# Plasma-Assisted Space-Charge Neutralization

## for High-Current Cyclotron Axial Injection Using Beam-Ionized $H_2$ and Kr Gas

IPAC 2026, Deauville, France

May 21, 2026

Chong Shik Park, Ph.D.

Department of Accelerator Science / Accelerator Research Center

Korea University, Sejong Campus

# Outline

- Motivation: space-charge limit in axial injection
- Plasma neutralizer concept before the main solenoid
- Analytical model: neutralization time and effective perveance
- WarpX simulation methods: PIC/MCC
- Results: vacuum, $H_2$, and Kr-assisted compensation
- Design window and next steps

# Motivation

## Compact cyclotron injection is space charge limited

- Low-energy, multi-mA proton transport before the spiral inflector is a high-perveance problem

### Injection conditions

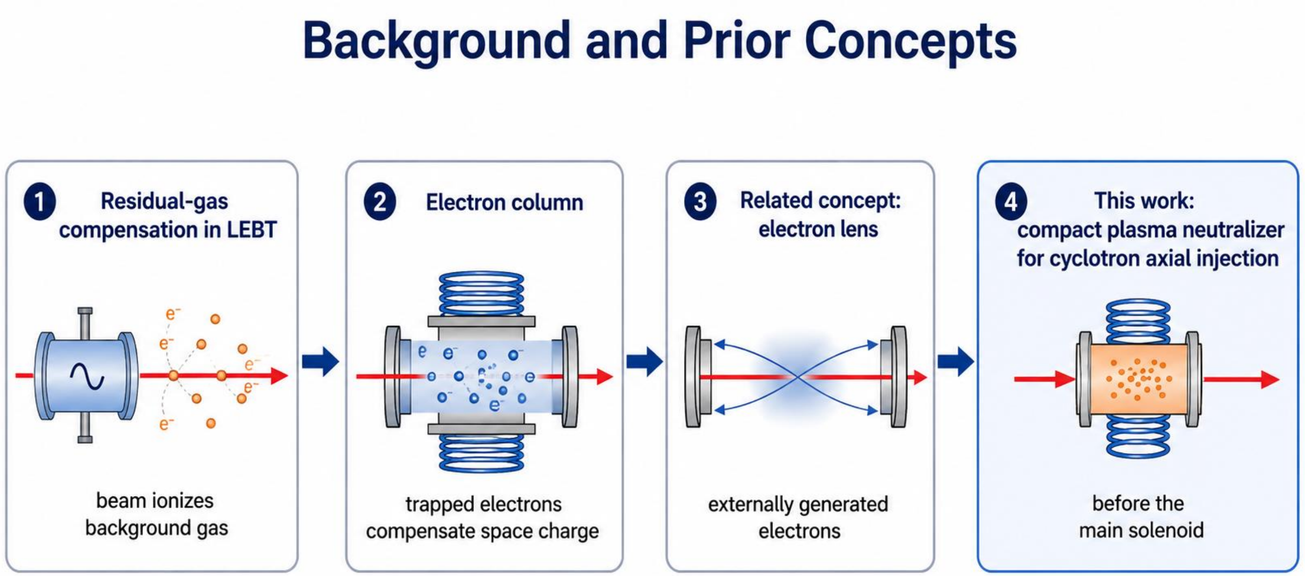
| | |
|---|---|
| Beam | $H^+$ |
| Energy | 30 keV |
| Current | multi-mA |
| Region | axial injection |
| Goal | high transmission into inflector |

$$K_0 = \frac{qI}{2\pi\varepsilon_0 c^3\beta^3\gamma^3}$$

- At tens of keV, $\beta$ is small, so perveance rises rapidly.
- Transverse defocusing competes with final focusing and matching.
- Loss before/after the inflector directly limits delivered beam current in cyclotrons.

