Space Charge Neutralization on a ~~Pulsed~~ Bunched Beam in MEBT with Gas Sheet Beam Profile Monitor

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Background: Gas-Sheet Beam Profile Monitor

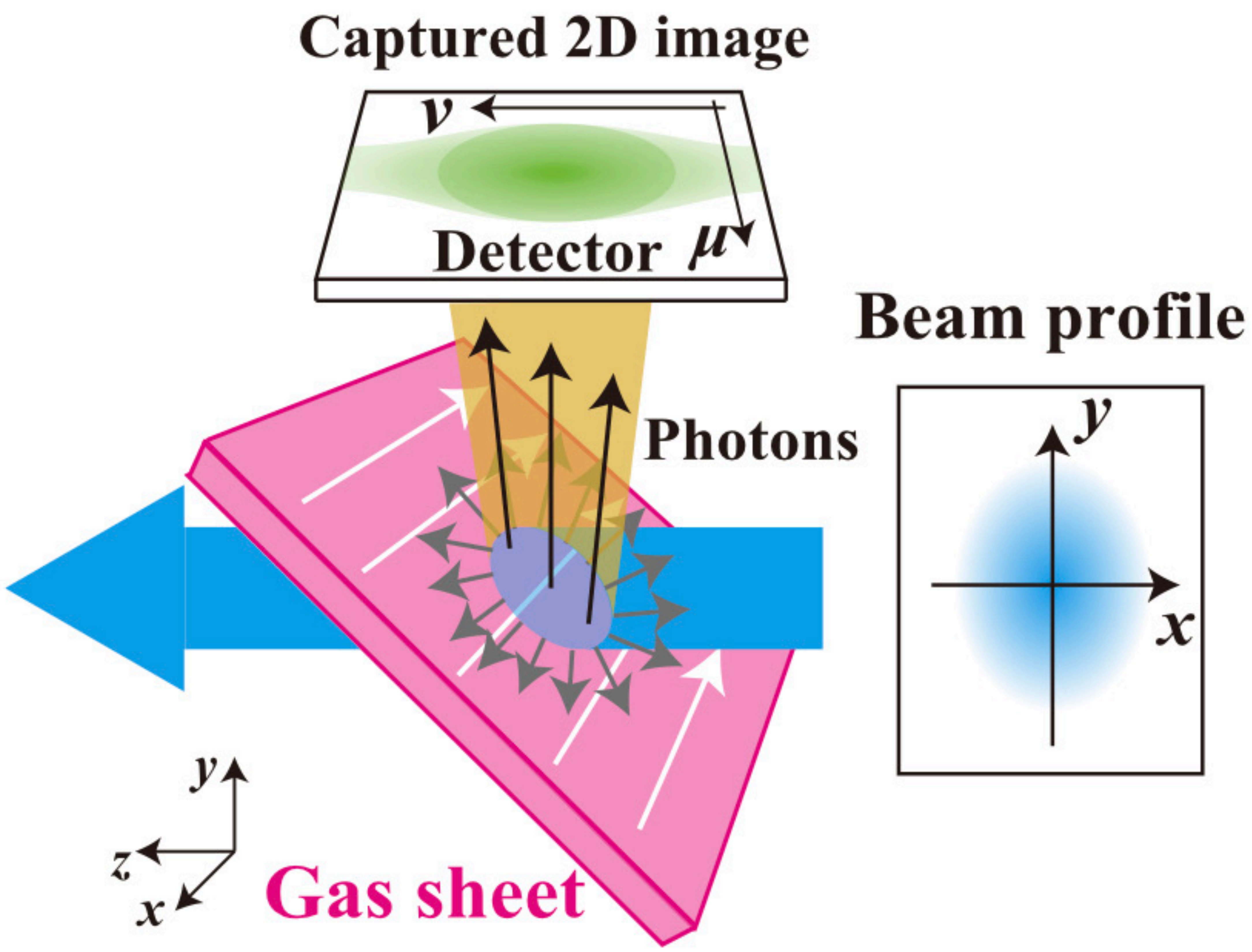
❖ **Non-invasive beam profile monitor**

High-intensity accelerator requires non-invasive monitoring
=> We developed "***Gas-Sheet Beam Profile Monitor***"

< Principle >

- Injecting a sheet-shaped gas into beamline
- Beam interacts with gas sheet
- Gas produces plasma and photons
- Detecting photons as an image
  —> distribution proportional to beam profile
- Beam profile can be obtained from the image

