university of groningen / faculty of science and engineering



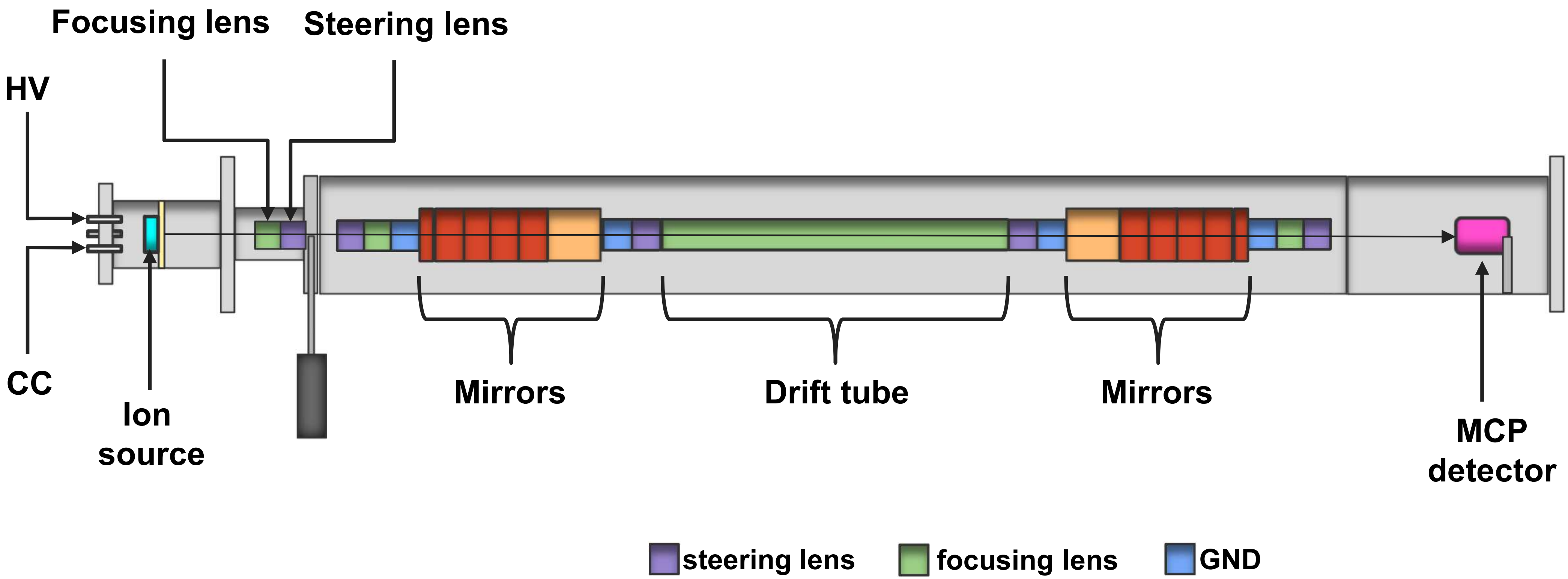
Setup & Methods

university of groningen / faculty of science and engineering

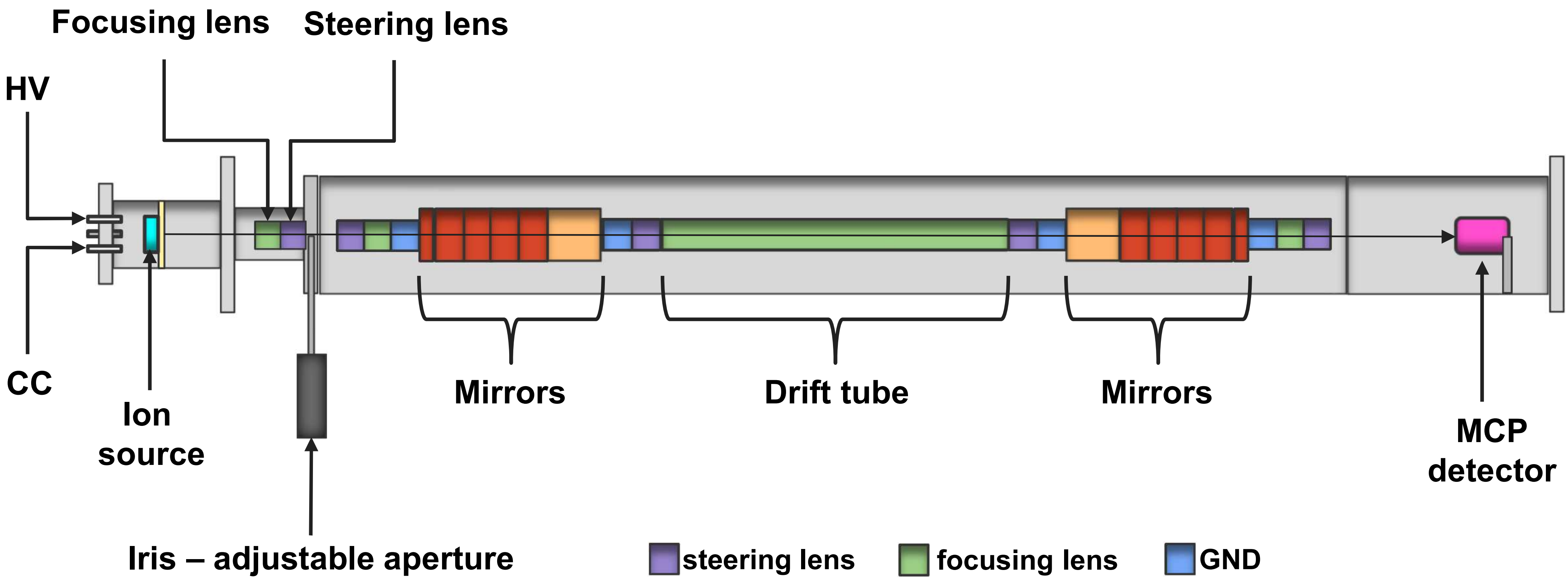


Setup & Methods

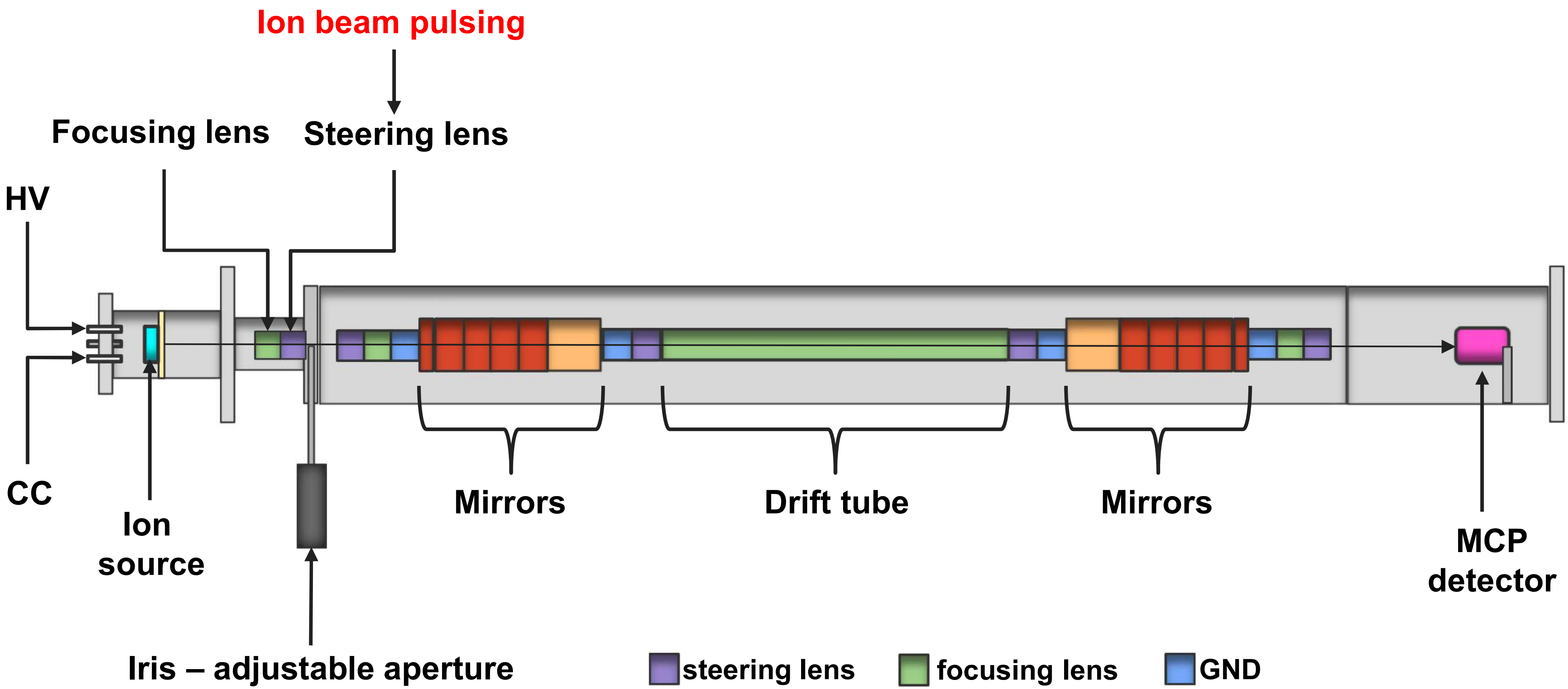
university of groningen / faculty of science and engineering



