Experimental Measurements of Electron Capture and Loss Cross Sections of Ions with Gaseous Targets

Fenna Ukena

21 January 2025

Accelerators at CERN

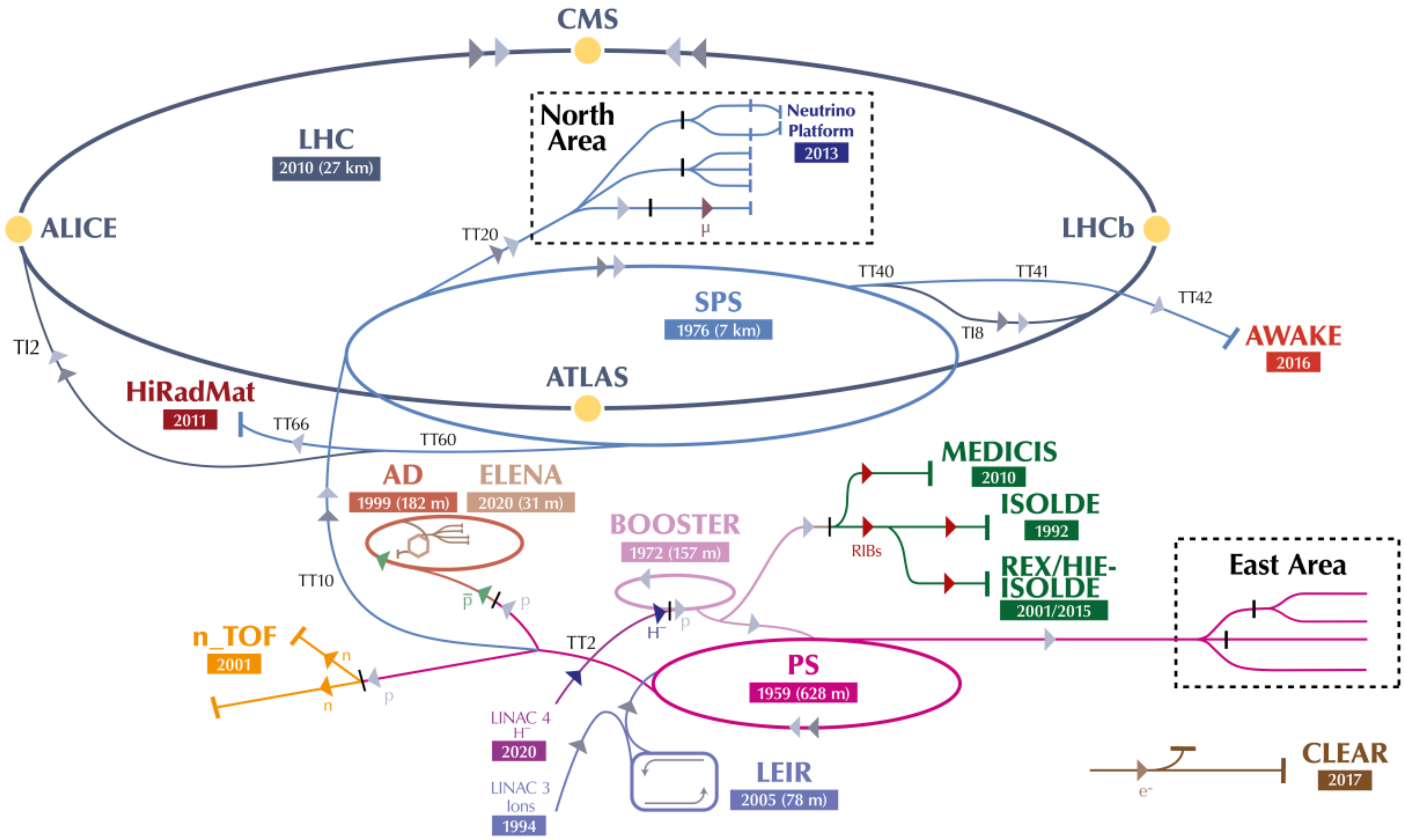
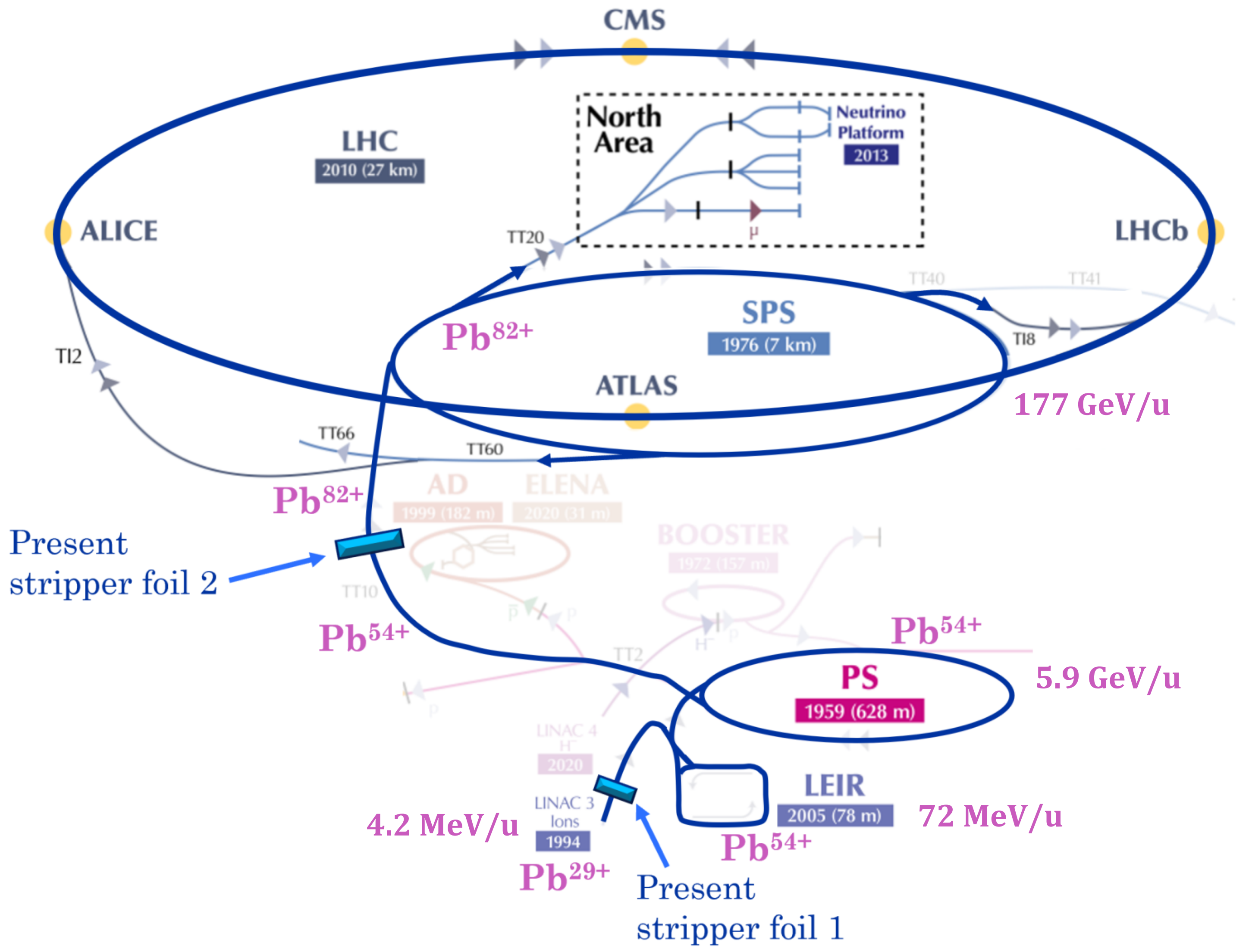


Image source: Lopienska, E. (2022), The CERN accelerator complex, Layout in 2022.

