Plasma-Column Neutralization

in a Cyclotron Injection Line

Motivation • analytical model • WarpX/PIC simulation methods • result comparison plan

Prepared for internal discussion

Why neutralization matters for cyclotron injection

Low-energy, high-current transport is dominated by space-charge defocusing.

weak residual gas ionization

electron–ion plasma column

Without sufficient neutralization

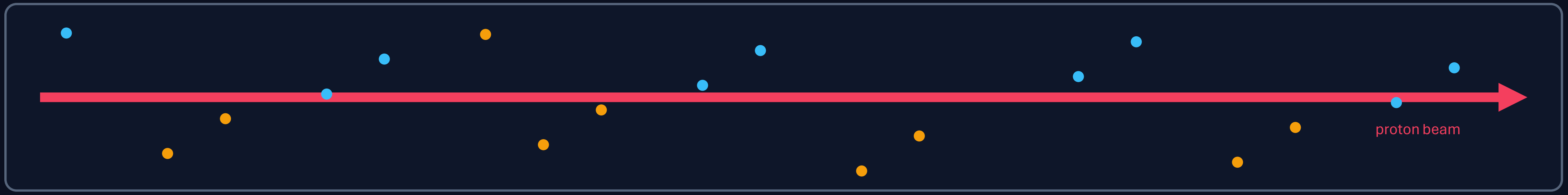
- Large radial electric field from the beam core
- Emittance growth and envelope mismatch
- Aperture losses before the cyclotron inflector
- Strong sensitivity to pressure, current, and chopping pattern

With controlled plasma column

- Electrons partially cancel positive beam charge
- Reduced tune depression and envelope growth
- More robust matching into injection optics
- A measurable path to model validation

Concept: beam-driven ionization creates a local plasma column

The beam is both the source of space-charge and the source of neutralizing plasma.



electron–ion plasma column

1 **Primary beam**

H^+ beam propagates through H_2 background gas.

2 **Ionization source**

$p + H_2 \rightarrow p + H_2^+ + e^-$ creates slow plasma species.

3 **Confinement / loss**

Electrons respond rapidly; ions and walls set the loss time.

4 **Neutralized transport**

Effective beam charge is reduced by f_n.

$$E_{r},\mathrm{eff} \approx (1 - f_{n})\, E_{r},\mathrm{beam}$$
$$\mathrm{K\_eff} = (1 - f_{n})\, K_{0}$$

Analytical model: neutralized envelope dynamics

Use a reduced model to set scaling laws and sanity checks for PIC results.

Beam envelope with neutralization

$$R'' + k(s)\,R - \varepsilon^2/R^3 - K\_eff/R = 0$$
$$K\_eff = (1 - f_n)\,K_0$$
$$K_0 = 2\,I\,/\,(I\_A\,\beta^3\gamma^3)$$

Neutralization build-up

$$dn_e/dt = n\_b\;n\_g\;\sigma_i(E\_b)\;v\_b - n_e/\tau\_loss$$
$$df_n/dt = 1/\tau_i - f_n/\tau\_loss$$
$$\tau_i = 1\,/\,(n\_g\;\sigma_i\;v\_b)$$