Setup & Methods

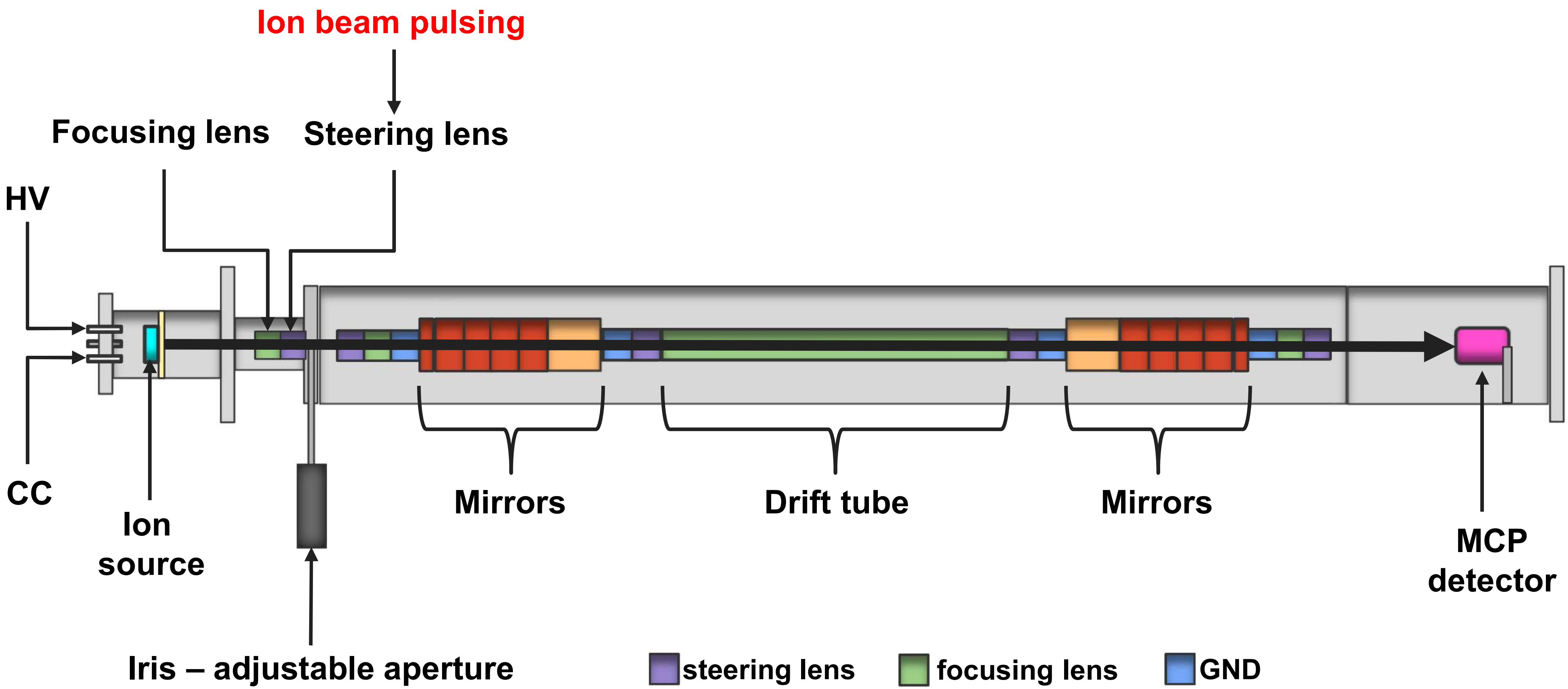


Setup & Methods



Setup & Methods

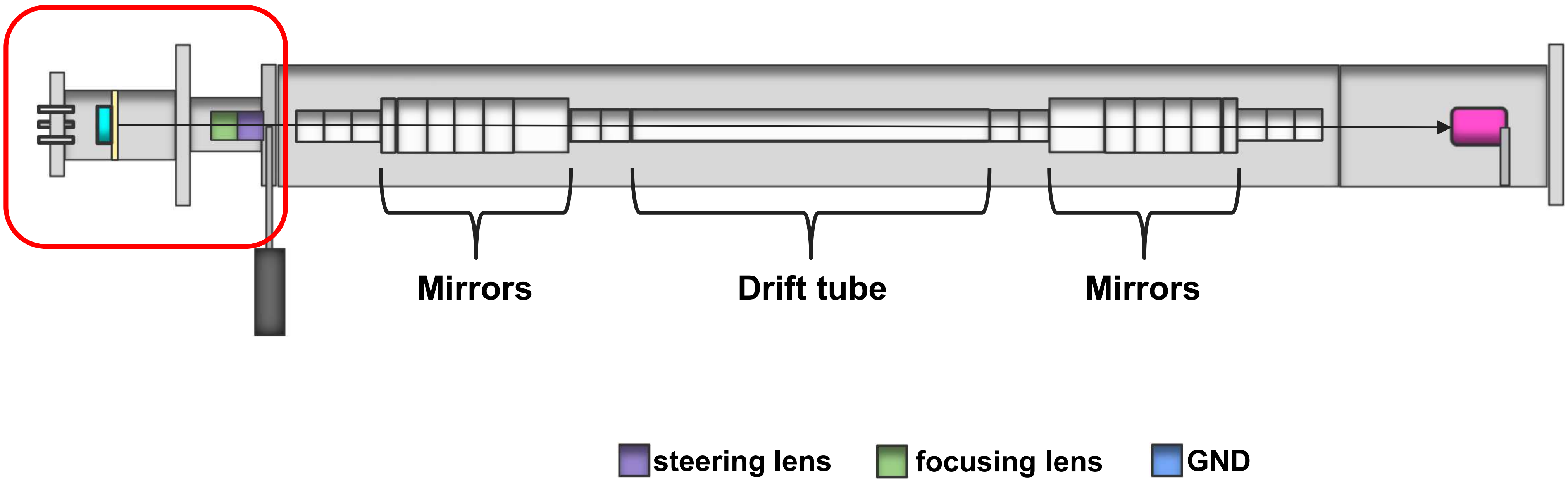
university of groningen / faculty of science and engineering