Ion Injector Chain at CERN



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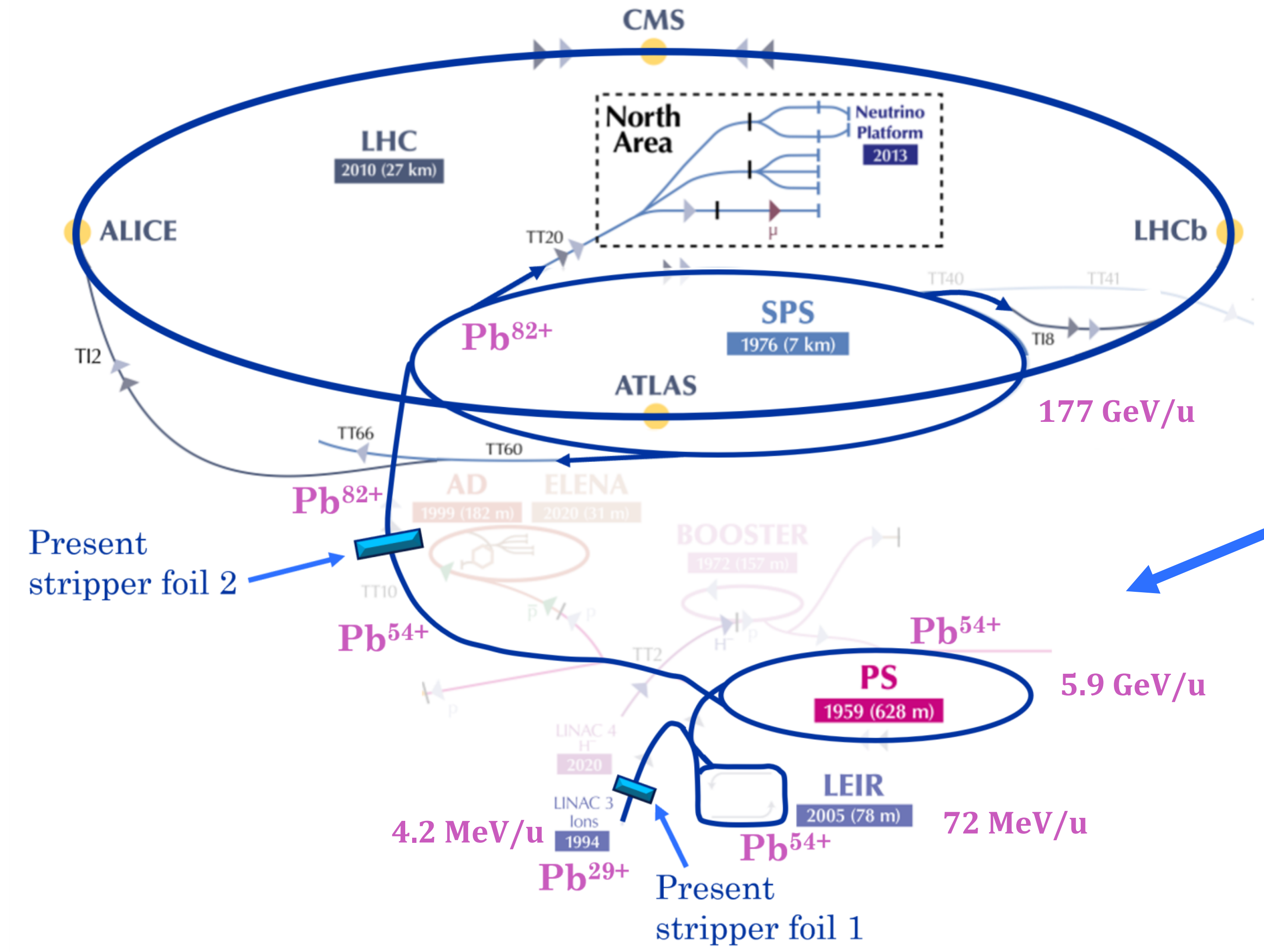

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Pb^{54+} ions are not fully stripped of electrons

→ susceptible to charge-changing processes

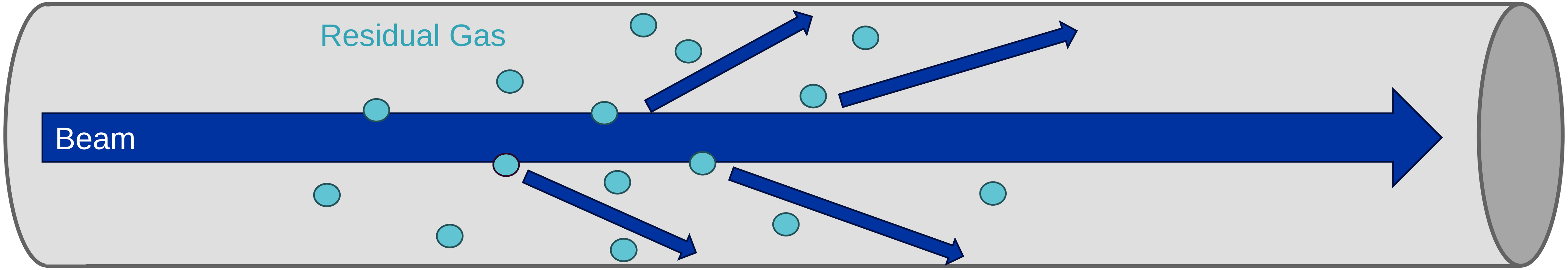
→ beam intensity losses

Aim: Measure cross sections for these processes and validate predictive models for future ion projects

Structure

1. **Beam-Gas Interactions**
2. **Cross Section and Lifetime**
3. **Concept**
4. **Experimental Setup**
5. **Steps of Analysis**
    - 3D Model
    - Simulation
    - Lifetime from Experiment in the PS
6. **Results**
7. **Conclusion**
8. **Outlook**