# From Passive Compensation to Controlled Electron Columns

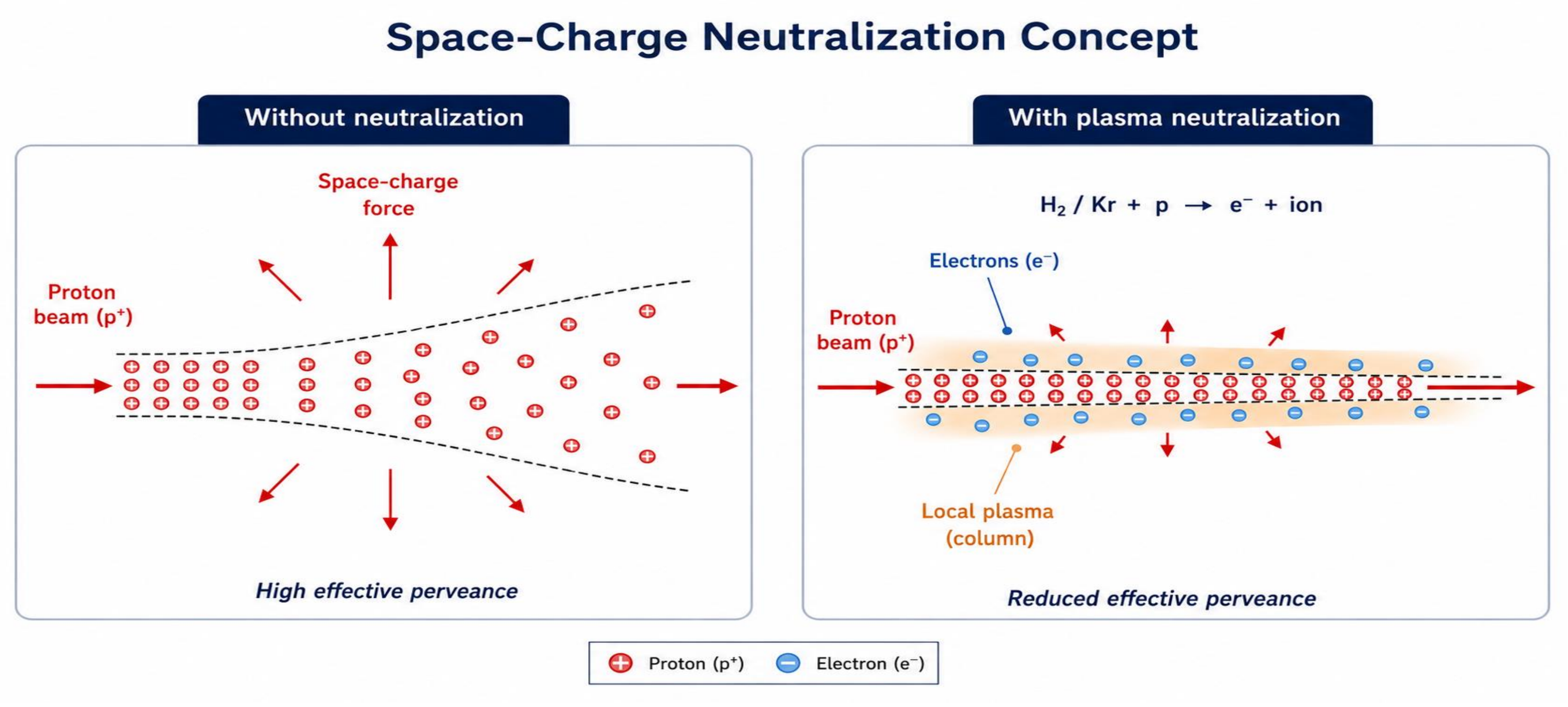
## Prior Works



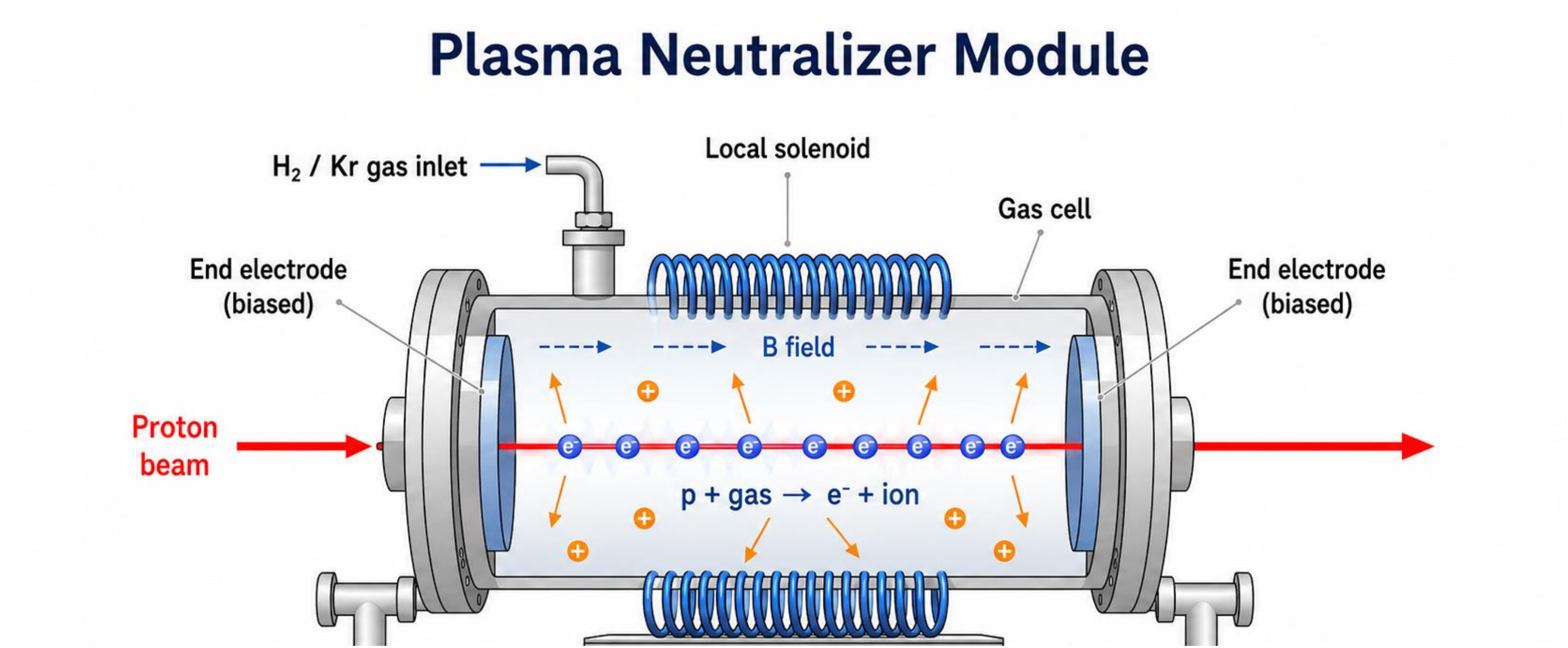

- Residual-gas compensation is common in low-energy beam transport.
- Electron-column studies use beam-induced ionization, solenoids, and electrodes to tune compensation.
- Electron lenses use externally generated electrons but require a dedicated electron source.