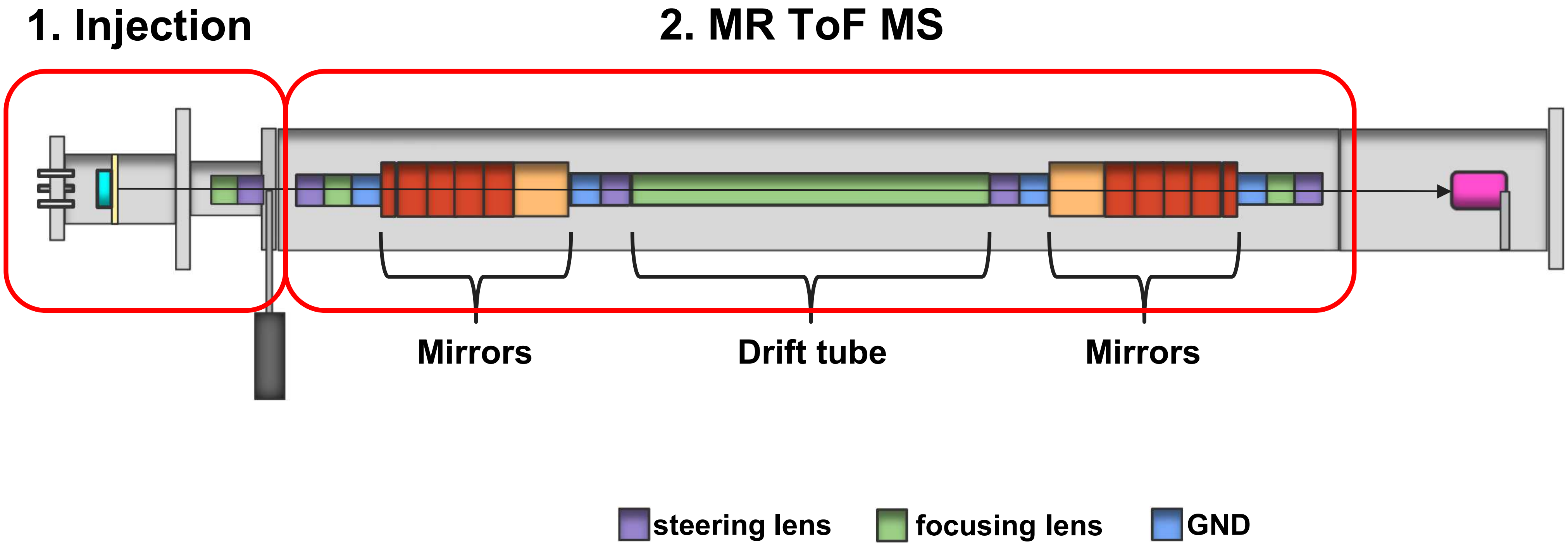
Setup & Methods

university of groningen / faculty of science and engineering

1. Injection

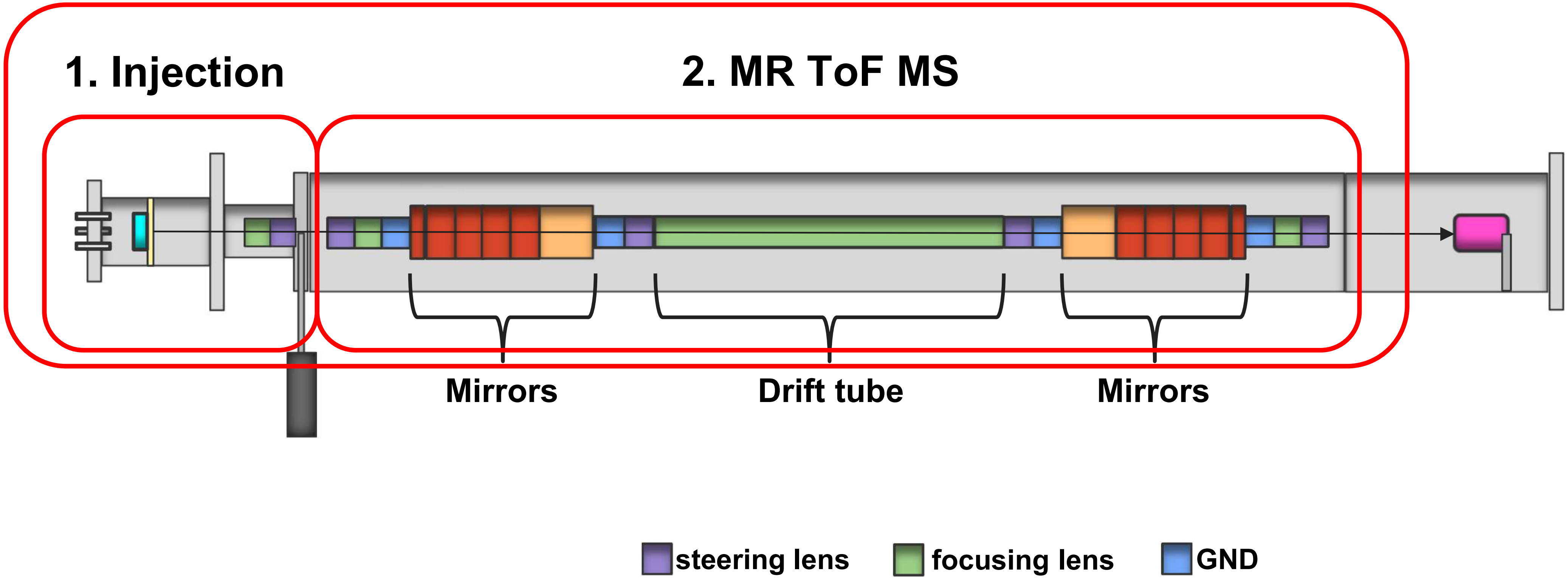


Setup & Methods



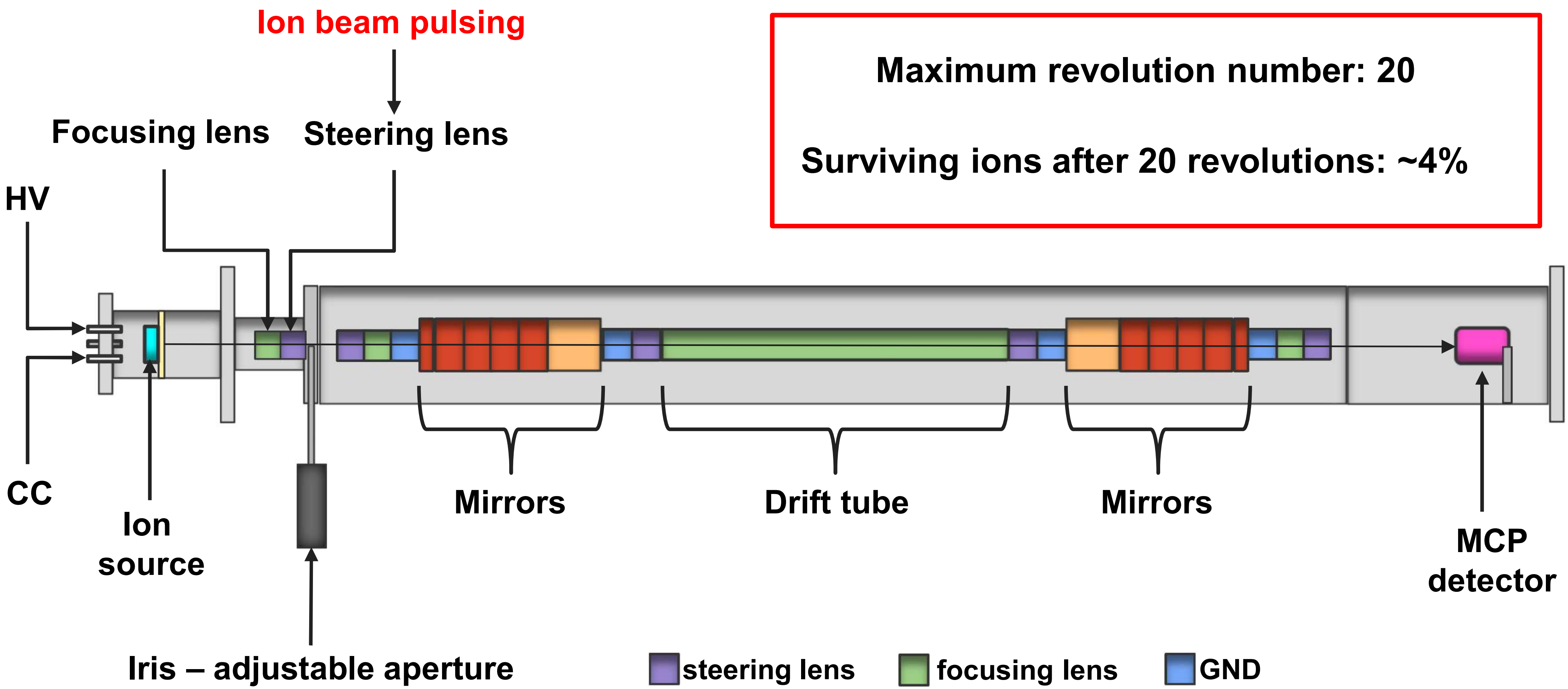
Setup & Methods

3. Whole system – multiple revolutions



Setup & Methods

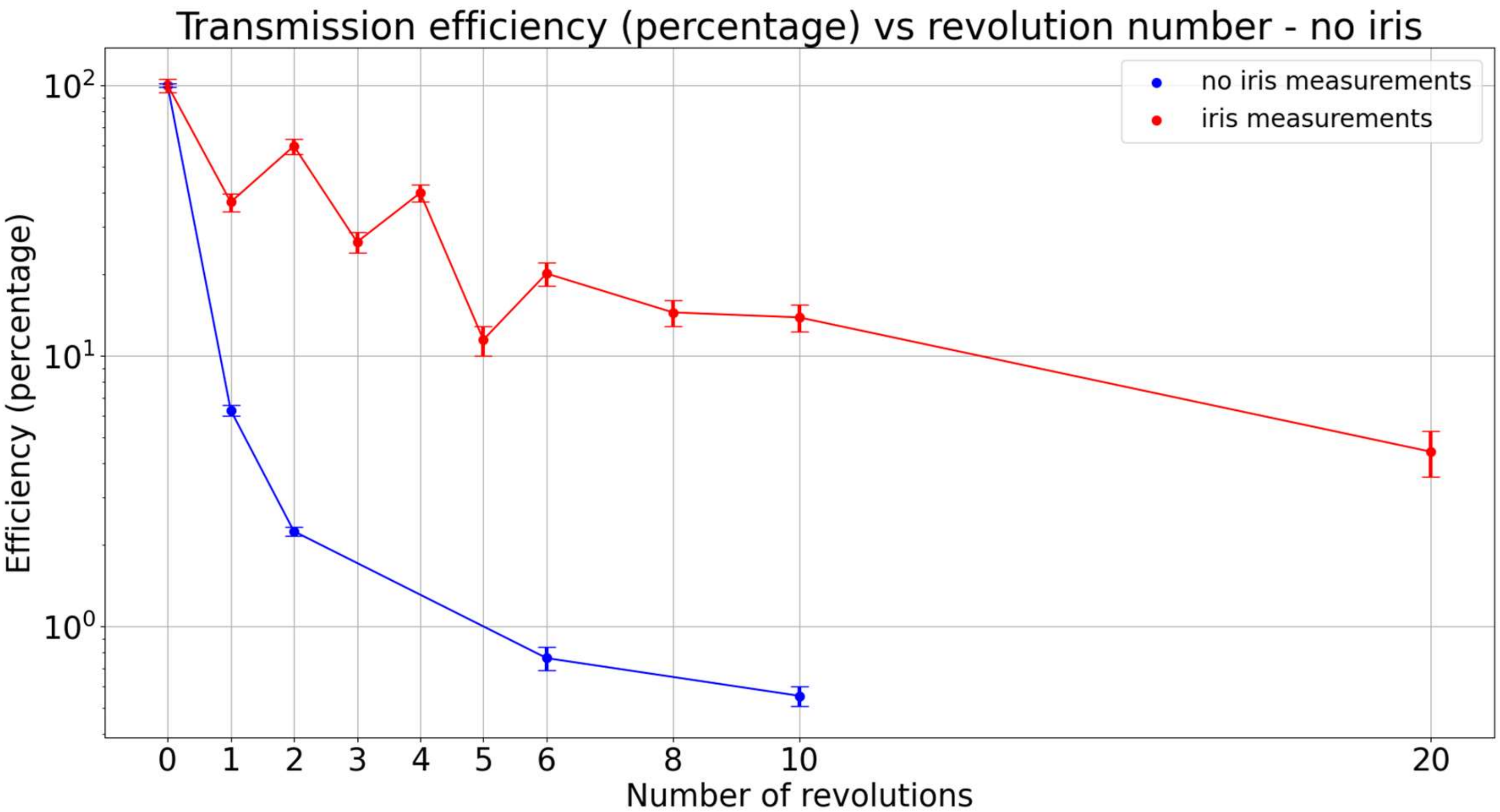
university of groningen / faculty of science and engineering



Maximum revolution number: 20

Surviving ions after 20 revolutions: ~4%

Results & Discussion



Transmission efficiency:

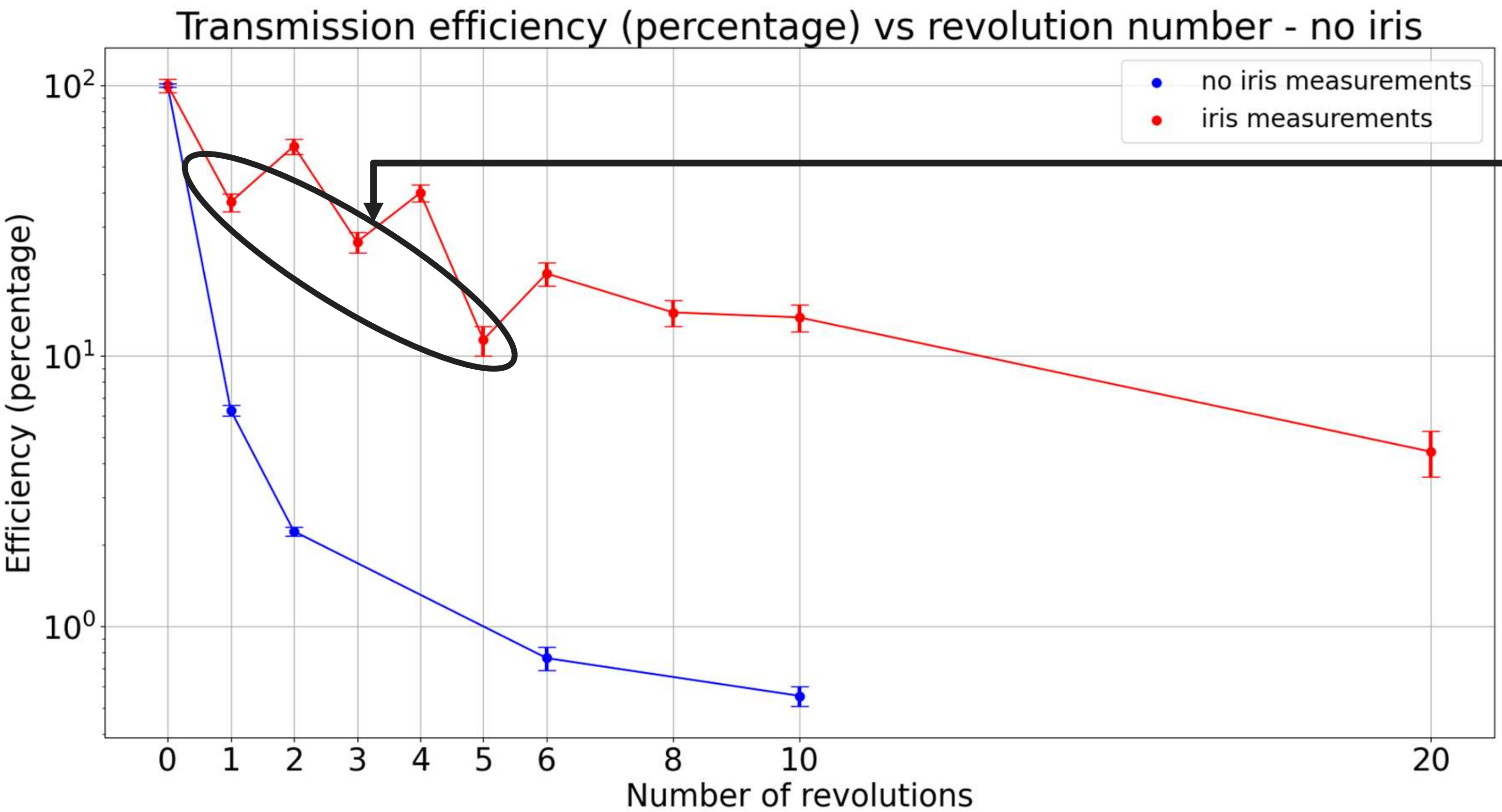
$$T = \frac{N_{ejected}}{N_{injected}} \cdot 100\%$$

$T =$ **Efficiency**

$N_{ejected} =$ **Number of injected ions**

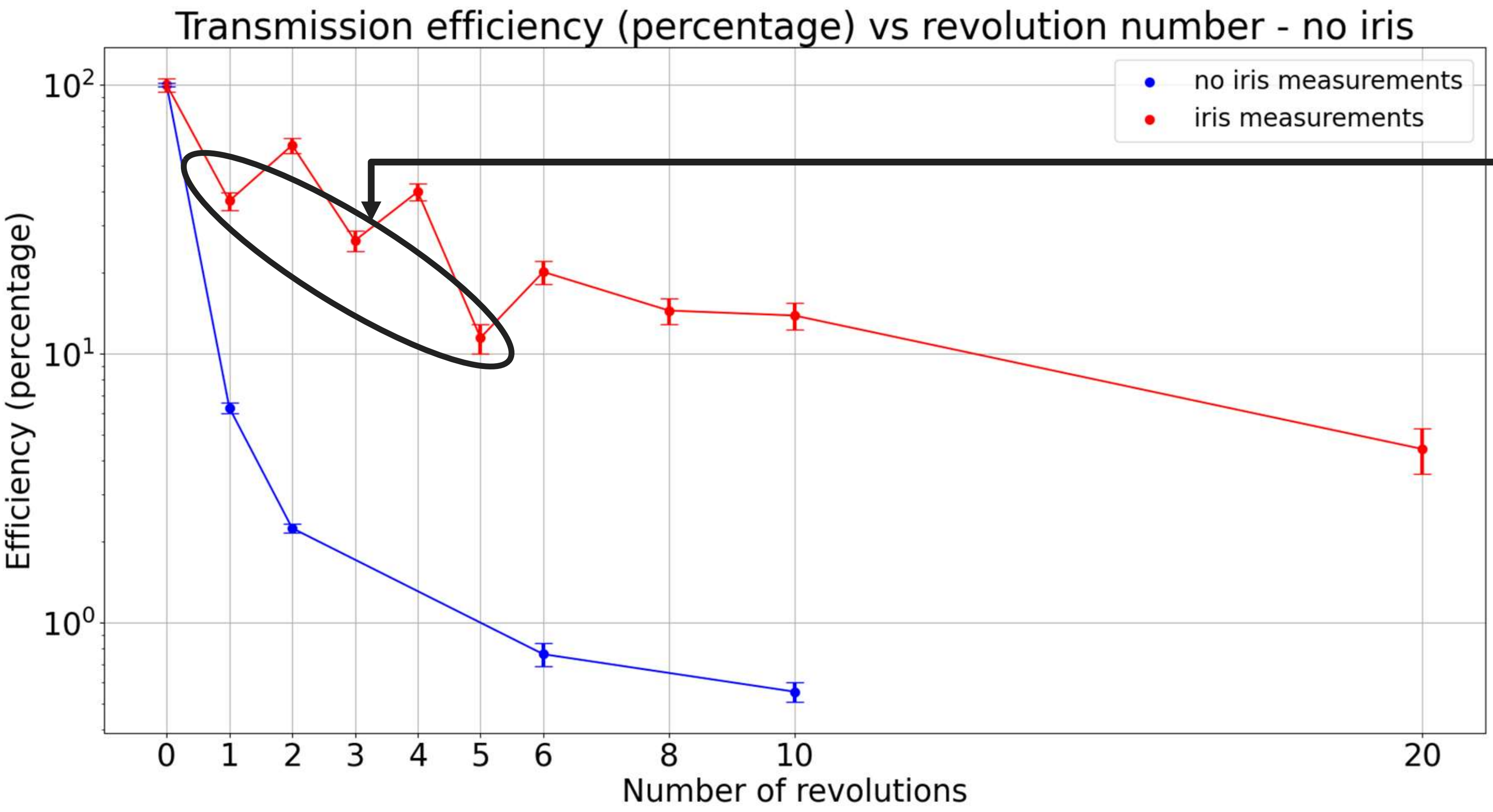
$N_{injected} =$ **Number of ejected ions**