Beam-Gas Interactions



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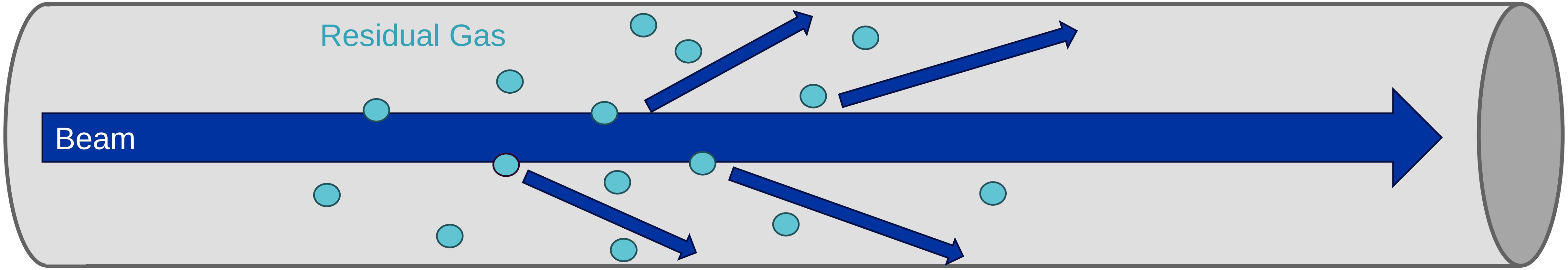

Electron Capture

$$B^{q+} + G \rightarrow B^{(q-k)+} + G^{k+}, k \geq 1$$

- e^- transfer from residual gas to beam ions

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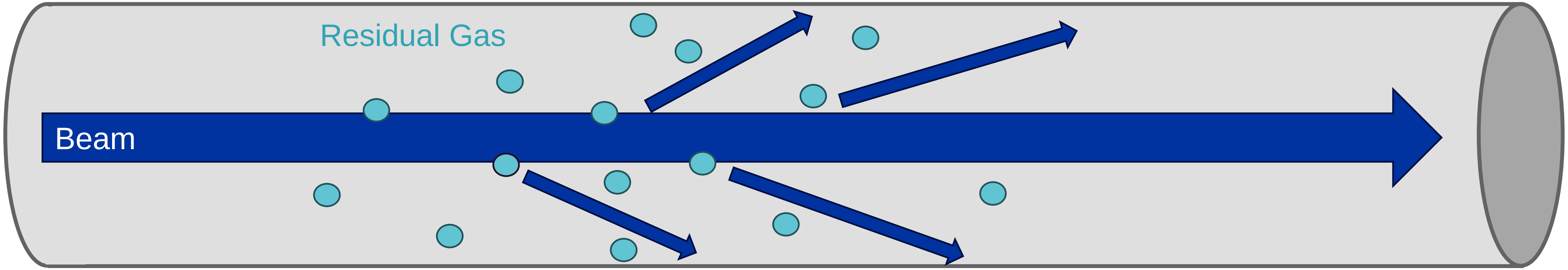

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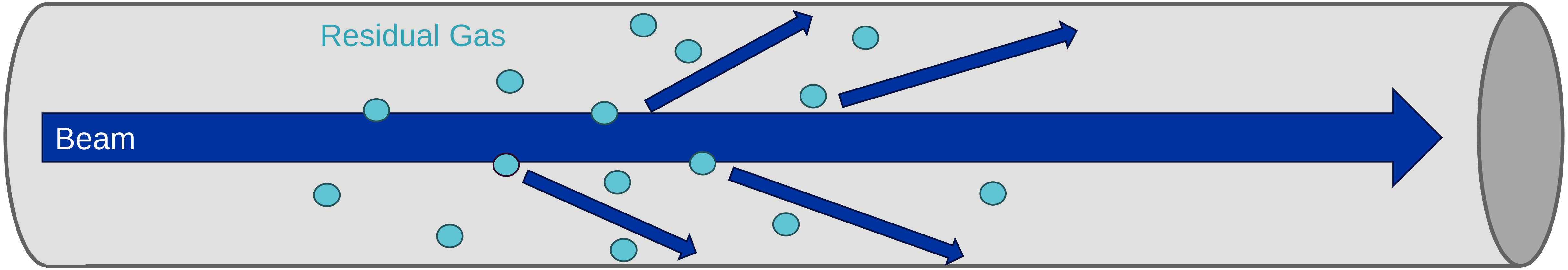
Electron Loss

$$B^{q+} + G \rightarrow B^{(q+m)+} + \Sigma G + me^-, m \geq 1$$

- e^- transfer from beam ions to residual gas
- Gas can be excited or ionized.

Beam-Gas Interactions



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- e^- transfer from beam ions to residual gas
- Gas can be excited or ionized

→ Charge-change of beam ions → Loss of beam intensity

Cross Section and Lifetime

Theory

- Wide range of semi-empirical models for electron capture and electron loss

→ Model by Schlachter et al. for electron capture

→ G. Weber model for electron loss

- Estimation of total cross section

$$\sigma_{tot} = \sigma_{EC} + \sigma_{EL}$$

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Experiment

- Calculation of lifetime using the experimental beam data of intensity loss

$$I(t) = I(t_0) \cdot e^{-\frac{t}{\tau}}$$

- Calculation of lifetime with total cross section and molecular density

$$\tau = \frac{1}{\sigma n \beta c}$$

Concept

Goals:

- Experimentally measure effects of electron loss and electron capture processes in the PS
- Comparison of experimental data and prediction of models for different ion species and gas types
- Validate semi-empirical models → lifetime predictions of future ion species

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Three Experiments:

- Pb^{54+} with Ar
- Pb^{54+} with He
- Mg^{7+} with Ar

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} **Measurements and Calculation of Cross Sections**

Problem: How do we isolate electron loss and electron capture losses from other losses in the PS to compare them to the models?

Experimental Setup

Beam Gas Ionization (BGI) monitor at the PS

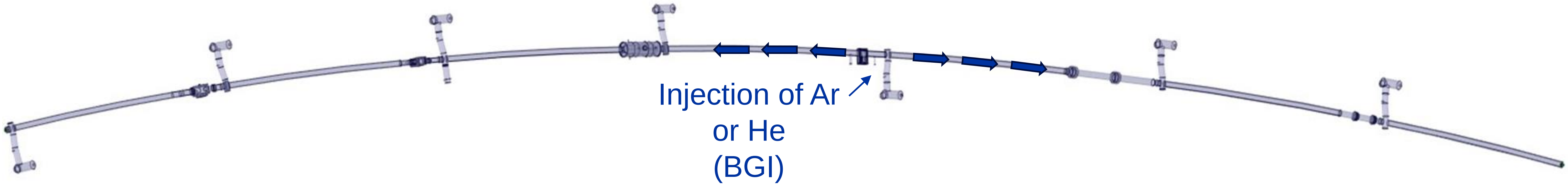
- Injects gas (normally argon), which is ionized by the passing beam to measure the transverse beam size

→ By utilizing the BGI injection system, we can inject gas around BGI location

- Injection of argon or helium
- Many magnitudes higher than the residual gas

Injection of Pb^{54+} and Mg^{7+} beams at energies of 72 MeV/u and 90 MeV/u

- Measurement of beam intensity decay for different pressures
- Fit of data to estimate beam lifetime and calculate cross sections