Interpretation

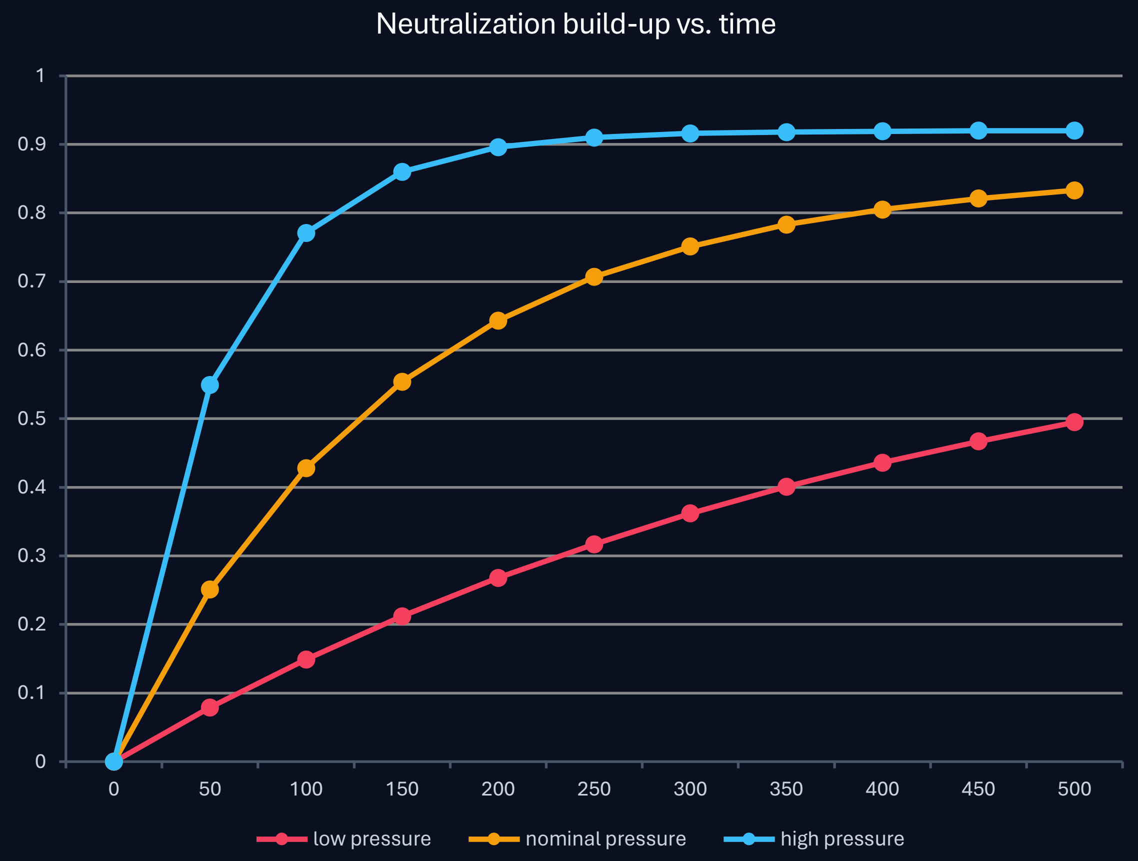
- Pressure controls ionization time scale through n_g = P/kBT.
- Cross-section table determines the absolute plasma source rate.
- Loss mechanisms set the steady-state neutralization f_n,∞.
- Envelope data can infer an effective f_n before full PIC validation.

Model limits

- Assumes quasi-axisymmetric beam/plasma column.
- Does not resolve non-neutral sheath, wall losses, or instabilities.
- Needs PIC/MCC for transient and kinetic effects.

Scaling expectation: pressure sets the neutralization time scale

Representative curves based on $f_n(t) = f\infty[1 - \exp(-t/\tau eff)]$. Replace with measured or simulated rates.



Design implications

- Long injection pulses allow plasma to reach quasi-steady neutralization.
- Short pulses or chopped beams can operate in a partially neutralized transient regime.
- Pressure optimization is a trade-off: better neutralization versus gas load and beam–gas loss.
- Diagnostics should resolve both fast build-up and slow recovery.

Replace with WarpX time histories

Simulation hierarchy: three progressively self-consistent methods

A staged workflow separates fast design scans from full collision-model validation.

1. Seeded neutralization

Impose initial plasma or effective neutralization factor f_n for fast optics scans.

2. Python callback source

Create e^-/H_2^+ pairs from local beam density using $\sigma_i(E)$ tables.

3. C++ BackgroundMCC

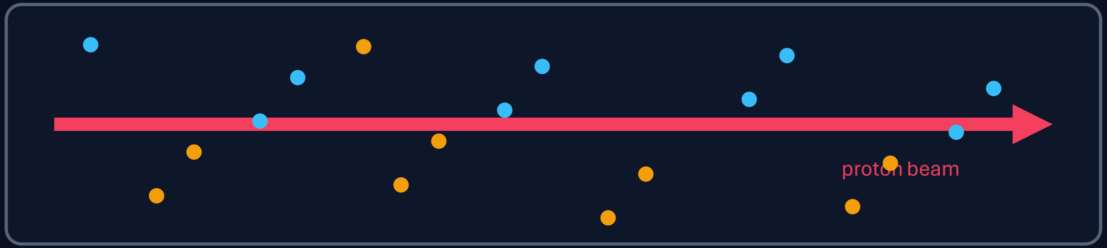
Production-quality ion-impact ionization process inside WarpX MCC.

Increasing physics fidelity

- Use the seeded model to bracket possible neutralization factors and optics sensitivity.
- Use the callback source to test rates, particle loading, and transient behavior without recompilation.
- Use the C++ MCC model for scalable, reproducible simulation campaigns.

Method 1 — seeded neutralization model

Fastest route for determining whether neutralization is required and how much is sufficient.



electron–ion plasma column

Implementation idea

- Initialize electron/ion populations around the beam, or scale the beam self-field by $1 - f_n$.
- Scan $f_n = 0, 0.25, 0.5, 0.75, 0.9$ to obtain an operating envelope.
- No cross-section data are required; therefore this is a calibration and sensitivity model, not a source model.