Results & Discussion



Oscillating efficiency

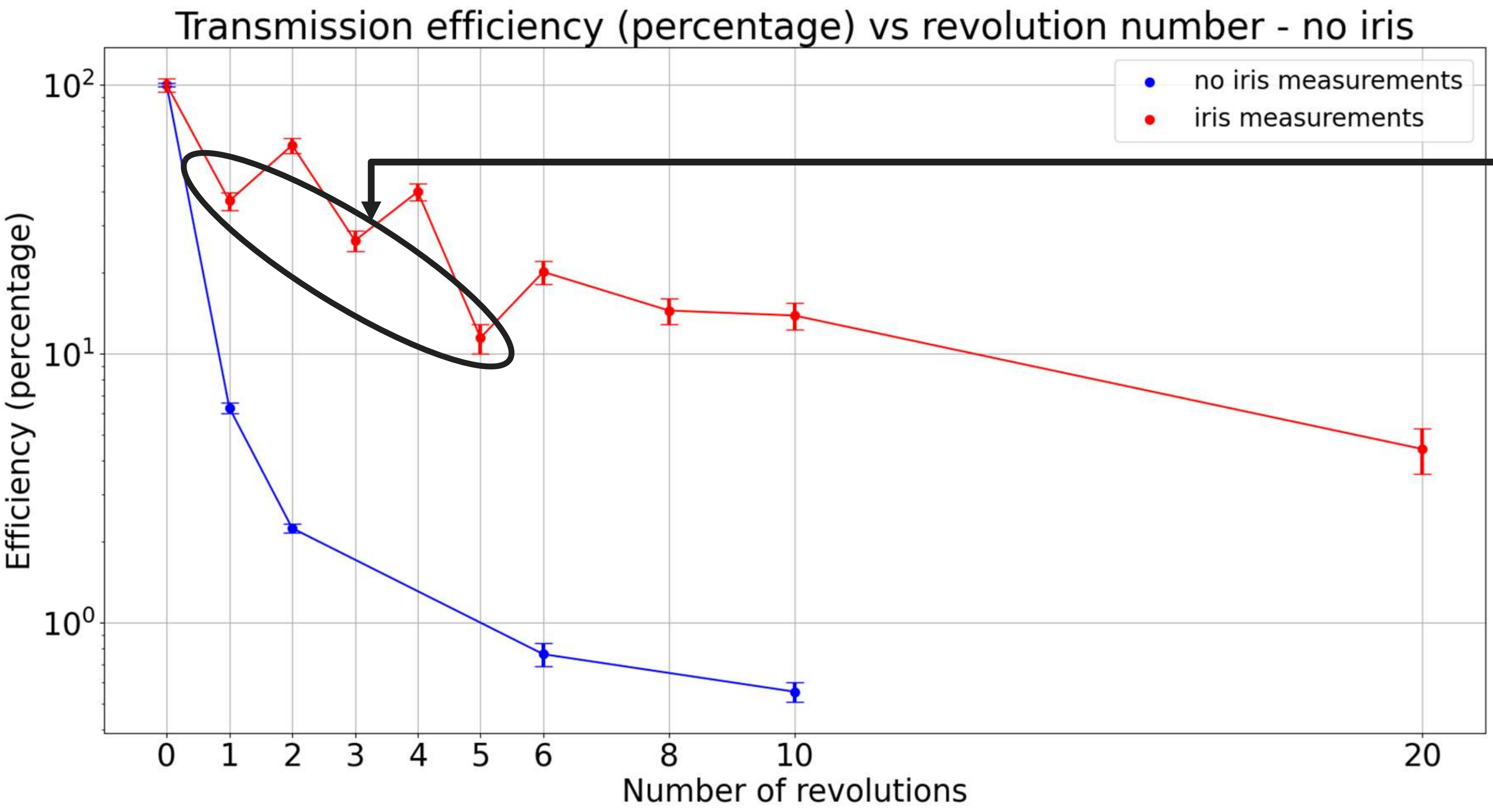
Results & Discussion



Oscillating efficiency

Offset in storage time

Results & Discussion

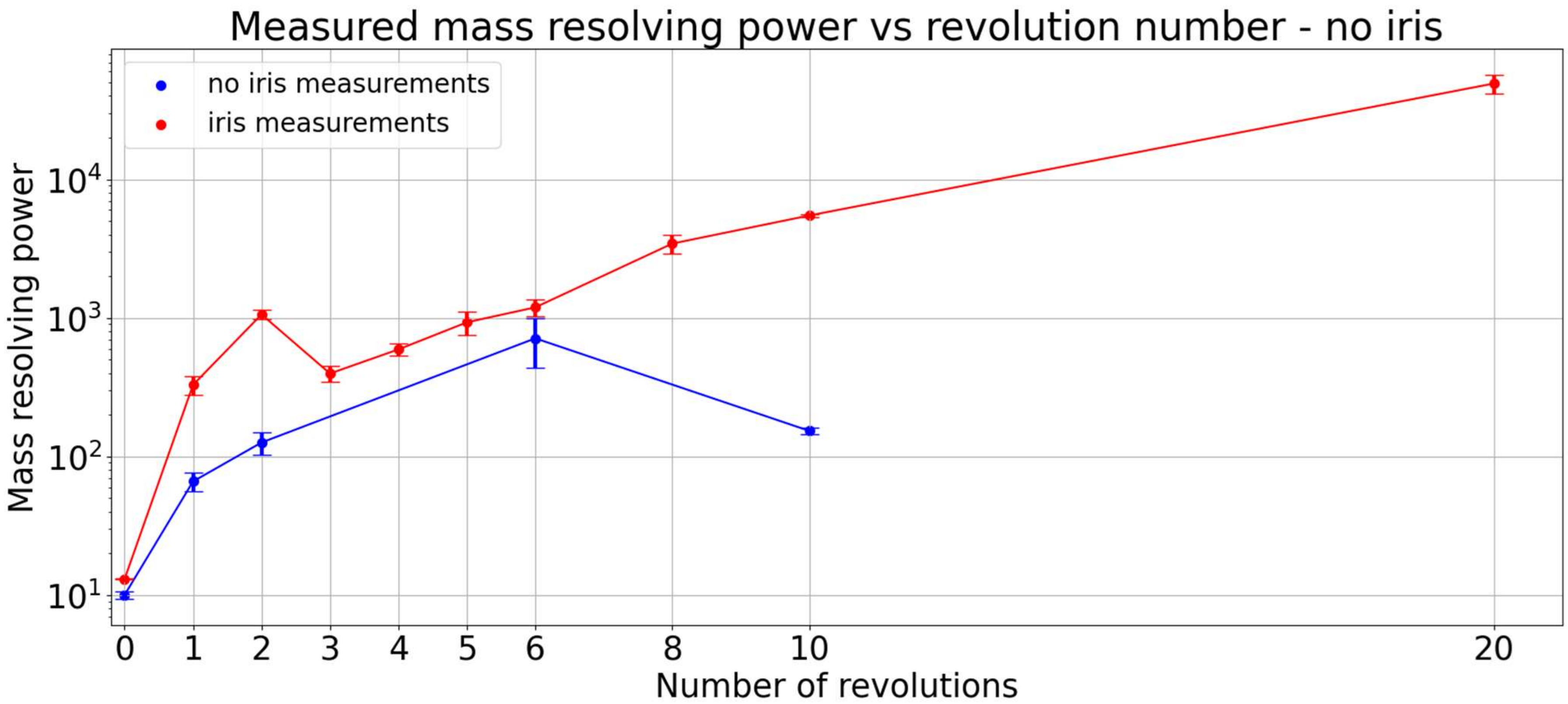


Oscillating efficiency

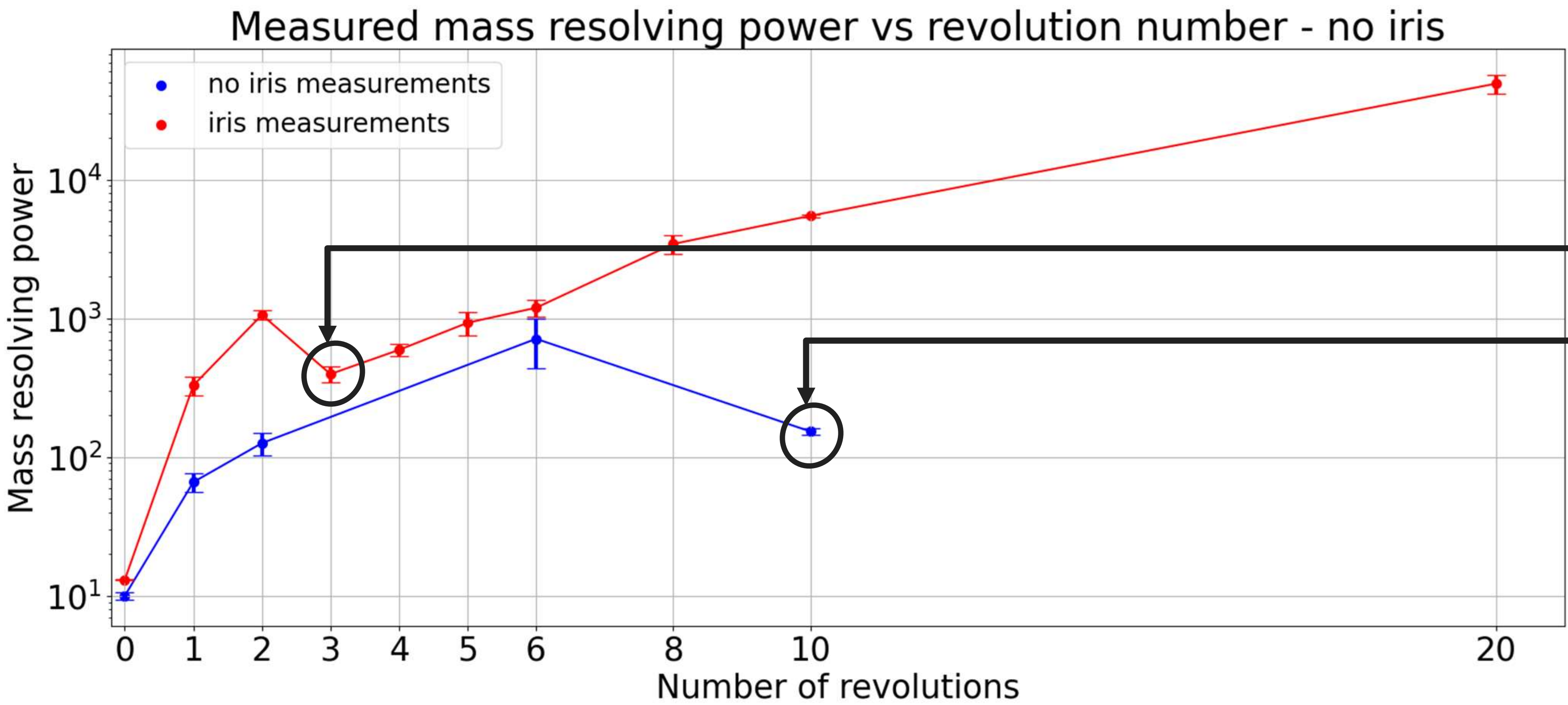
Offset in storage time

Cutoff for wide peaks

Results & Discussion



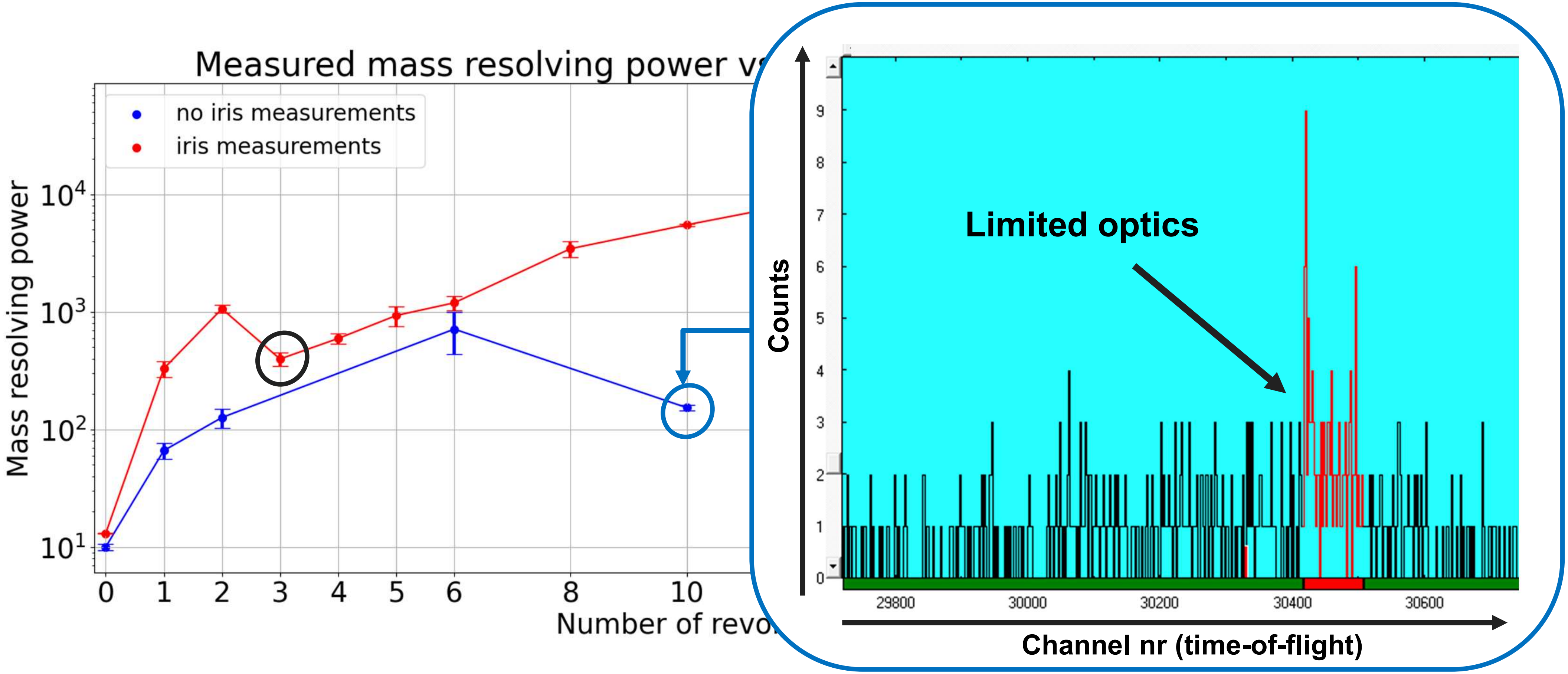
Results & Discussion



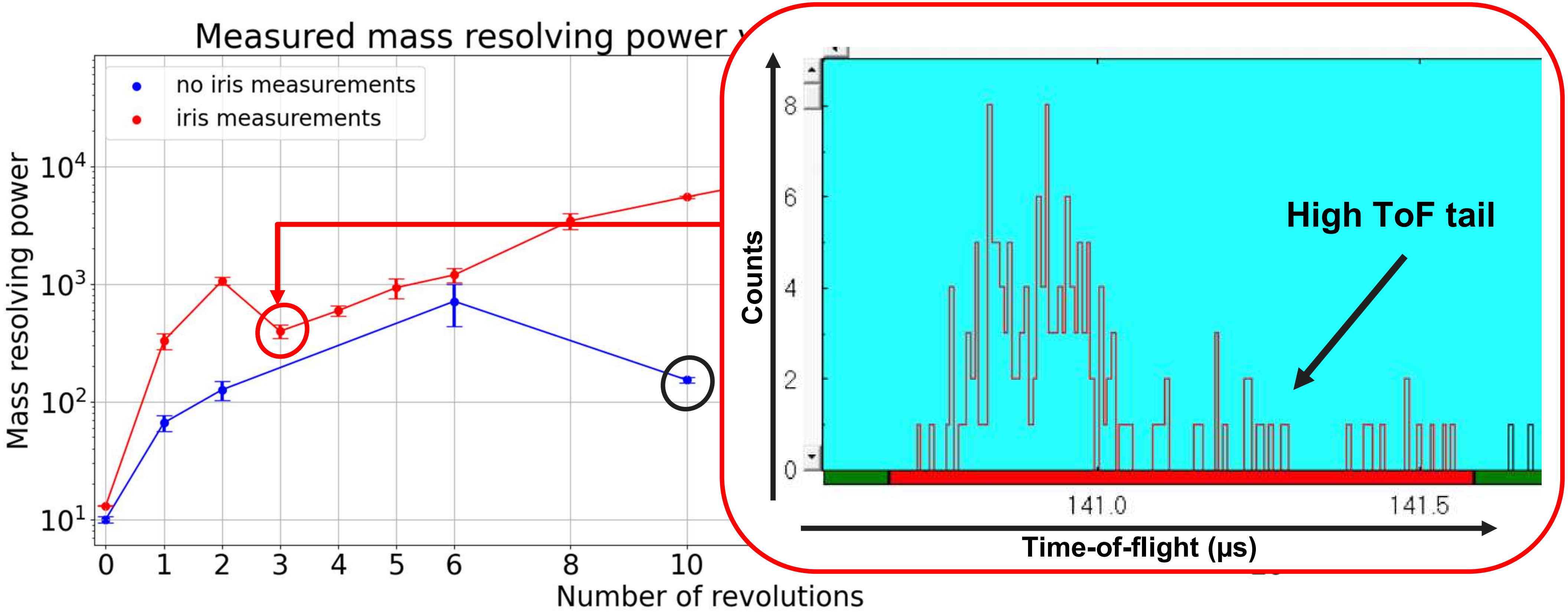
Wider peak shape

$$R = \frac{t}{2\Delta t}$$

Results & Discussion



Results & Discussion



Discussion

Future improvements:

- **Pulsing technique**

Solutions:

Discussion

Future improvements:

Solutions:

- **Pulsing technique**

↓

Peak tail on long ToF end

Discussion

university of groningen / faculty of science and engineering

Future improvements:

- **Pulsing technique**

↓

Peak tail on long ToF end

↓

Ion losses on multiple revolutions

Solutions:

Discussion

university of groningen / faculty of science and engineering

Future improvements:

- **Pulsing technique**

Peak tail on long ToF end

Ion losses on multiple revolutions

Solutions:

Stacked-ring ion guide

- better bunching -

Discussion

university of groningen / faculty of science and engineering

Future improvements:

Solutions:

- **Pulsing technique** → **Stacked-ring ion guide**
  - **better bunching -**

- **Ion source emission**

Discussion

Future improvements:

- **Pulsing technique** → **Stacked-ring ion guide - better bunching -**
- **Ion source emission** → **- denser ion bunches -**

Solutions:

Discussion

Future improvements:

Solutions:

- **Pulsing technique** → **Stacked-ring ion guide**
  - better bunching -
- **Ion source emission** → **- denser ion bunches -**
- **Better peak shapes**

Discussion

Future improvements:

- Pulsing technique → Stacked-ring ion guide - better bunching -
- Ion source emission → - denser ion bunches -
- Better peak shapes → Continue iterative voltage calibration - better optics -

Solutions:

Stacked-ring ion guide
- better bunching -

- denser ion bunches -

Continue iterative voltage calibration
- better optics -

Discussion

Future improvements:

- Pulsing technique → Stacked-ring ion guide - better bunching -
- Ion source emission → - denser ion bunches -
- Better peak shapes → Continue iterative voltage calibration - better optics -; Longer measurements - better statistics -

Solutions:

Stacked-ring ion guide
- better bunching -

- denser ion bunches -

Continue iterative voltage calibration
- better optics -

Longer measurements
- better statistics -

Conclusion

Highlights:

- **MR ToF MS ion beam optics optimized**

K. Blaum, “High-accuracy mass spectrometry with stored ions,” Physics Reports, vol. 425, no. 1, pp. 1–78, 2006.

Conclusion

Highlights:

- **MR ToF MS ion beam optics optimized**
- **Pulsing with iris – better solution**

K. Blaum, "High-accuracy mass spectrometry with stored ions," Physics Reports, vol. 425, no. 1, pp. 1–78, 2006.

Conclusion