Steps of the Analysis

Analysis of the gas distribution

1. Building a 3D model of significant Sections of the PS
2. Simulation of the injected Ar and He gas and gas distribution along the PS beamline to generate a pressure profile for each injection, and calculation of the total average pressure in the PS

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Calculation of the cross section

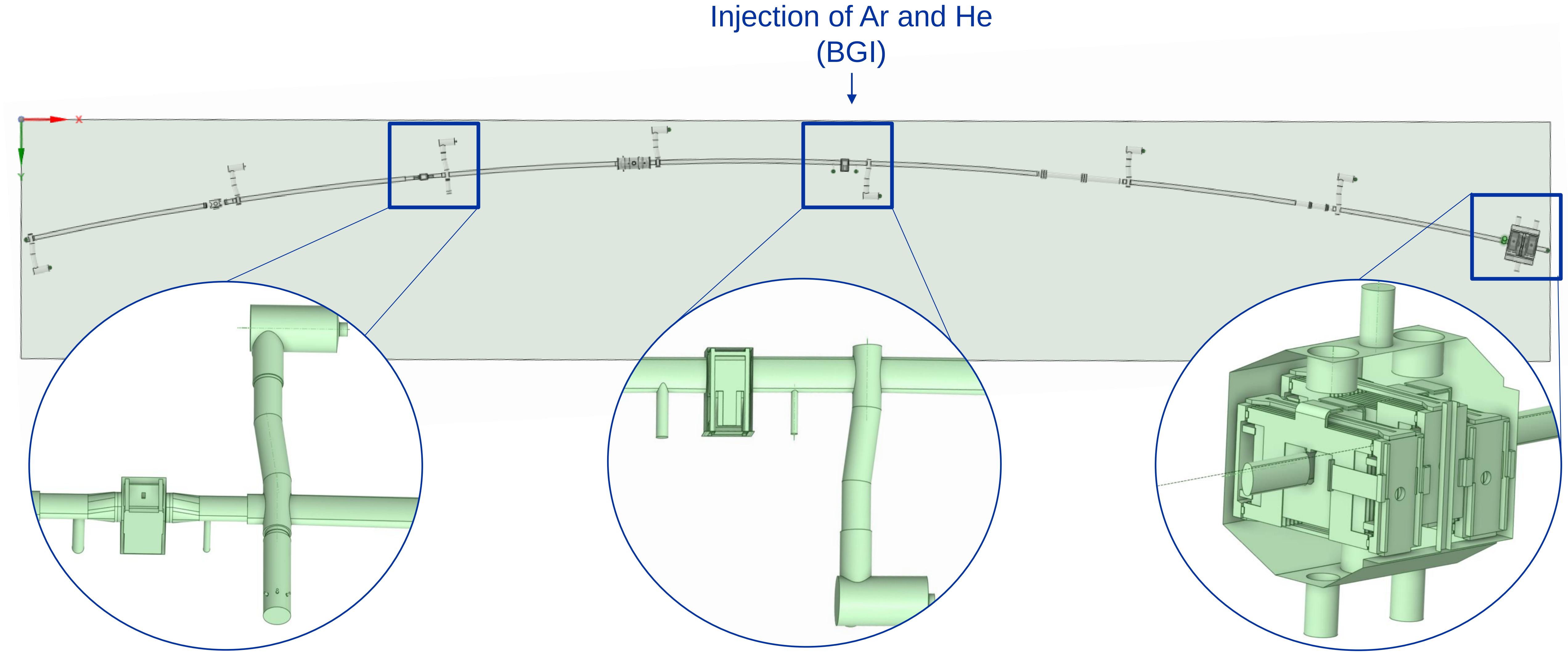
3. Calculation of lifetime and cross section in the PS using the experimental data

$$I(t) = I(t_0) \cdot e^{-\frac{t}{\tau}}$$

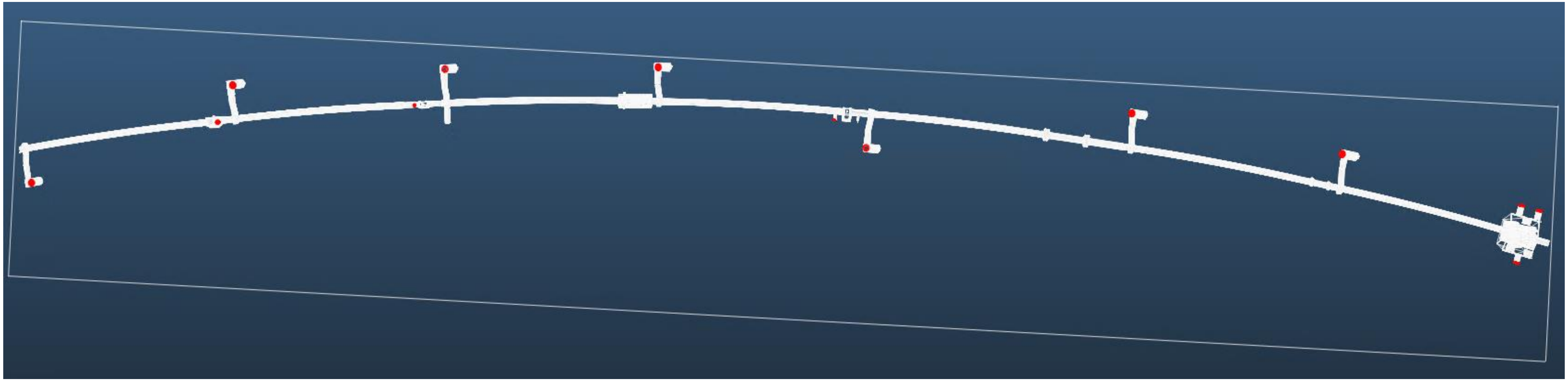
$$\sigma = \frac{1}{\tau\, n\, \beta\, c}$$

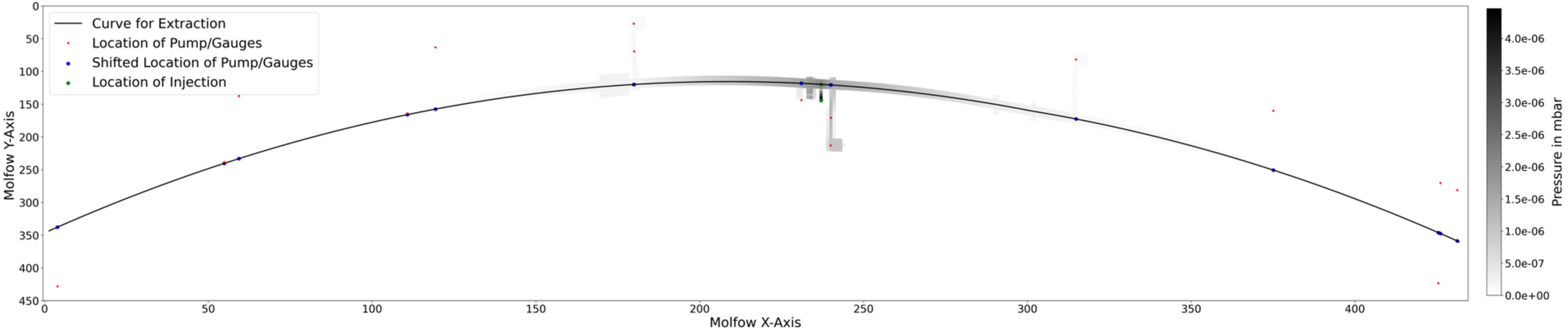
4. Calculating the theoretical cross section using the different models for electron loss and capture