We were successful to obtain a profile corresponding with a wire-scanner monitor

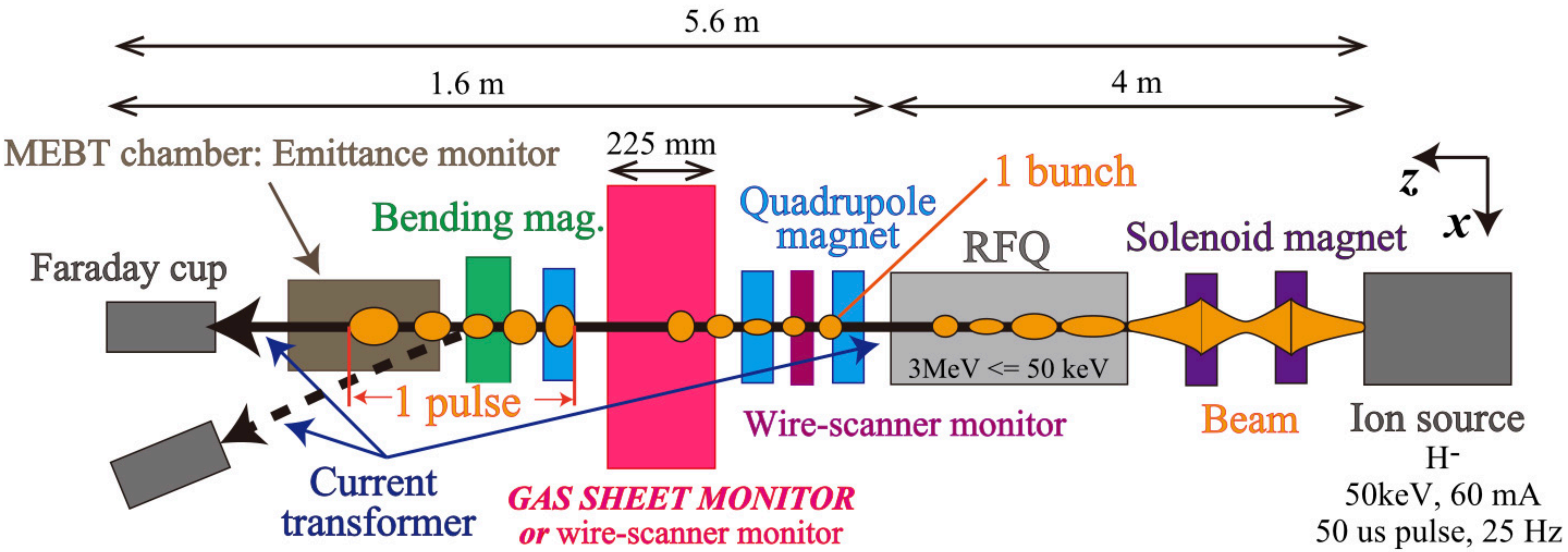


Background: invasiveness of GSM

❖ **How is invasiveness of GSM?**

GSM is non-invasive monitor but injecting an extra gas
—> Quantified the invasiveness from perspectives of
- beam current reduction
- phase space distribution change