Highlights:

- **MR ToF MS ion beam optics optimized**
- **Pulsing with iris – better solution**
- **Up to 20 revolutions**
- **Resolution increased:**

~712 (no iris) → ~49,197 (iris)

K. Blaum, "High-accuracy mass spectrometry with stored ions," Physics Reports, vol. 425, no. 1, pp. 1–78, 2006.

Conclusion

university of groningen / faculty of science and engineering

Highlights:

- MR ToF MS ion beam optics optimized
- Pulsing with iris – better solution
- Up to 20 revolutions
- Resolution increased:

~712 (no iris) → ~49,197 (iris)

Outlook:

- Addition of ring ion guide

  - currently in construction -

K. Blaum, "High-accuracy mass spectrometry with stored ions," Physics Reports, vol. 425, no. 1, pp. 1–78, 2006.

Conclusion

university of groningen
faculty of science and engineering

Highlights:

- MR ToF MS ion beam optics optimized
- Pulsing with iris – better solution
- Up to 20 revolutions
- Resolution increased:

~712 (no iris) → ~49,197 (iris)

Outlook:

- Addition of ring ion guide
  - currently in construction -
- Resolution needed for isobaric separation

K. Blaum, “High-accuracy mass spectrometry with stored ions,” Physics Reports, vol. 425, no. 1, pp. 1–78, 2006.

Conclusion

Highlights:

- **MR ToF MS ion beam optics optimized**
- **Pulsing with iris – better solution**
- **Up to 20 revolutions**
- **Resolution increased:**

Outlook:

- **Addition of ring ion guide**

  - currently in construction -

- **Resolution needed for isobaric separation**

~712 (no iris) → ~49,197 (iris) → ≥ 100,000

K. Blaum, "High-accuracy mass spectrometry with stored ions," Physics Reports, vol. 425, no. 1, pp. 1–78, 2006.

Acknowledgements

university of groningen / faculty of science and engineering

Julia Even

Marko Brajković

Briain Hartigan

Xiancheng Chen

Jennifer Cipagauta Mora

Arif Soylu

Niels Bouwman

Nathan Moores

Conclusion

Highlights:

- **MR ToF MS ion beam optics optimized**
- **Pulsing with iris – better solution**
- **Up to 20 revolutions**
- **Resolution increased:**

Outlook:

- **Addition of ring ion guide**

  - currently in construction -

- **Resolution needed for isobaric separation**

~712 (no iris) → ~49,197 (iris) → ≥ 100,000

K. Blaum, "High-accuracy mass spectrometry with stored ions," Physics Reports, vol. 425, no. 1, pp. 1–78, 2006.

References

[1] W. N. Cottingham and D. A. Greenwood, An Introduction to Nuclear Physics, 2nd ed. Cambridge University Press, 2001, isbn: 0-521-65733-4..

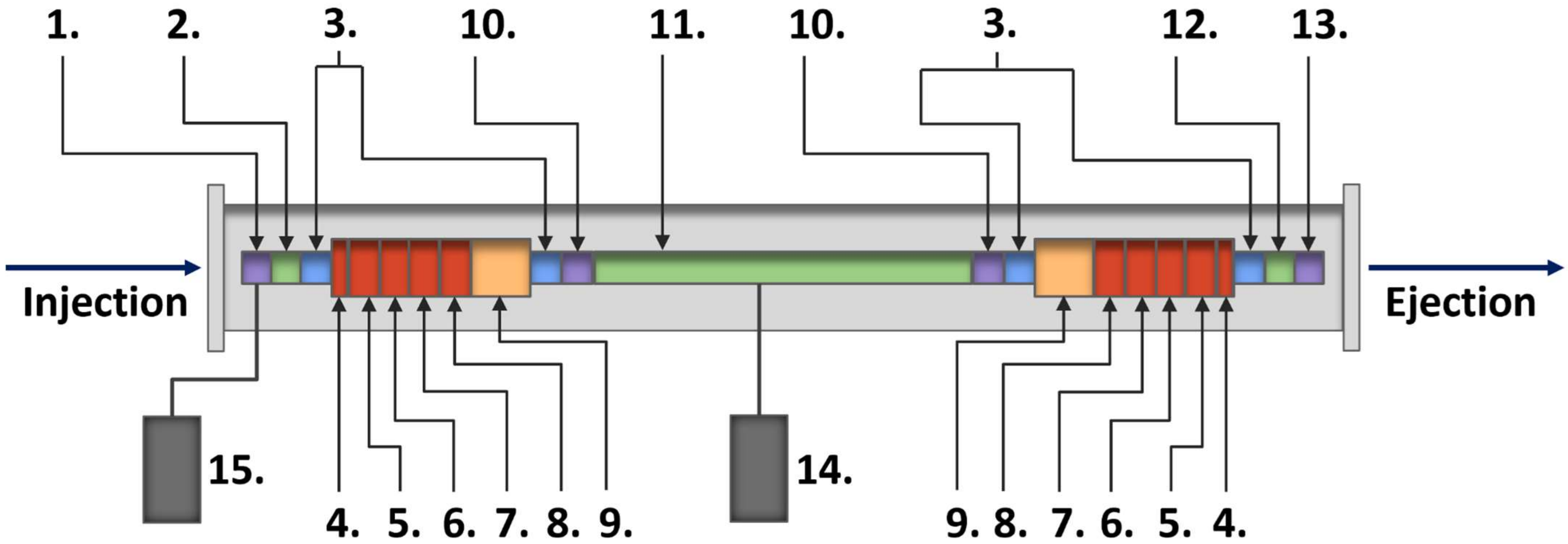
[2] M. Wang, W. Huang, F. Kondev, G. Audi, and S. Naimi, “The ame 2020 atomic mass evaluation (ii). tables, graphs and references*,” Chinese Physics C, vol. 45, no. 3, p. 030 003, Mar. 2021. doi: 10.1088/1674-1137/abddaf. [Online]. Available: https://dx.doi.org/10.1088/1674-1137/abddaf

[3] J. Even, X. Chen, A. Soylu, et al., “The next project: Towards production and investigation of neutron-rich heavy nuclides,” Atoms, vol. 10, no. 2, 2022, issn: 2218-2004. doi: 10.3390/atoms10020059.