- **This work translates the electron-column idea to a single-pass cyclotron axial injection line.**

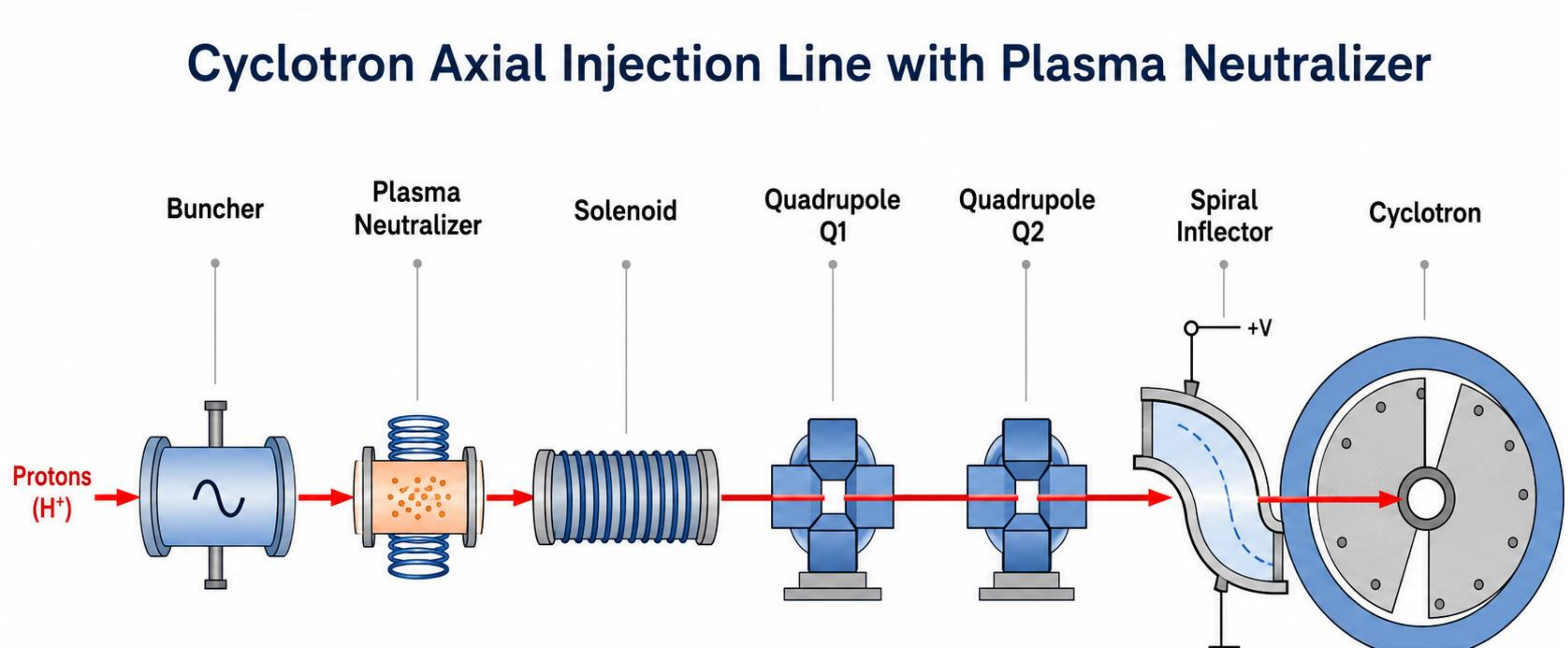
# Physical Concept: Effective Space Charge Compensation



# Compact Plasma Neutralizer Module



# Plasma-Assisted Neutralizer



# Placement Trade-Off

Why before solenoid?

## Before main solenoid — baseline

- Compensates beam before the main matching section.
- More physical space for gas cell, local solenoid, electrodes, and diagnostics.
- Keeps controlled gas load away from the inflector region.
- Preserves $Q_1/Q_2$ tuning and final inflector integration.

## After main solenoid

- Closer to inflector, so compensation may act nearer the most constrained aperture.
- But integration is harder: gas load, fields, electrodes, and diagnostics near final matching.
- Could perturb $Q_1/Q_2$ optics or inflector-region vacuum requirements.