Outputs

- Envelope suppression versus f_n
- Transmission and aperture loss sensitivity
- Back-calculated effective neutralization from measured beam sizes

Role in workflow

- Defines target neutralization level for source models.
- Provides a rapid benchmark for PIC/MCC consistency.
- Useful for experiment planning and diagnostics placement.

Method 2 — Python callback proton-impact source

Self-consistent particle source in WarpX without modifying the core C++ code.

$$\Delta N\_pairs \approx n\_b\ n\_g\ \sigma_i(E\_b)\ v\_b\ \Delta t\ \Delta V\ /\ w$$
$$p + H_2 \rightarrow p + H_2^+ + e^-$$

Strengths

- Rapid prototyping
- Transparent event-rate control
- Good bridge between reduced model and compiled MCC

Risks to check

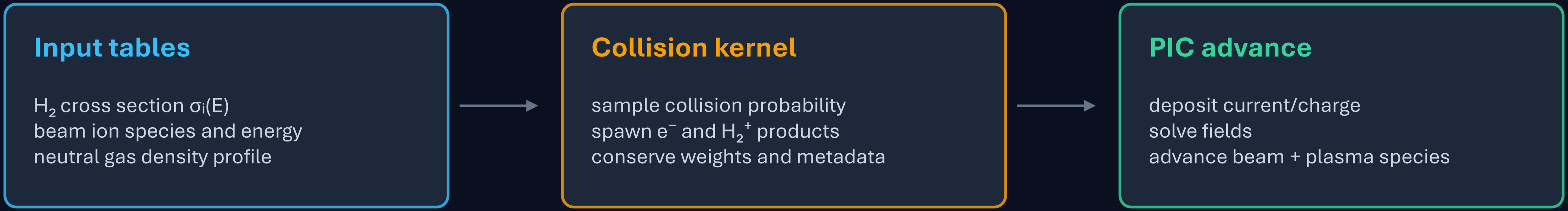
- Particle noise from low-rate rare events
- Time-step dependence of source sampling
- Load balance when plasma becomes localized

Algorithm loop

1. Deposit beam density n_b(x,y,z)
2. Read gas density n_g and σ_i(E_b)
3. Sample ionization events per cell
4. Create e^- and H_2^+ macroparticles
5. Advance all species with self-consistent fields

Method 3 — C++ ion-impact ionization BackgroundMCC process

Production implementation for reproducible, scalable simulation campaigns.



Input tables

H_2 cross section $\sigma_i(E)$
beam ion species and energy
neutral gas density profile

Collision kernel

sample collision probability
spawn e^- and H_2^+ products
conserve weights and metadata