[4] R. N. Wolf, G. Marx, M. Rosenbusch, and L. Schweikhard, “Static-mirror ion capture and time focusing for electrostatic ion-beam traps and multi-reflection time-of-flight mass analyzers by use of an in-trap potential lift,” International Journal of Mass Spectrometry, vol. 313, pp. 8–14,2012, issn: 1387-3806. doi: https://doi.org/10.1016/j.ijms.2011.12.006.

[5] K. Blaum, “High-accuracy mass spectrometry with stored ions,” Physics Reports, vol. 425, no. 1, pp. 1–78, 2006, issn: 0370-1573. doi: https://doi.org/10.1016/j.physrep.2005.10.011.

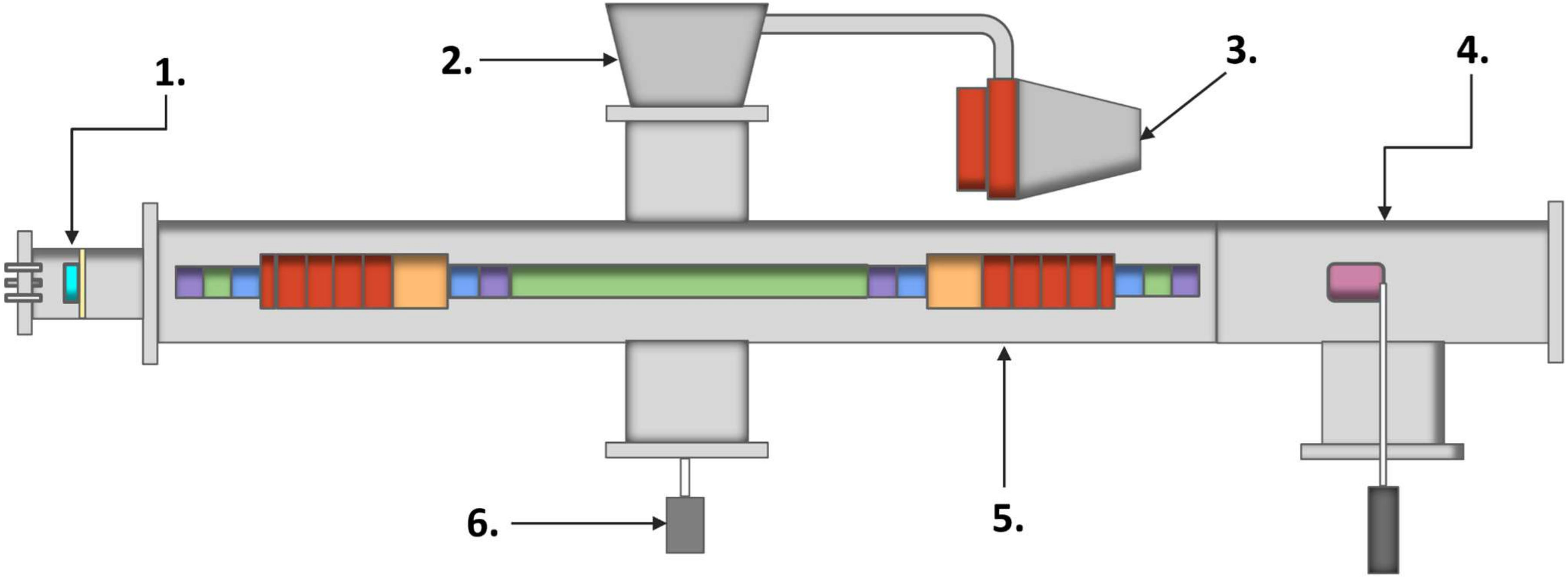
Backup slides



The electrodes of the MR ToF MS: 1. Steering electrodes; 2. Mirror lens; 3. Grounded sections; 4. Mirror 6 (M6); 5. Mirror 5 (M5); 6. Mirror 4 (M4); 7. Mirror 3 (M3); 8. Mirror 2 (M2); 9. Mirror 1 (M1); 10. Deflector lenses; 11. Drift tube; 12. Mirror lens; 13. Steering electrodes; 14. Drift tube switch; 15. Injection steering switch.

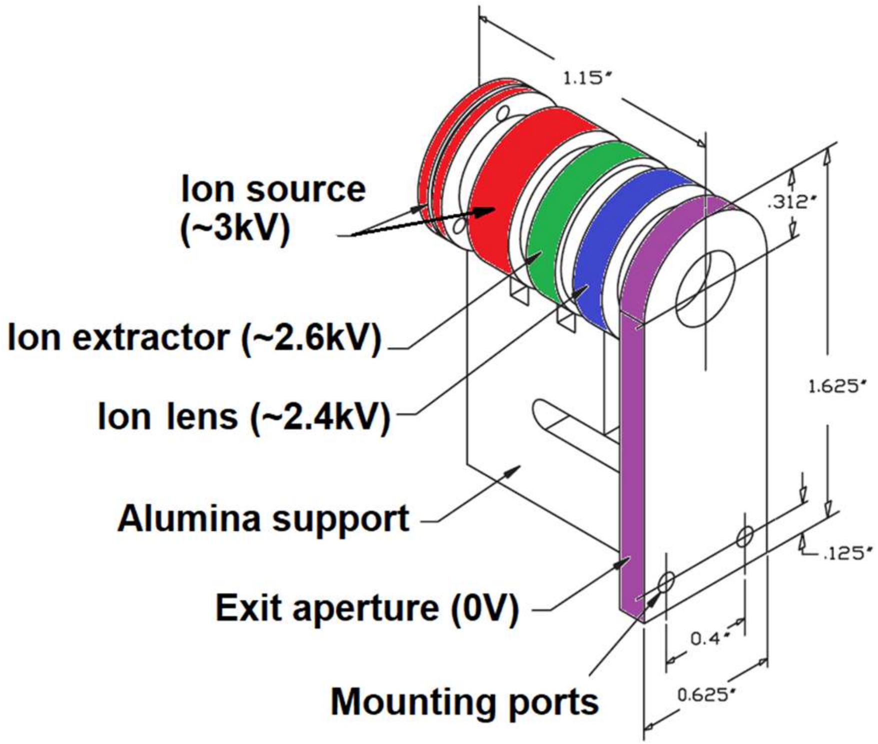
Backup slides

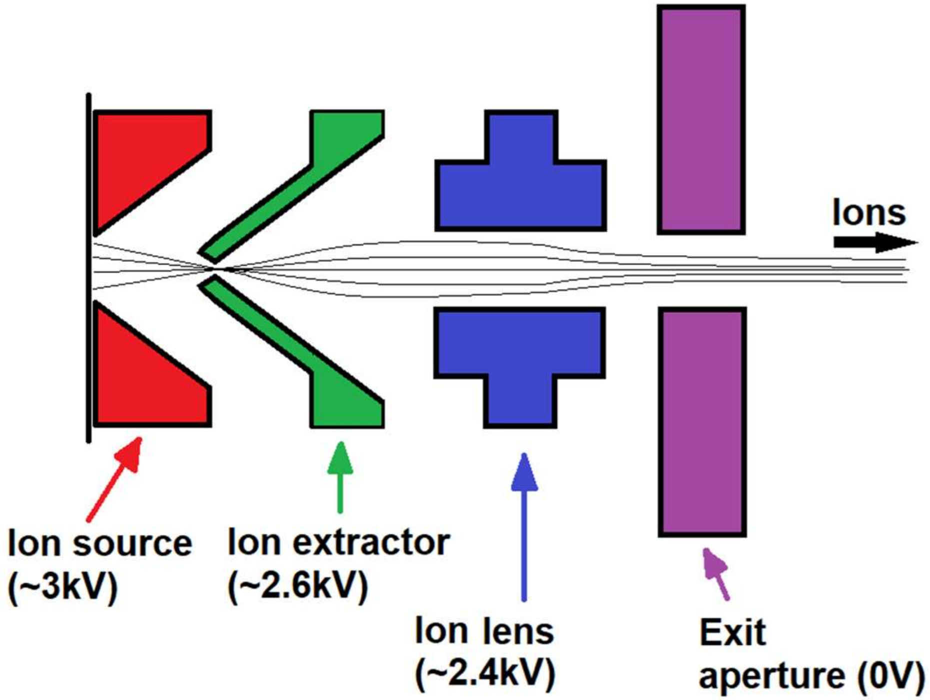
university of groningen / faculty of science and engineering



The setup pumping schematic: 1. The injection region, housing the ion source; 2. The HIPACE 700 H turbopump used for high vacuum; 3. The HISCROLL 18 scroll prepump, used for partial vacuum; 4. The ejection region, housing the detector; 5. The MR ToF MS region; 6. The Bayard–Alpert PBR 260 hot cathode ionization vacuum gauge.

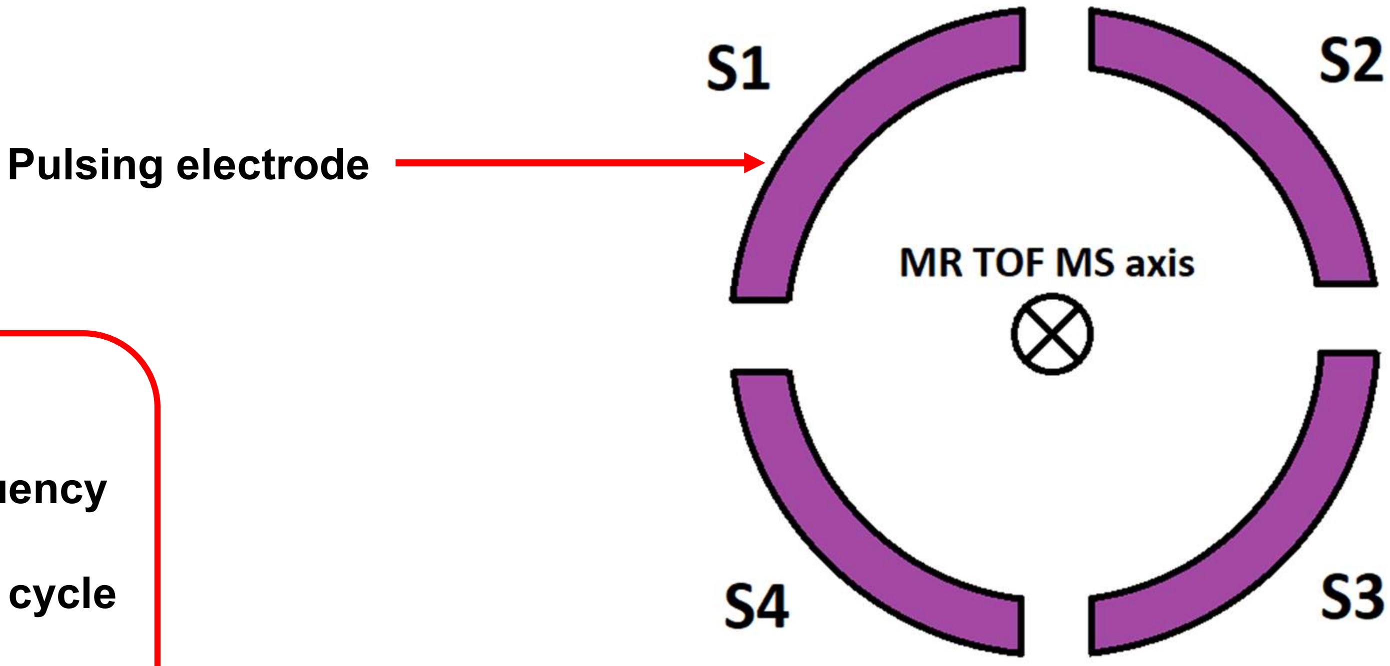
Backup slides





The ion gun technical drawing (left), and electrode cross-section (right)