1. 3D model of the PS using SpaceClaim



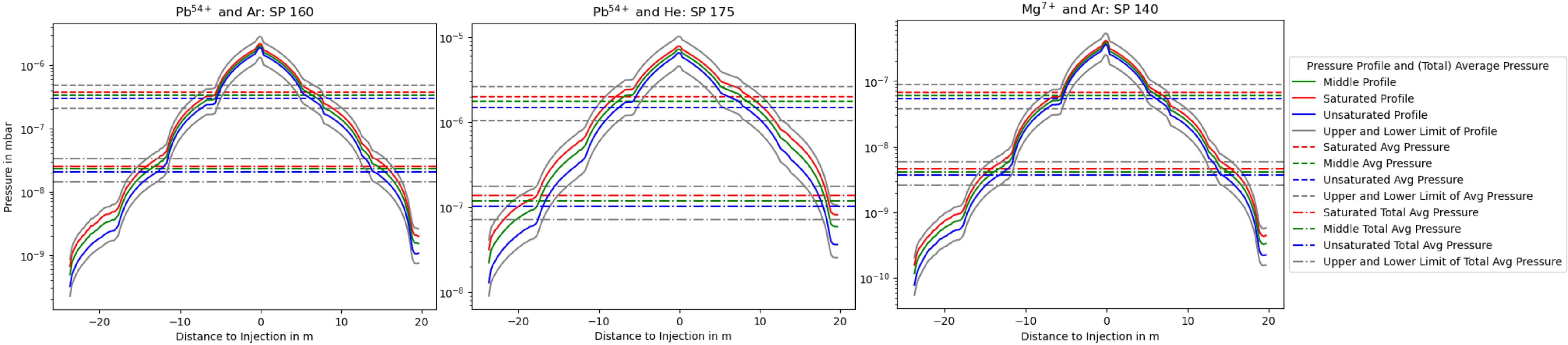
2. Simulation of the injected gas using Molflow





2. Simulation of the injected gas: Pressure Profile

- Setpoints (SP) correspond to the amount of gas injected
- Pumping speed estimation dependent on the pressure
- Saturation of the pumps represented via different profiles



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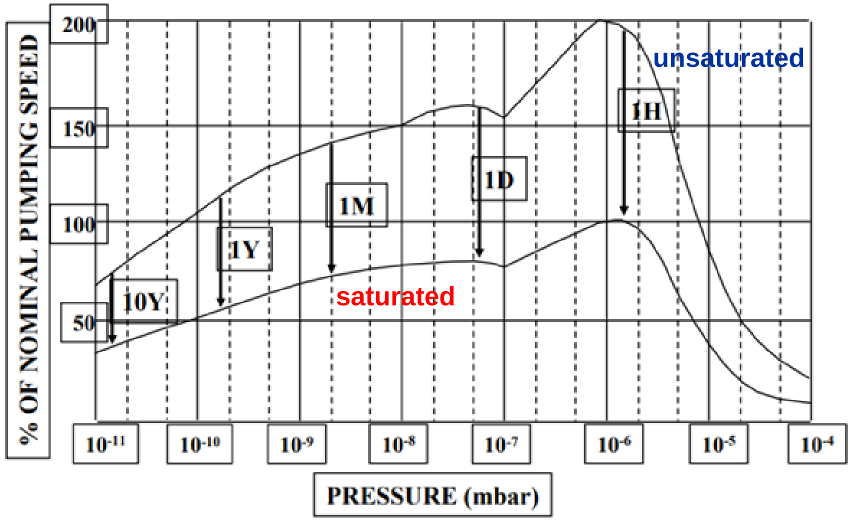
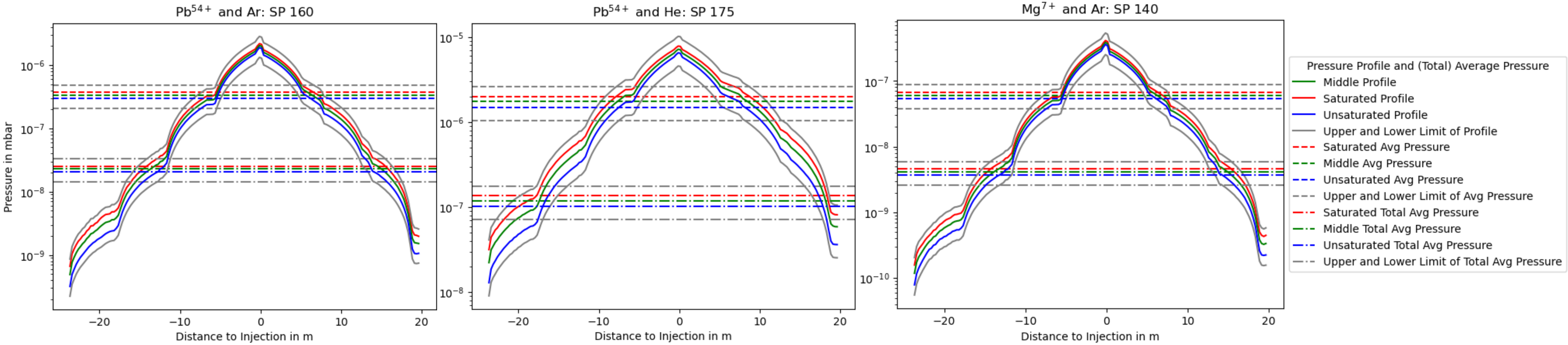