# Effective Perveance Reduction

- For a nonrelativistic proton beam, the generalized perveance is

$$K_0 = \frac{qI_b}{2\pi\varepsilon_0 m_p c^3 \beta^3 \gamma^3} = \frac{2I_b}{I_{A,p}\beta^3\gamma^3} \text{ where } I_{A,p} = \frac{4\pi\varepsilon_0 m_p c^3}{q}$$

$$K_{\text{eff}} = K_0(1 - \eta(t))$$

where $\eta(t) \approx \frac{n_e - n_i}{n_p}$

- Electrons only limit

$$\frac{K_{\text{eff}}}{K_0} = 1 - \frac{n_e}{n_p}$$

- At 30 keV, $\beta$ is small, so $K_0 \propto 1/(\beta\gamma)^3$ becomes large.
- The plasma neutralizer aims to reduce the effective perveance by generating electrons near the beam core.
- Positive gas ions reduce the net compensation unless they are cleared.
- Kr has a larger proton-impact ionization cross section than $H_2$, the electron source turns on faster.

# Beam Potential and Electron Trapping Voltage

- On-axis beam potential: for a round uniform beam

$$\phi_b \approx \frac{30 B_f I_b}{\beta}\left[1 + 2\ln\left(\frac{b}{a}\right)\right]$$

- Biased-voltage estimate

$$|V_{\text{bias}}| \geq \phi_b + \alpha T_e [eV]$$

- For example:
- $E_b = 30\, keV,\, I_b = 10\, mA,\, a = 2\, mm,\, b = 10\, mm,\, B_f = 1,$

$$\phi_b \approx 160\, V$$

where $B_f$: bunching factor / peak-to-average current enhancement

- The beam potential sets the voltage scale for electron trapping.
- Bunching increases peak current and raises the required electrode bias.

# Why add Krypton

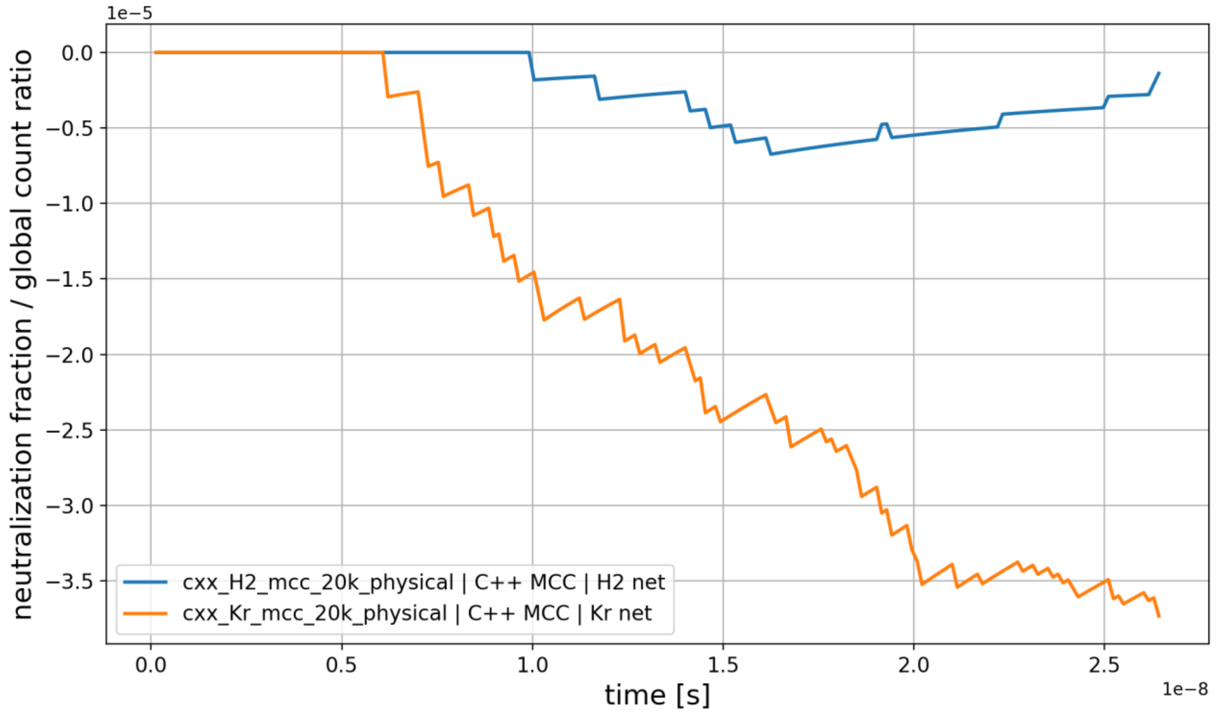
## Physical Motivation

- Larger ionization probability increases electron source term $S_i$.

$$\sigma_{H_2} \sim 2 \times 10^{-20} m^2$$
$$\sigma_{Kr} \sim 1 \times 10^{-19} m^2$$

- Negative values indicate ion accumulation or faster electron loss in the open-boundary diagnostic; source validation is instead based on Ne and Ni production.
- Faster electron build-up helps pulsed injection.
- Short cell length limits added scattering and gas load.
- Need to check ion accumulation and overcompensation.

$$S_i \propto n_g \sigma_g v_p n_p$$



# Simulation Setup and Cases

| Case | Gas/plasma | Purpose |
| --- | --- | --- |
| Vacuum | none | uncompensated reference |
| $H_2$ | $H_2$-seeded gas | baseline compatible gas |
| Kr | Kr-seeded gas | fast transient neutralization |

**Core scattering interactions**

| | |
| --- | --- |
| $H_2$-seeded gas | $p + H_2 \rightarrow p + H_2^+ + e^-$ |
| Kr-seeded gas | $p + Kr \rightarrow p + Kr^+ + e^-$ |

- PIC/MCC model includes ionization, plasma build-up, solenoidal confinement, and beam evolution.
- WarpX code has been used for PIC/MCC model simulations
- Adopted $H_2$ and Kr proton-impact ionization cross section data.