Backup slides



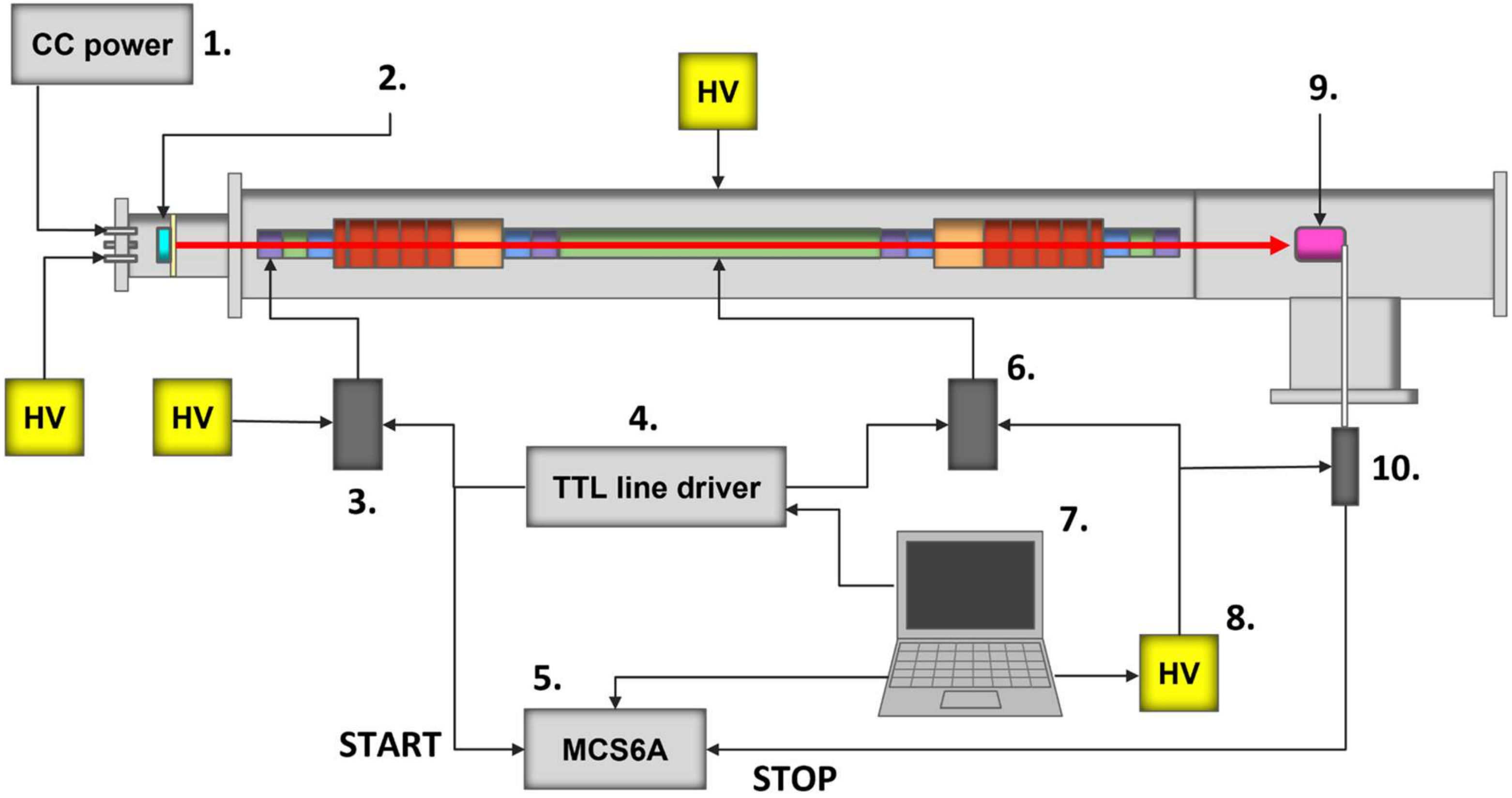
Cross-section of steering lens: Four steering electrodes S1-S4

Pulsing:

- 1Khz frequency
- 0.999 duty cycle
- 1μs long pulses

Backup slides

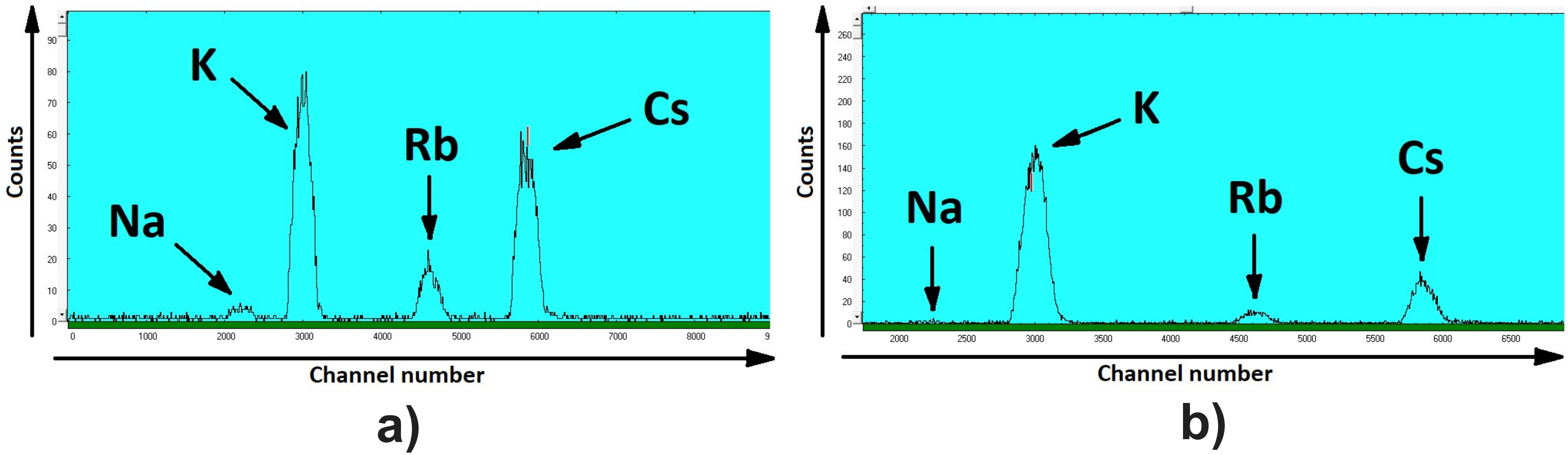
university of groningen / faculty of science and engineering



The setup electrical schematic - no iris

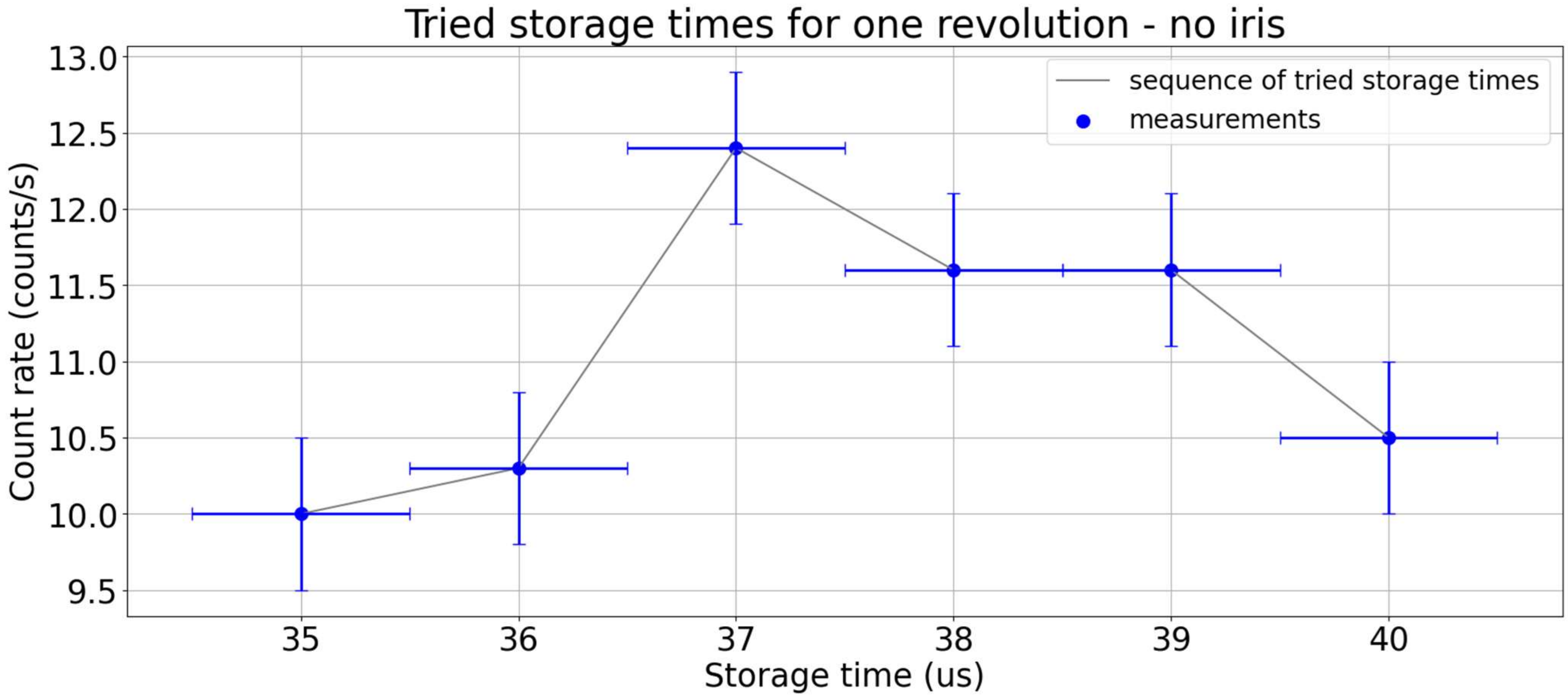
1. CC power supply;
2. Thermionic emission ion source and ion gun;
3. High voltage switch for the injection steering electrode S1;
4. TTL line driver;
5. MCS6A unit;
6. High voltage switch for the drift tube lift voltage;
7. Computer;
8. Multi-channel high voltage (HV) module;
9. MCP detector;
10. MCP detector stand of adjustable height.