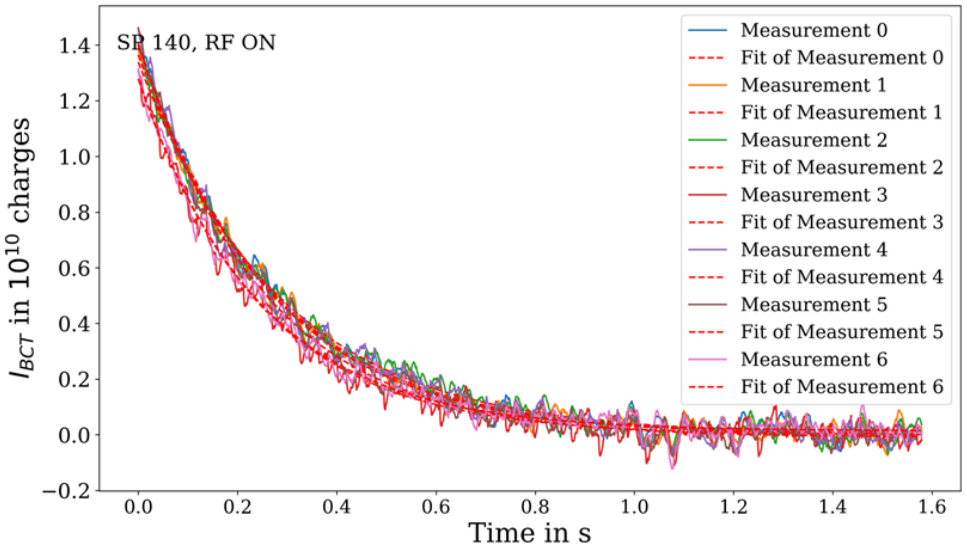
3. Lifetime from Experiment in the PS

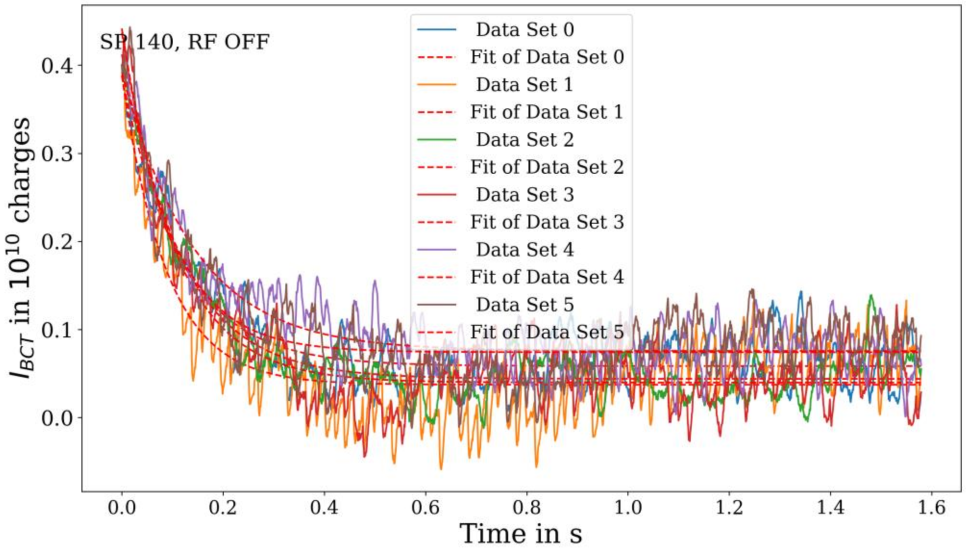
- Beam-gas interactions dominate at high gas pressures
- The injected beam intensity was low for Mg^{7+}
- Exponential fit to calculate the lifetime of the beam at each gas injection

$$I(t) = I(t_0) \cdot \ e^{-\frac{t}{\tau}} + c$$

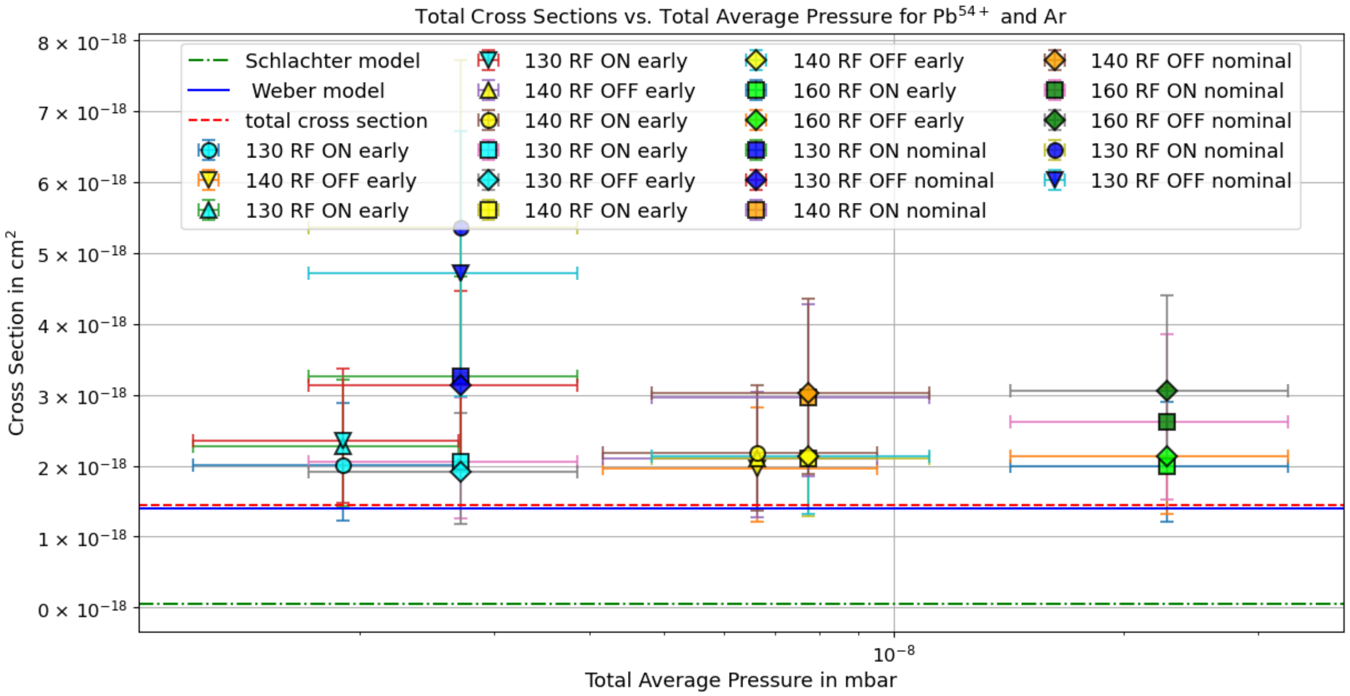
- Only the highest pressure levels gave clear beam lifetimes
- The pressure profiles are used to calculate cross section σ