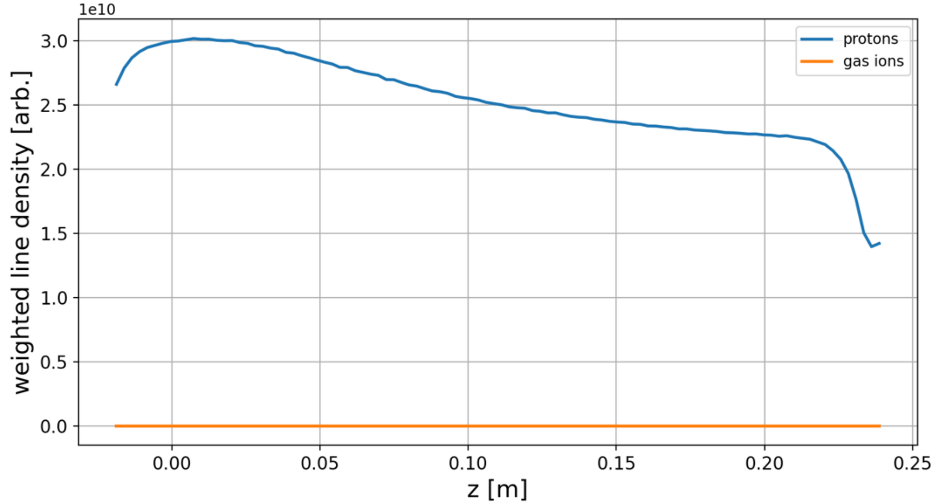
- 10 mA proton beam
- Neutralizer pressure is 1e-5 torr
- Solenoid strength is 0.1 T
- End-electrode bias voltage is −200 V

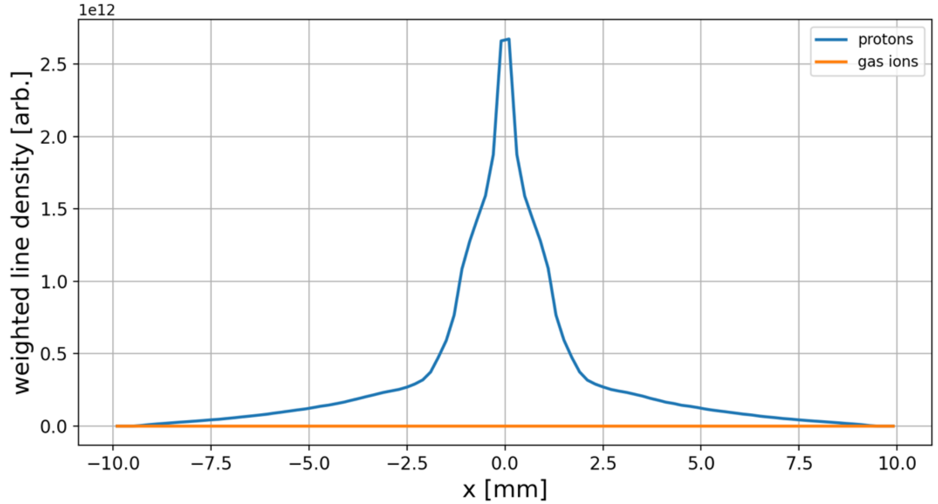
# Baseline: Vacuum/No Neutralization

Defines the magnitude of the space-charge problem

**Expected behavior**

- No gas ionization; no trapped electron population.
- $K_{\mathrm{eff}}/K_0$ remains near 1.
- Beam density profile expands rapidly before final matching.
- Sets required neutralization level.