with ***J-PARC RFQ test stand***



Background: invasiveness of GSM

❖ **Invasiveness: beam current reduction**

Beam current was measured at 11-deg. bent line

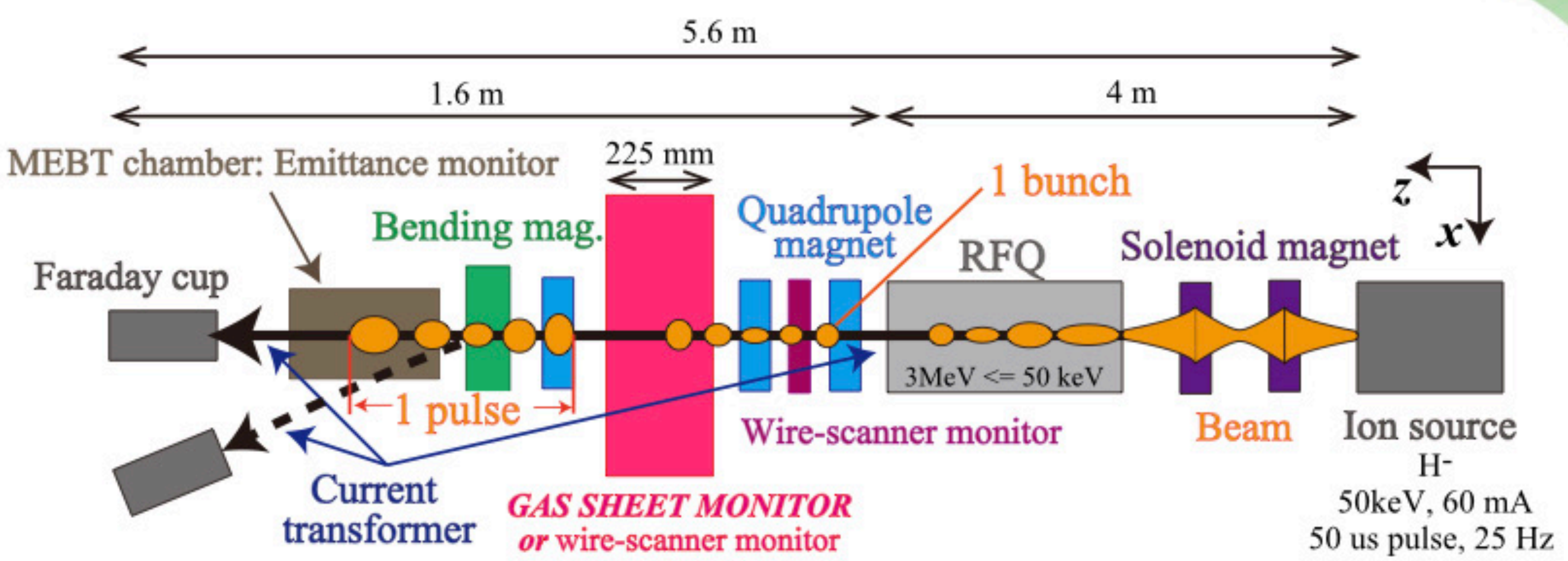
< Prediction >

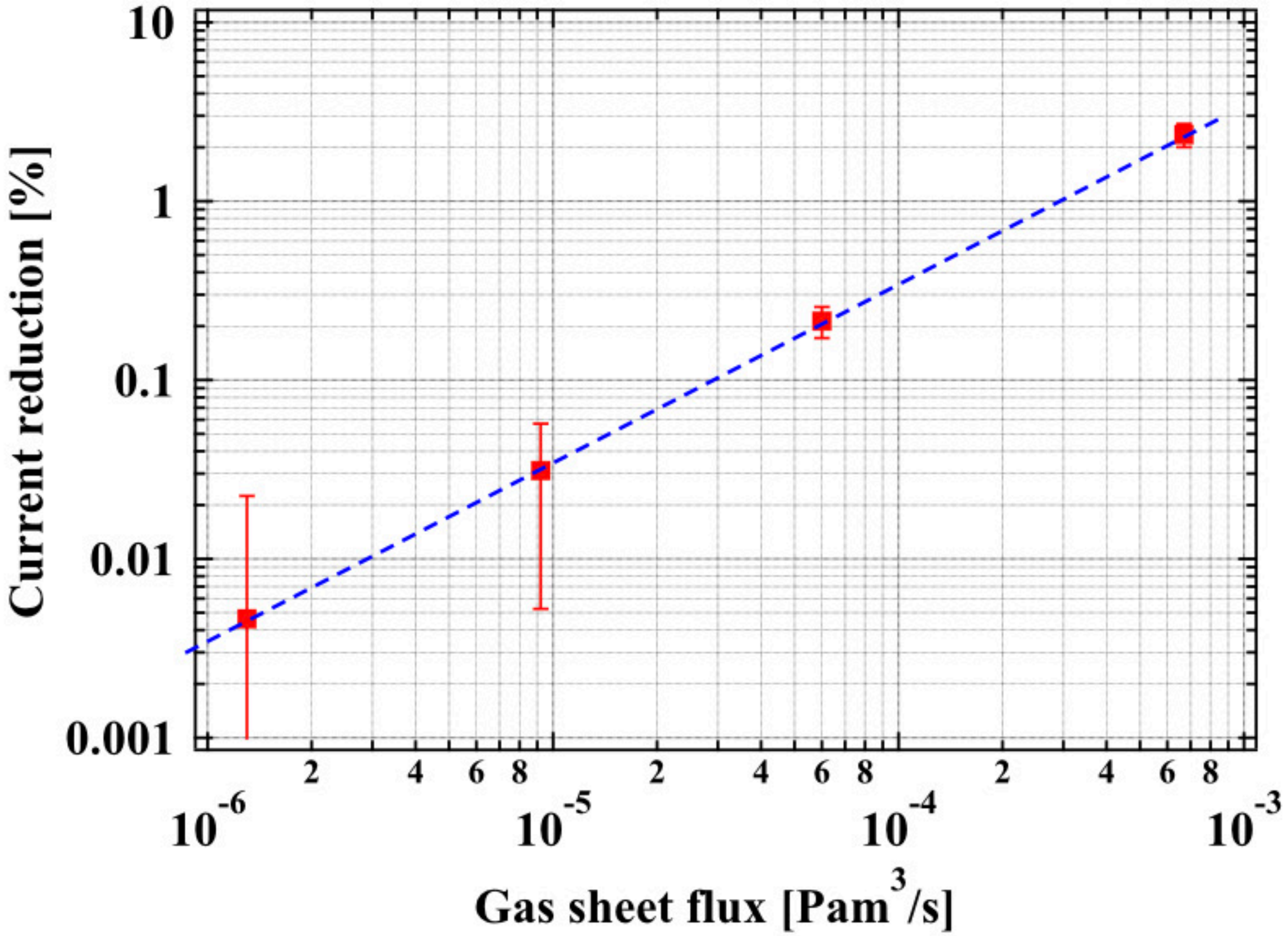
Extra electron weakly attaches to H atom
—> Gas may strip the electron