$$\sigma = \frac{1}{\tau\, n\, \beta\, c}$$



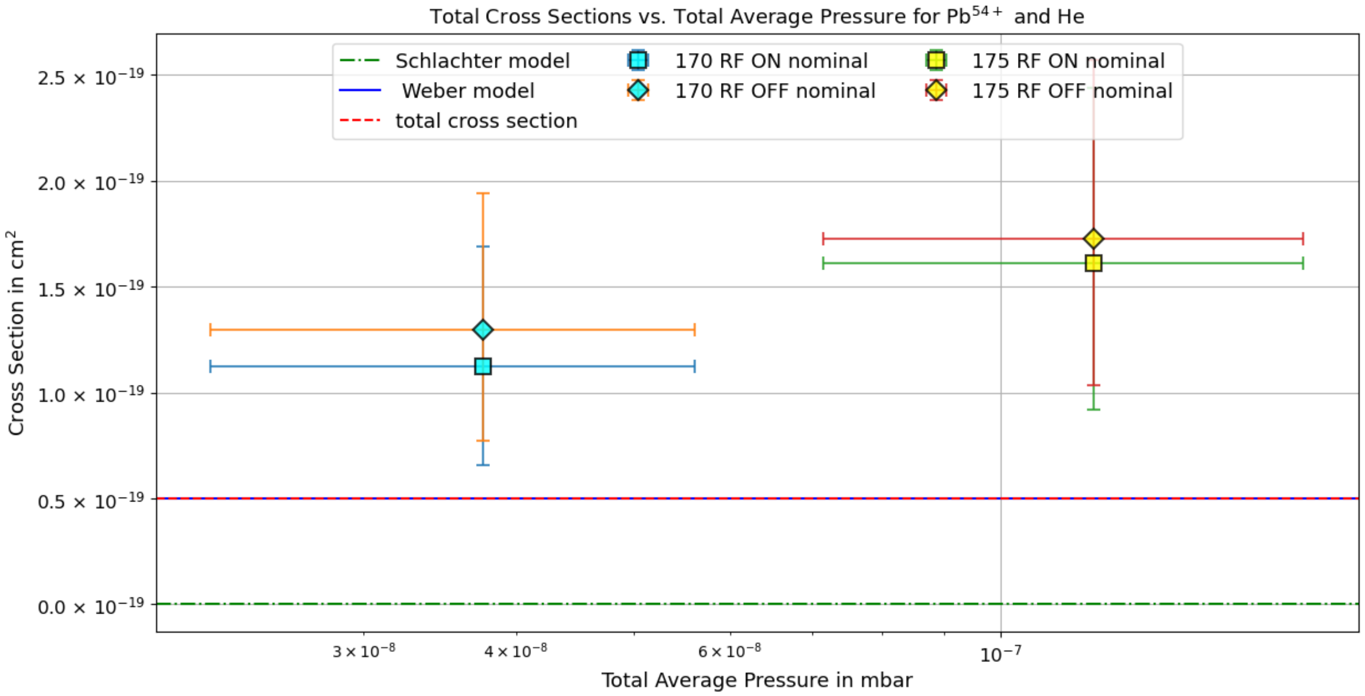


Results: Pb^{54+} with Ar gas



- Close agreement between the experimental values and the model predictions
- The measured cross section is higher than the predicted lifetime of the semi-empirical formula
  - EARLY beam: factor of 1.32 – 1.63 (avg: 1.46)
  - NOMINAL beam: factor of 1.81 – 3.71 (avg: 2.44)
- Time difference between the measurements of the EARLY beam and the NOMINAL beam

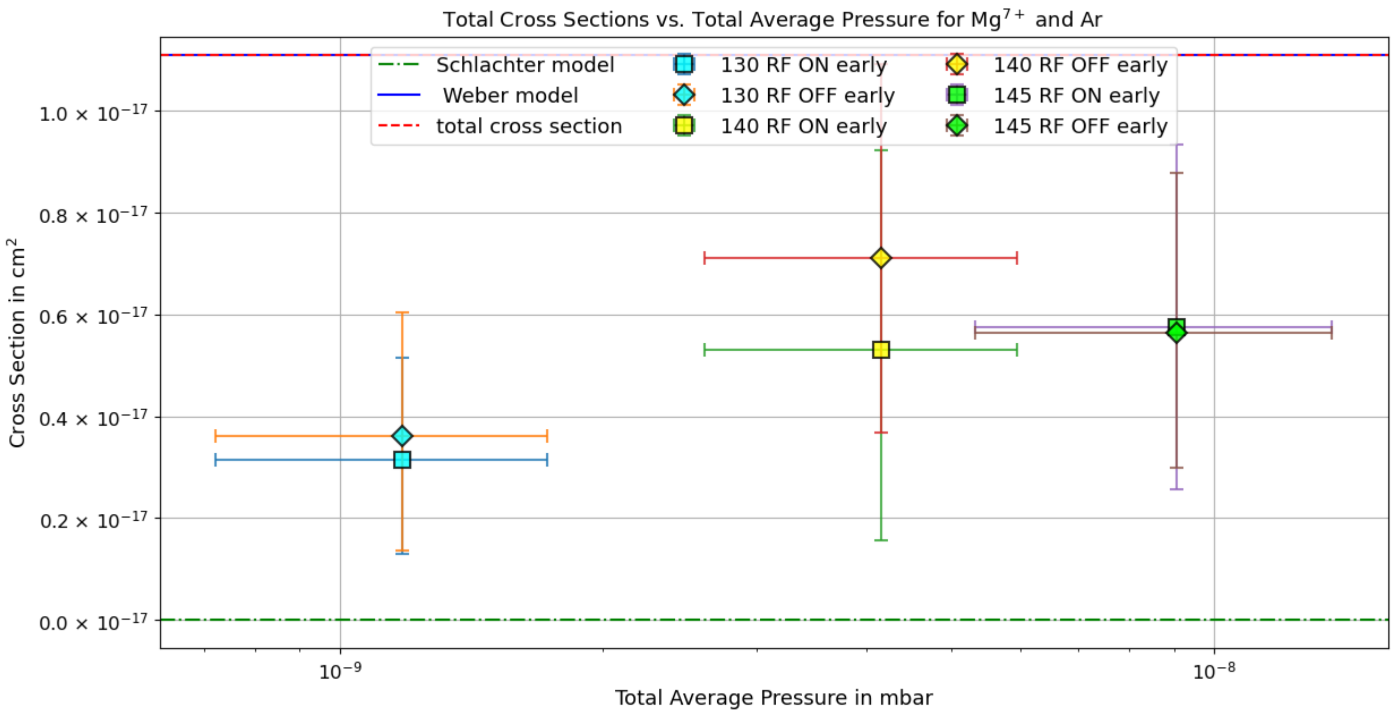
Results: Pb^{54+} with He gas



- Higher deviations compared to the experiment with Ar gas
- The measured cross section is a factor of 2.25 - 3.45 (avg: 2.88) higher than the predicted lifetime of semi-empirical formula
- Electron capture contribution: 0.01%

Results: Mg^{7+} with Ar gas

- The measured cross section is a factor of 1.93 - 3.53 (avg: 2.36) times lower than the predicted lifetime of the semi-empirical formula
- The measured cross section of Pb^{54+} is higher than predicted, while for Mg^{7+} it is the opposite
- Predictions of the models result in higher losses than those measured
- Ongoing checks of formula validity for loosely bound projectile electrons and high-Z targets



Conclusion

- **Ion cross section experiments with Pb^{54+} and Mg^{7+} beams in the CERN PS, using different levels of injected Ar and He gas with the BGI injection system**
  - Exponential intensity decay was observed for high pressure injections, and beam lifetimes was extracted
  - Pressure analysis resulted in a more accurate representation of the gas distribution
  - Calculations of ion beam cross section as a function of pressure were performed
- **New experimental methodology has been proven to give reasonable results**