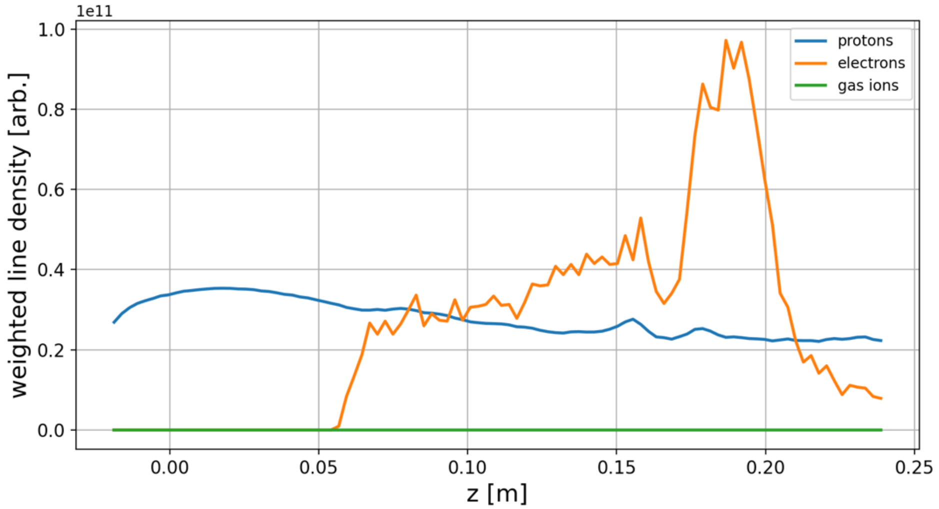


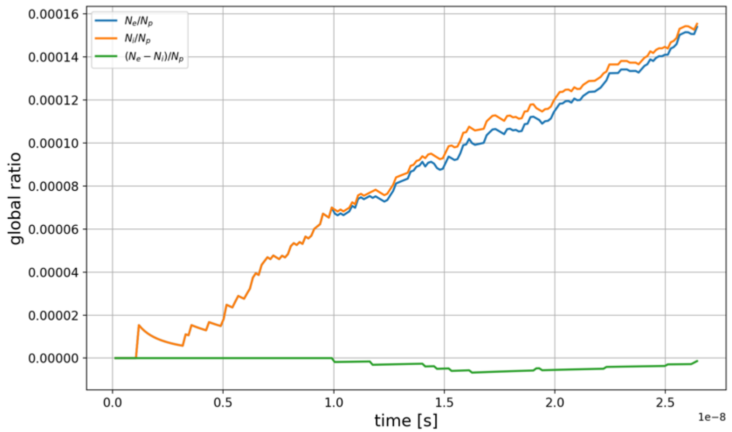



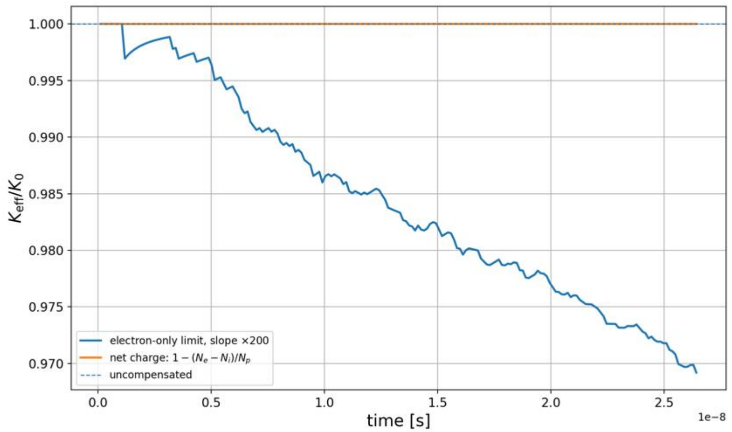
# $H_2$ Neutralization: Conservative Baseline Gas

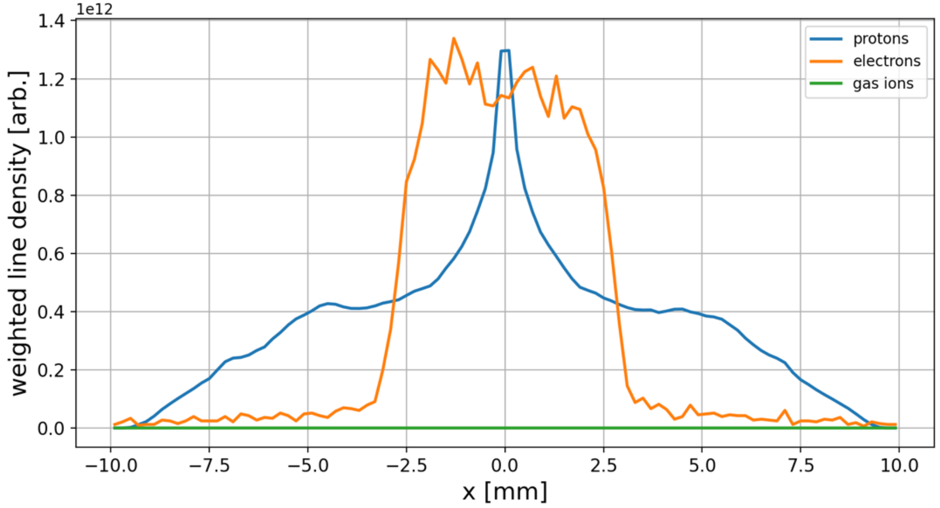
## Beam-ionized $H_2$ provides natural space-charge compensation

- $H_2$ is compatible with proton-source and LEBT operation.
- Electron build-up is finite, so time scale matters.
- Partial compensation reduces $K_{\text{eff}}$, but may not be fastest.
- Use as the reference for Kr comparison.