PIC advance

deposit current/charge
solve fields
advance beam + plasma species

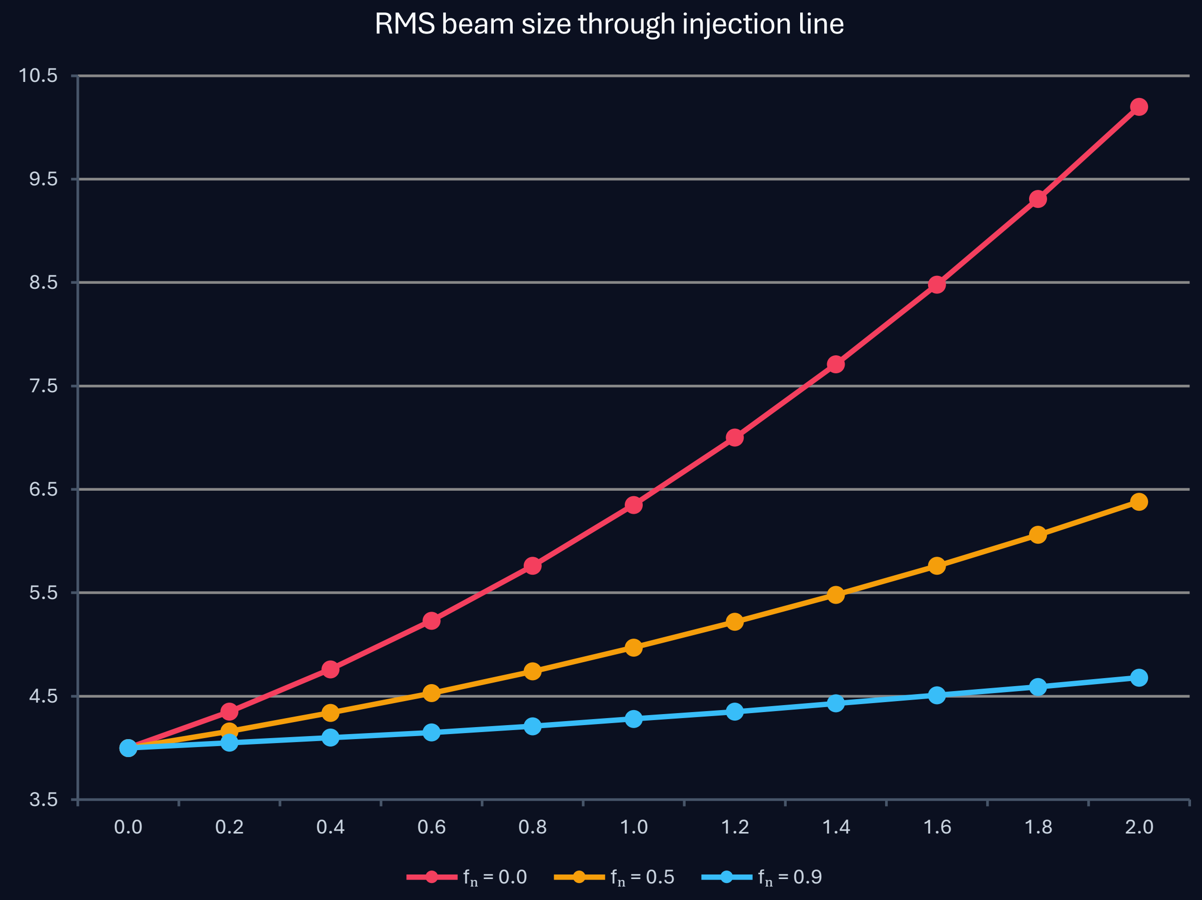
Validation criteria

- C++ MCC and Python callback should agree for the same $\sigma_i(E)$, n_g, Δt, and particle weights.
- Neutralization inferred from fields, species density, and envelope behavior should be mutually consistent.
- Energy conservation and particle accounting should be tested in a fixed-cell benchmark before full beamline runs.

Best for final parameter scans and production runs

Representative result: neutralization suppresses envelope growth

Illustrative plot for presentation structure — replace with final WarpX/beamline data.



Interpretation

- The final RMS size is strongly sensitive to the neutralization fraction.
- If measured beam sizes fall between $f_n = 0.5$ and 0.9 curves, the effective plasma density is already high enough to matter.
- The same plot becomes a practical calibration target for WarpX and diagnostics.

Placeholder result

Result comparison: what each method should reproduce

Use the seeded model as a reduced benchmark and test source models against density, field, and beam observables.

Observable	Seeded model	Python source	C++ MCC
Neutralization $f_n(t)$	prescribed	computed	computed
Plasma density profile	initialized	self-consistent	self-consistent
Beam envelope / centroid	fast scan	PIC response	PIC response
Particle accounting	not applicable	debuggable	production
Computational cost	low	medium	lowest at scale

Primary comparison metrics

- f_n from charge density: $1 - \langle n_e \rangle / \langle n\_b \rangle$
- f_n from radial field: $1 - E_r\text{,eff}/E_r\text{,beam}$
- beam optics response: rms size, centroid, emittance, loss

Acceptance test

- Python and C++ source models agree within statistical PIC noise.
- Source rates scale linearly with pressure and cross-section table.
- Beam transport agrees with seeded model at matching effective f_n.

Validation strategy: connect simulation outputs to beamline observables

Neutralization is not directly a single measurement; infer it from a consistent set of diagnostics.

Beam diagnostics

- profile / wire scanner
- slit-scan emittance
- current transmission

Plasma diagnostics

- residual gas pressure
- collector / clearing electrode current
- time response after beam on/off

Simulation probes

- species density maps
- radial electric field
- ionization event rate

Effective neutralization target:
$f_n,\text{beam} \approx f_n,\text{field} \approx f_n,\text{density}$

Summary and next actions

A staged model hierarchy reduces risk before production-scale WarpX campaigns.

Key messages

- Plasma-column neutralization can substantially reduce low-energy beam space-charge defocusing in a cyclotron injection line.
- The reduced analytical model provides scaling laws for pressure, ionization rate, and envelope response.
- Three simulation methods should be compared using the same cross sections, gas density, and beam parameters.
- The final result should be validated using both plasma observables and beam transport observables.

Immediate next steps

1. Finalize H_2 cross-section tables
2. Benchmark single-cell ionization rate
3. Run pressure/current scan in seeded model
4. Compare Python and C++ source rates
5. Replace placeholder plots with simulation outputs

Backup: add detailed WarpX input decks and code snippets

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