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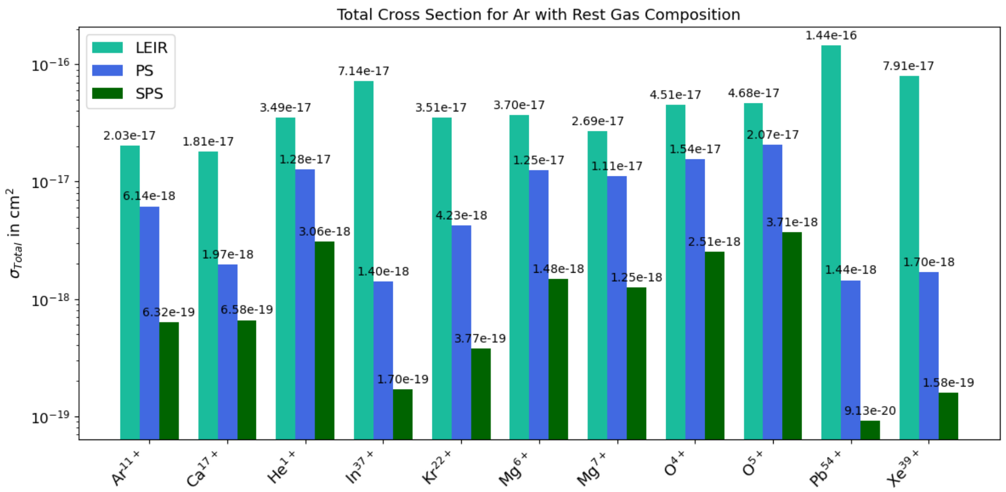
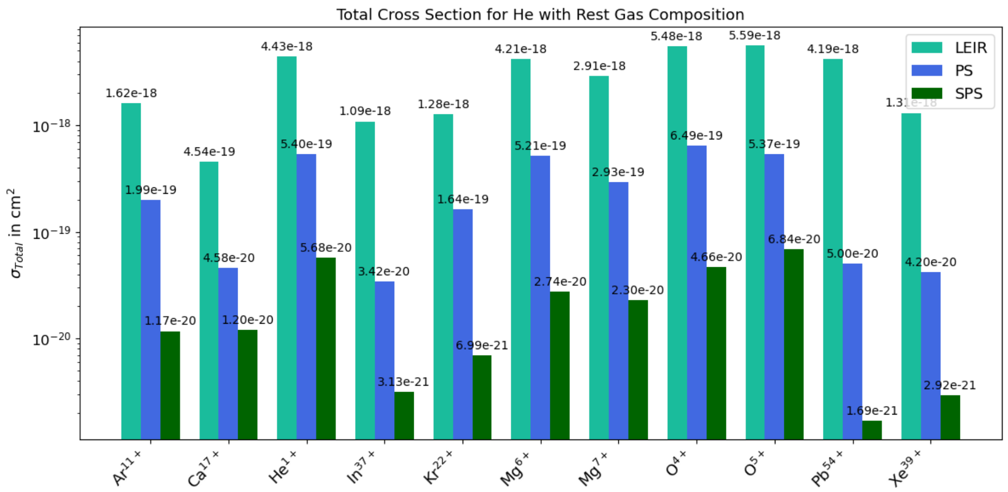
  - Calculations of ion beam cross section as a function of pressure were performed
- **New experimental methodology has been proven to give reasonable results**
- **Measured cross sections were compared with the predictions of the semi-empirical models**
  - Close agreement, with a factor of 1.4 – 3.7, between the prediction models and the measurements
  - Comparison showed potential improvements in the experiment and/or models
  - Models are valuable tool for the estimation of cross sections to evaluate future ion species

Outlook

- **Ion lifetime experiments with an O^{4+} beam in the CERN PS will take place in June/July 2025, using different levels of injected Ar and He gas**
  - New experimental setup will include the use of two injection systems, enabling more measurements





Thank you!!

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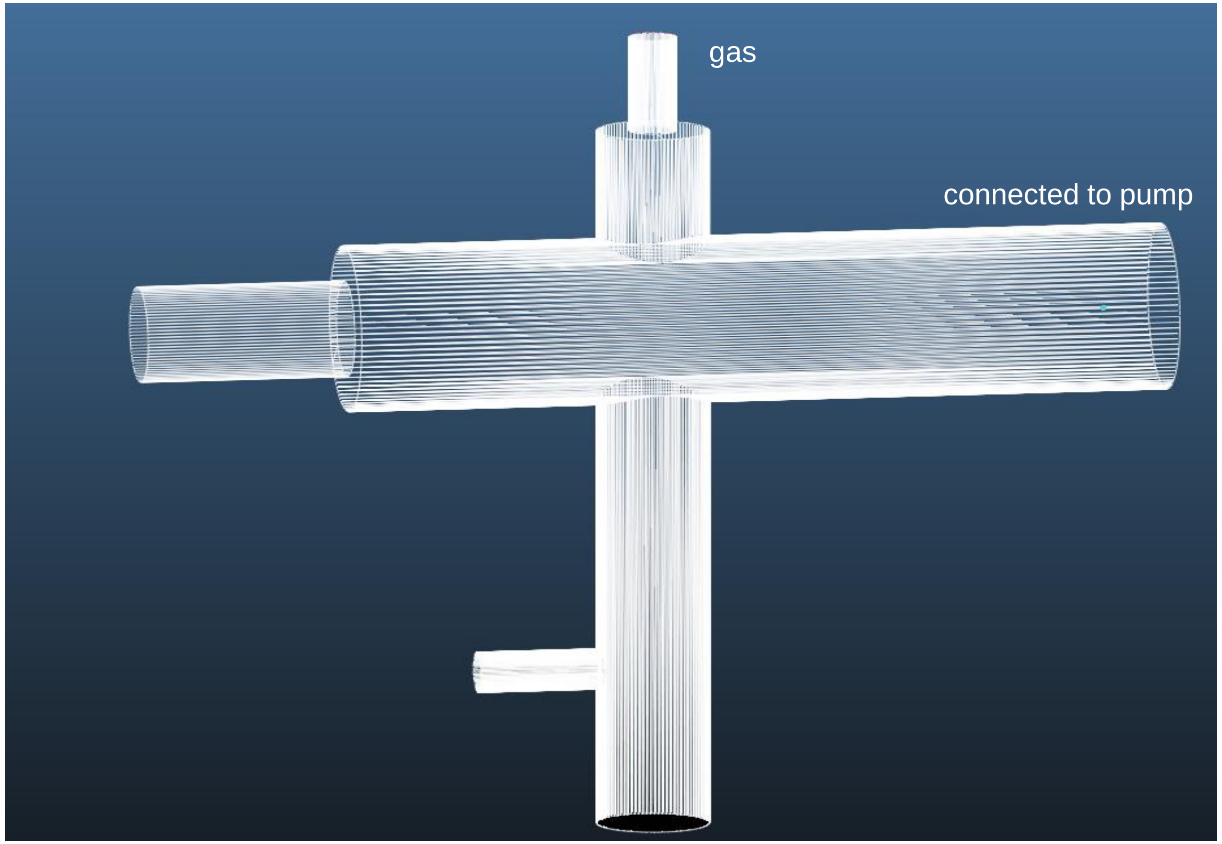
Flow



- Series of simulations to estimate effective pumping speed S_{eff}
- Error of gauge: 30%

$$Q = S_{eff} P$$