Backup slides



The time-of-flight spectra of the ion source: a) and b) are separated by a few hours

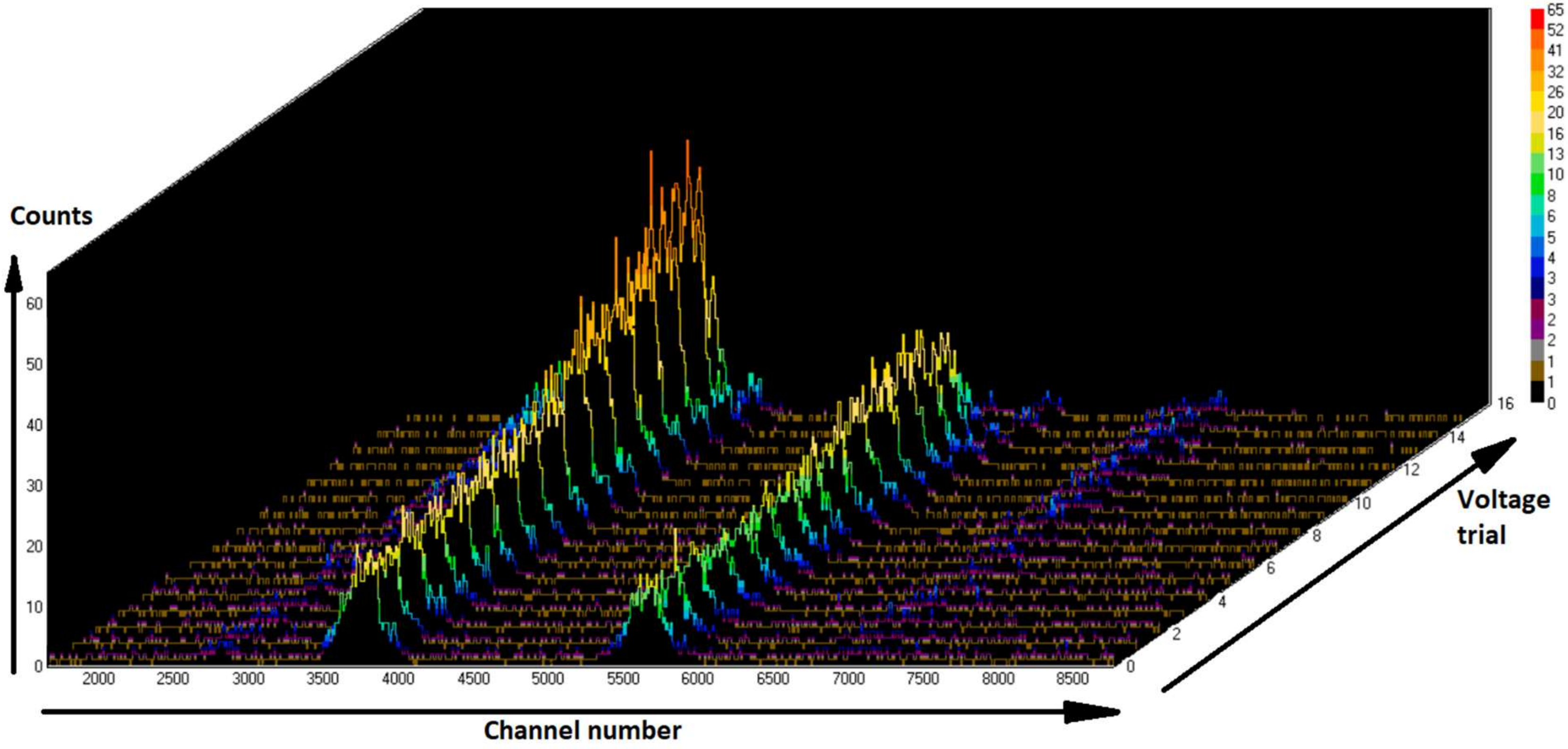
Backup slides



The ion count rates for the tried storage times for one revolution. These were performed in the setup configuration without the iris. For ease of readability, the measurements (in blue) were connected by a fine grey line.

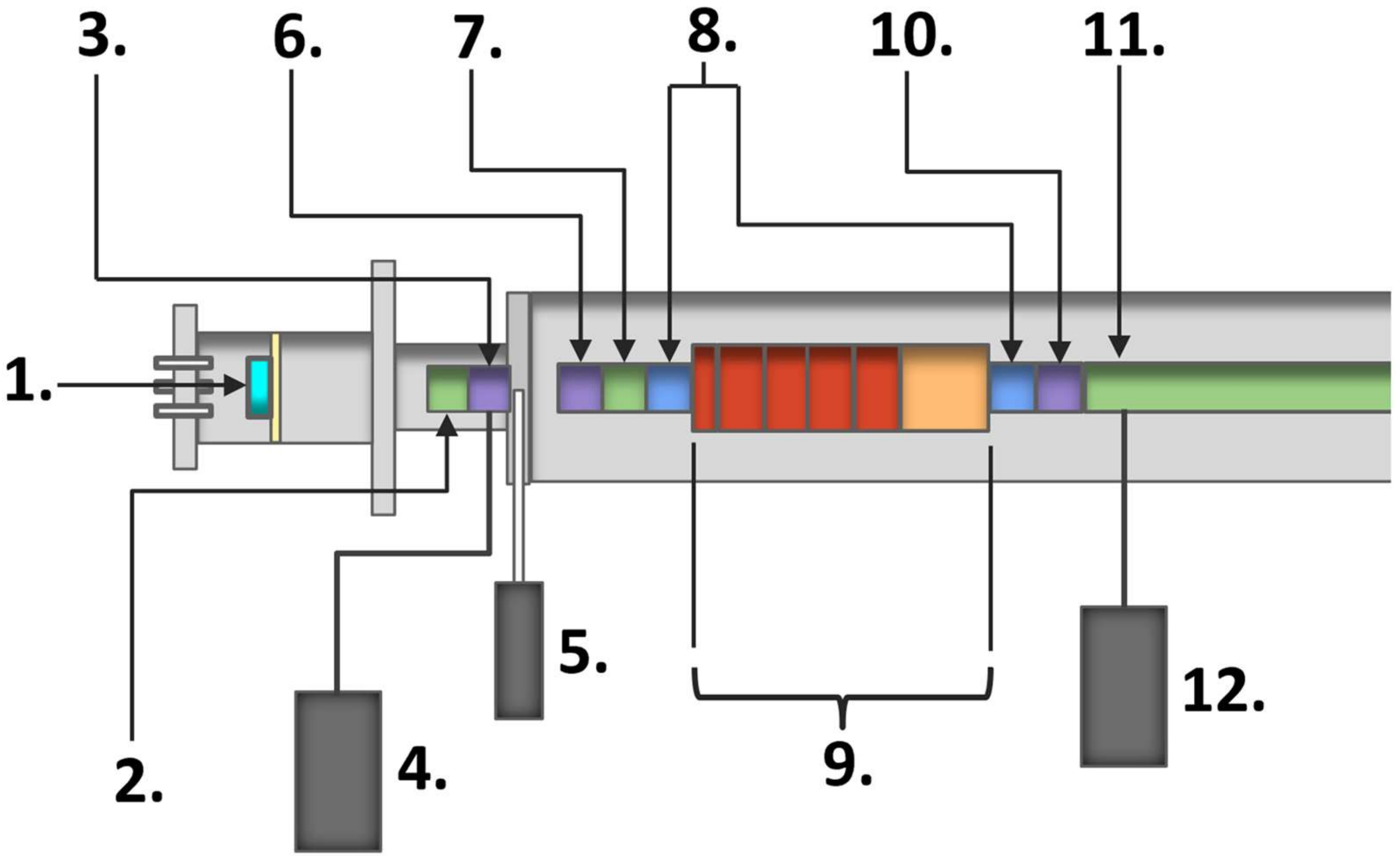
Backup slides

university of groningen / faculty of science and engineering



The time-of-flight spectra corresponding to the [0V, 1500V] voltage range in 100V steps, for the optimization of the lift voltage. A trend in the number of counts can be inferred from the change in peak heights for varying set voltages.

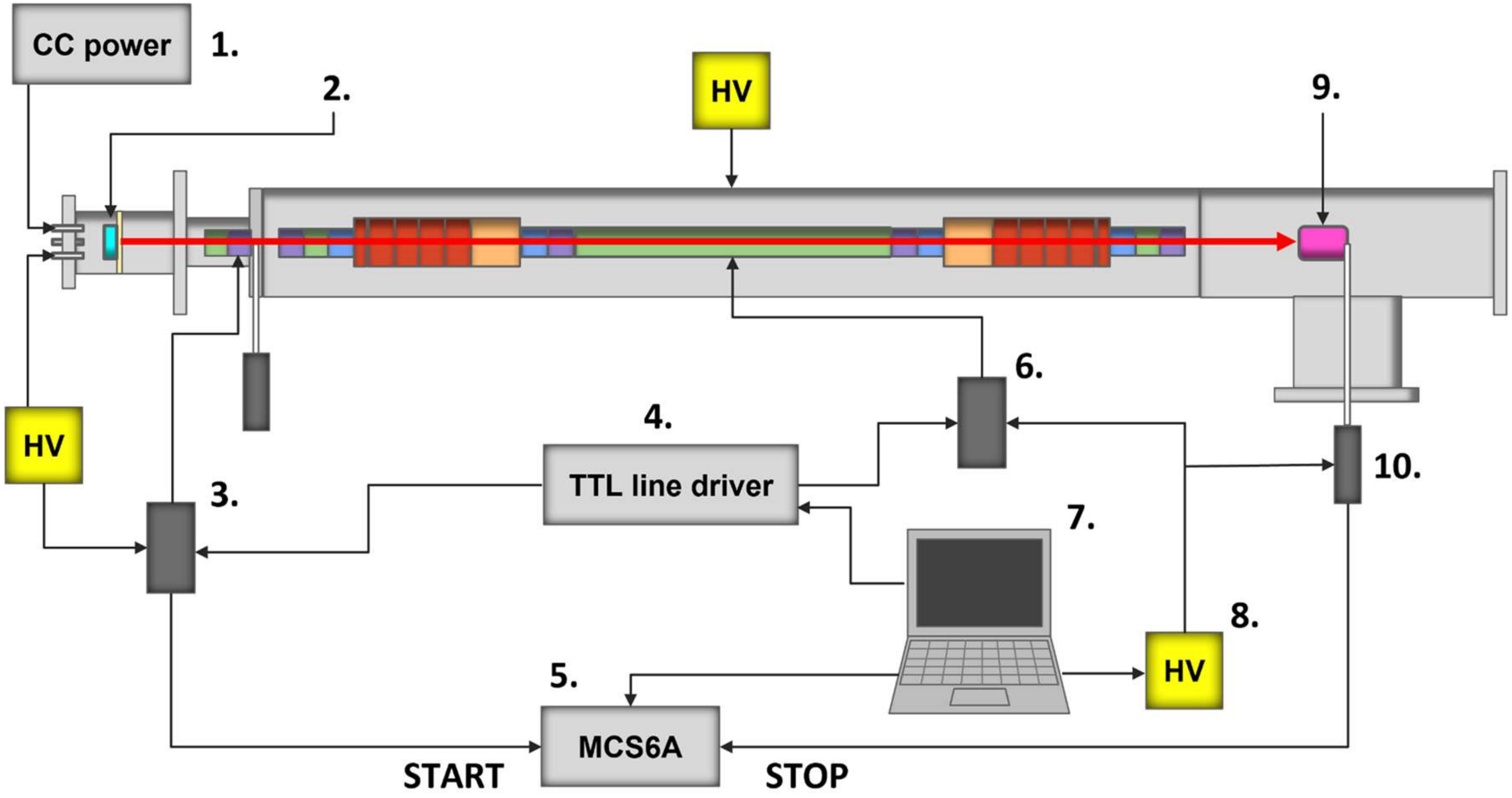
Backup slides



The MR ToF MS electrodes - with iris

1. Ion gun and source;
2. Added mirror lens;
3. Added steering electrodes;
4. Injection steering switch;
5. Iris with aperture adjustment arm;
6. Steering electrodes (injection side);
7. Mirror lens (injection side);
8. Grounded sections;
9. MR ToF MS mirror electrodes (injection side);
10. Deflector lenses;
11. Drift tube;
12. Drift tube switch.

Backup slides



The setup electrical schematic - iris included

1. CC power supply;
2. Thermionic emission ion source and ion gun;
3. High voltage switch for the added steering electrode S1;
4. TTL line driver;
5. MCS6A unit;
6. High voltage switch for the drift tube lift voltage;
7. Computer;
8. Multi-channel high voltage (HV) module;
9. MCP detector;
10. MCP detector stand of adjustable height.

Backup slides

university of groningen / faculty of science and engineering

The storage time, count rate, mass resolving power and transmission efficiency for the setup with no iris

Number of revolutions	Storage time (μs)	Count rate (counts/s)	Mass resolution	Efficiency (%)
0	0±0.5	66.8±0.6	10.0±0.6	100 ±2
1	37±0.5	4.2±0.2	66±10	6.3 ±0.3
2	78±0.5	1.50±0.05	126±23	2.25 ±0.08
6	230±0.5	0.51±0.05	712±277	0.76 ±0.08
10	366±0.5	0.37±0.03	153±9	0.55 ±0.05

Backup slides

university of groningen / faculty of science and engineering

The storage time, count rate, mass resolving power and transmission efficiency for the setup with the iris

Number of revolutions	Storage time (μs)	Count rate (counts/s)	Mass resolution	Efficiency (%)
0	0±0.5	6.3±0.3	13±0.2	100±6
1	36.8±0.05	2.3±0.2	329±52	37±3
2	73.7±0.05	3.7±0.2	1059±80	60±4
3	110±0.5	1.7±0.2	397±52	26±3
4	148±0.5	2.5±0.2	592±59	40±3
5	191±0.5	0.72±0.09	929±174	11±2
6	226±0.5	1.3±0.2	1192±166	20±2
8	307±0.5	0.9±0.1	3438±536	14±2
10	383±0.5	0.87±0.1	5484±121	14±2
20	776±0.5	0.28±0.06	49197±7808	4±1