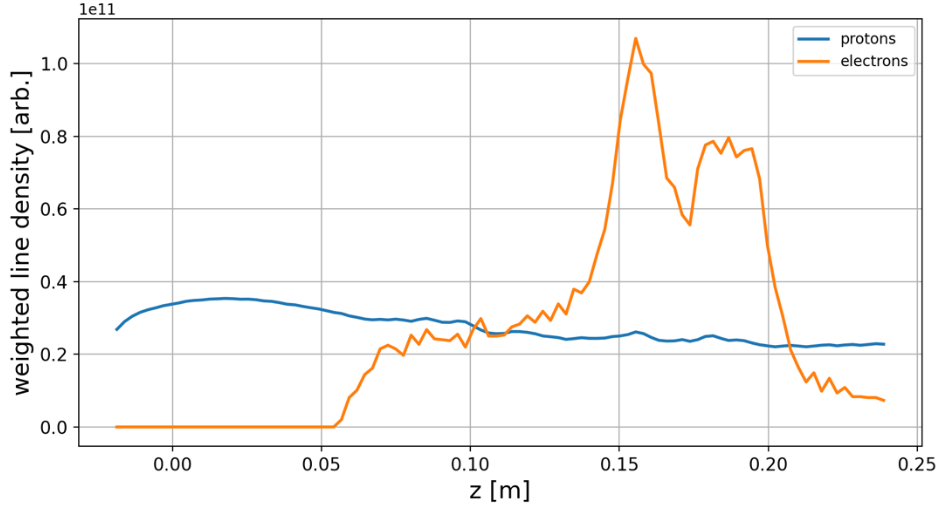



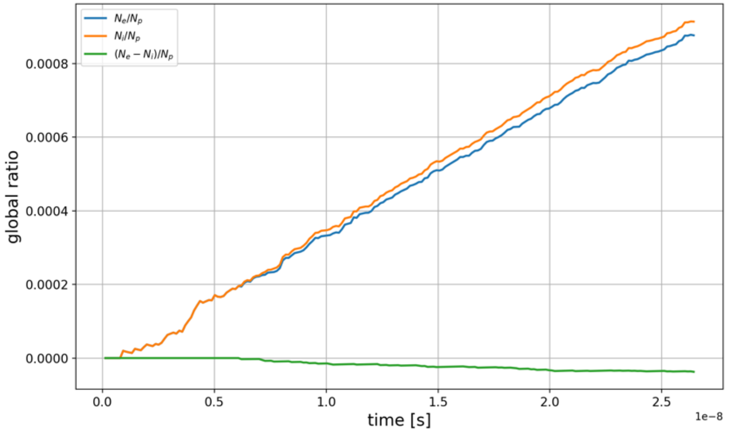



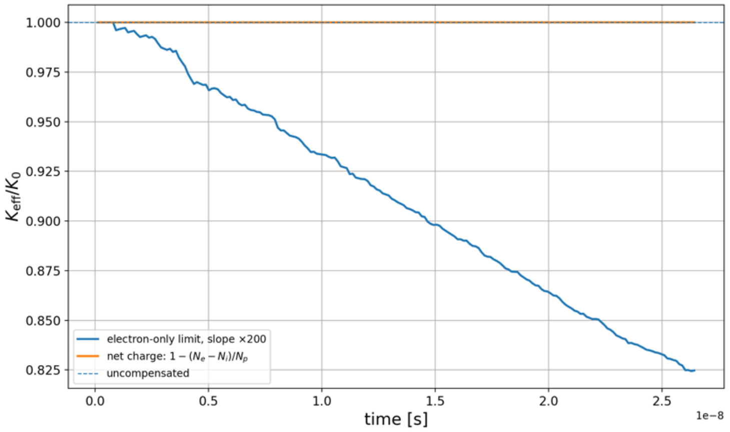
# Kr-assisted Neutralization: Faster Transient Response

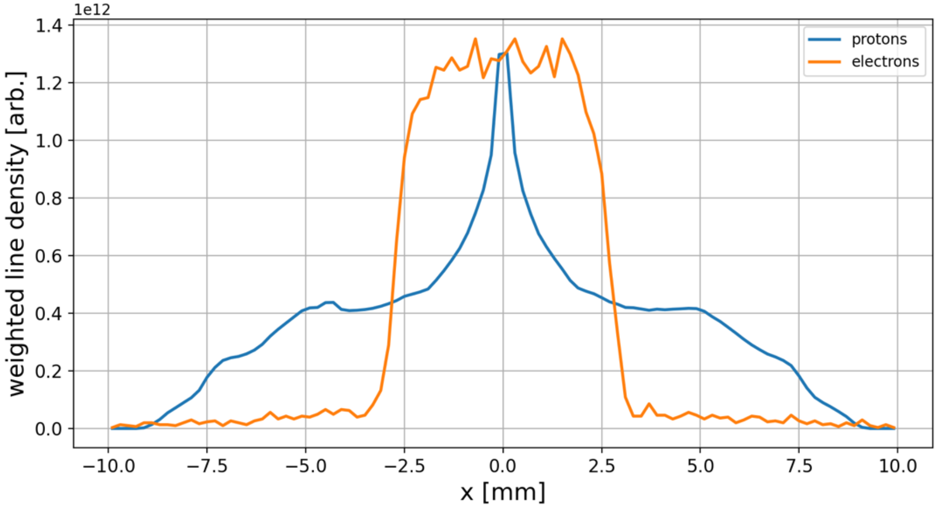
## Compare against $H_2$ under otherwise similar beamline assumptions

- Faster electron production and earlier compensation.
- Improved response for pulsed/ramped injection.
- Check for overcompensation and ion accumulation.
- Translate particle build-up into $K_{\mathrm{eff}}$ reduction.



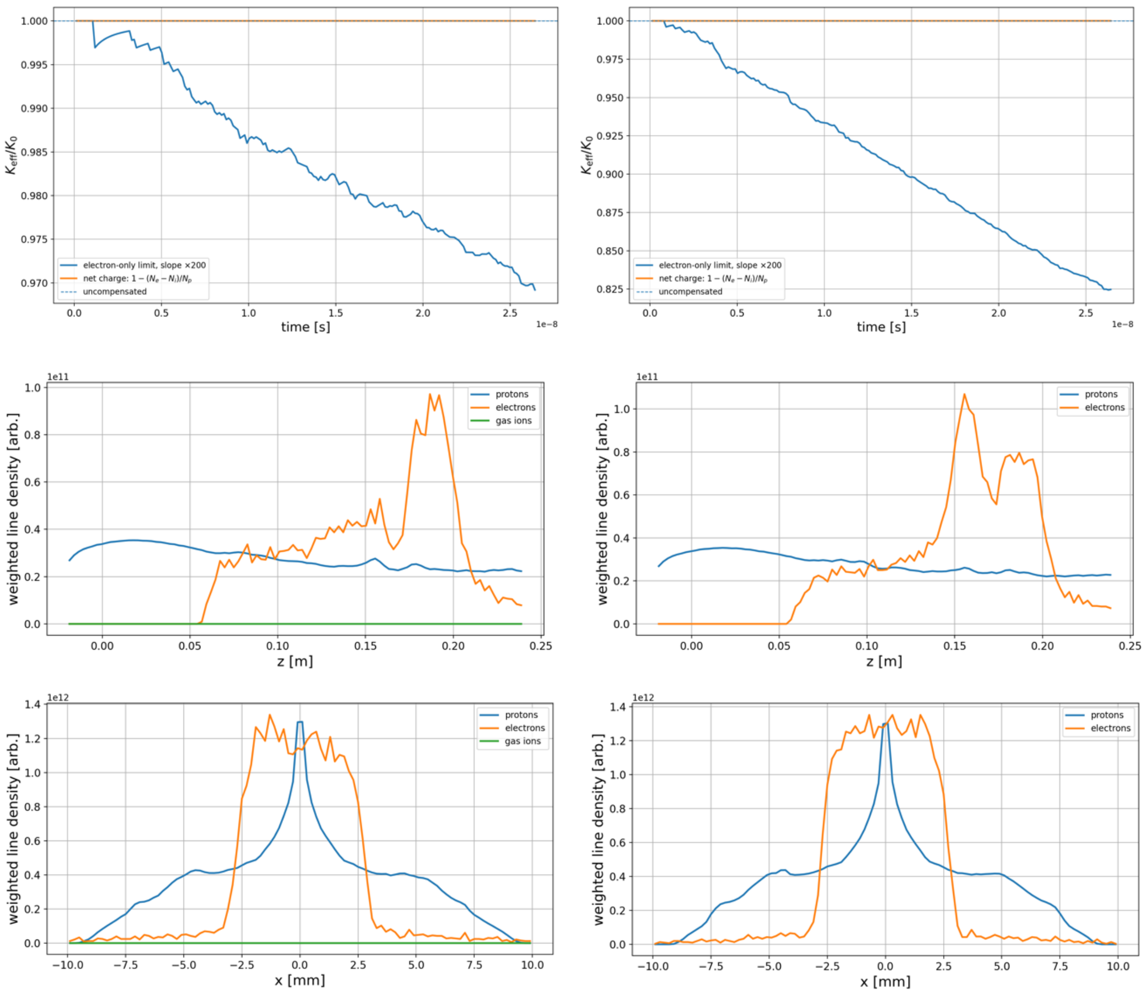



# Beam-Transport Impact

### from plasma metric to accelerator metric




## Summary Table

| Case | $K_{\text{eff, e}}/K_0$ | Beam Density Profile |
|---|---|---|
| Vacuum | ≈ 1 | No electron column |
| $H_2$ | 0.970 | Localized Electron Column |
| Kr | 0.825 | Localized Electron Column |

**Effective perveance reduction must translate into smaller beam size at the inflector entrance.**

# Design Window and Next Steps

Balance fast neutralization against optics, gas load, scattering, and stability

## Design knobs

| | |
|---|---|
| Cell length | interaction length and compactness |
| Gas pressure | ionization rate and gas load |
| Kr fraction | transient response |
| Local solenoid | electron confinement |
| Electrode bias | longitudinal trapping |
| Aperture | compatibility with matching optics |

## Conclusions

- A compact beam-ionized plasma cell is a promising pre-solenoid neutralizer.
- Analytical estimates and PIC/MCC outputs should be presented through η(t) and $K_{\mathrm{eff}}/K_0$.
- Kr seeding is mainly valuable for faster transient response.
- Next: full parameter scan and coupling to realistic inflector acceptance.

KOREA UNIVERSITY

# Thank you for your attention!