$$H^- + Gas \rightarrow H^0 + Gas + e^-$$
$$H^- + Gas \rightarrow H^+ + Gas + 2e^-$$

< Result >

- Reduction ratio linearly increased against gas flux
- Ratio agrees with the e^- stripping cross-section

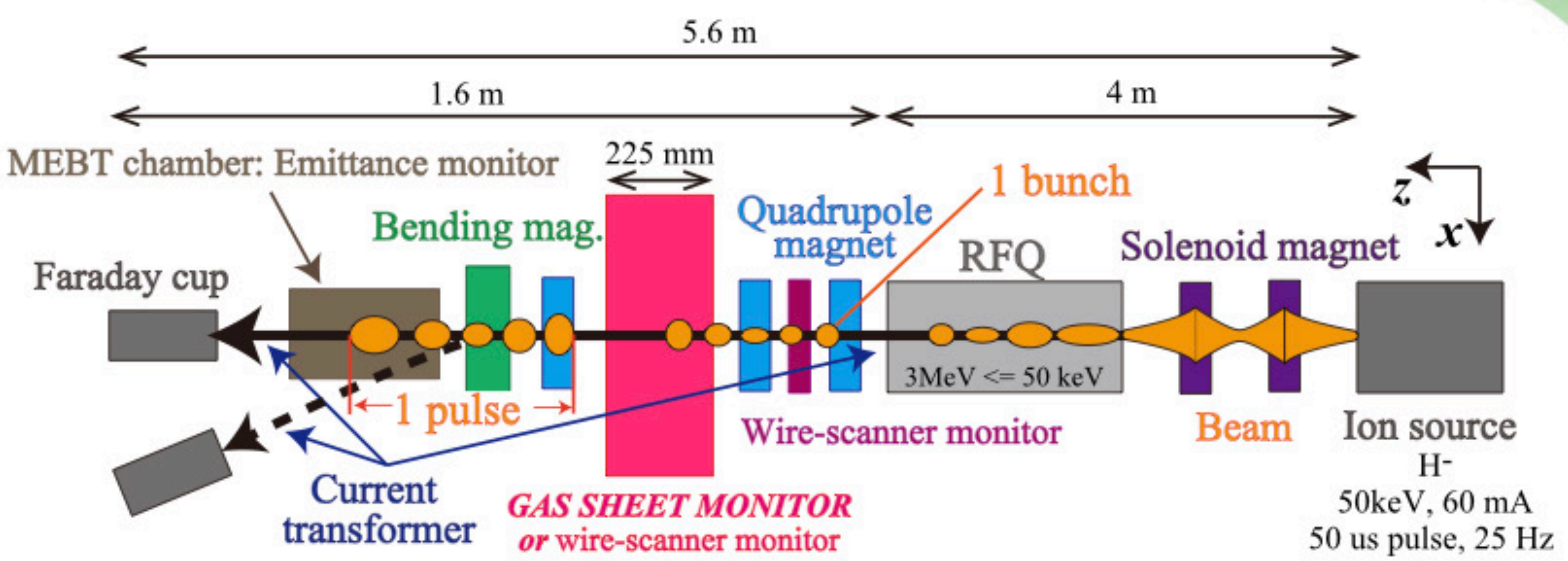




Background: invasiveness of GSM

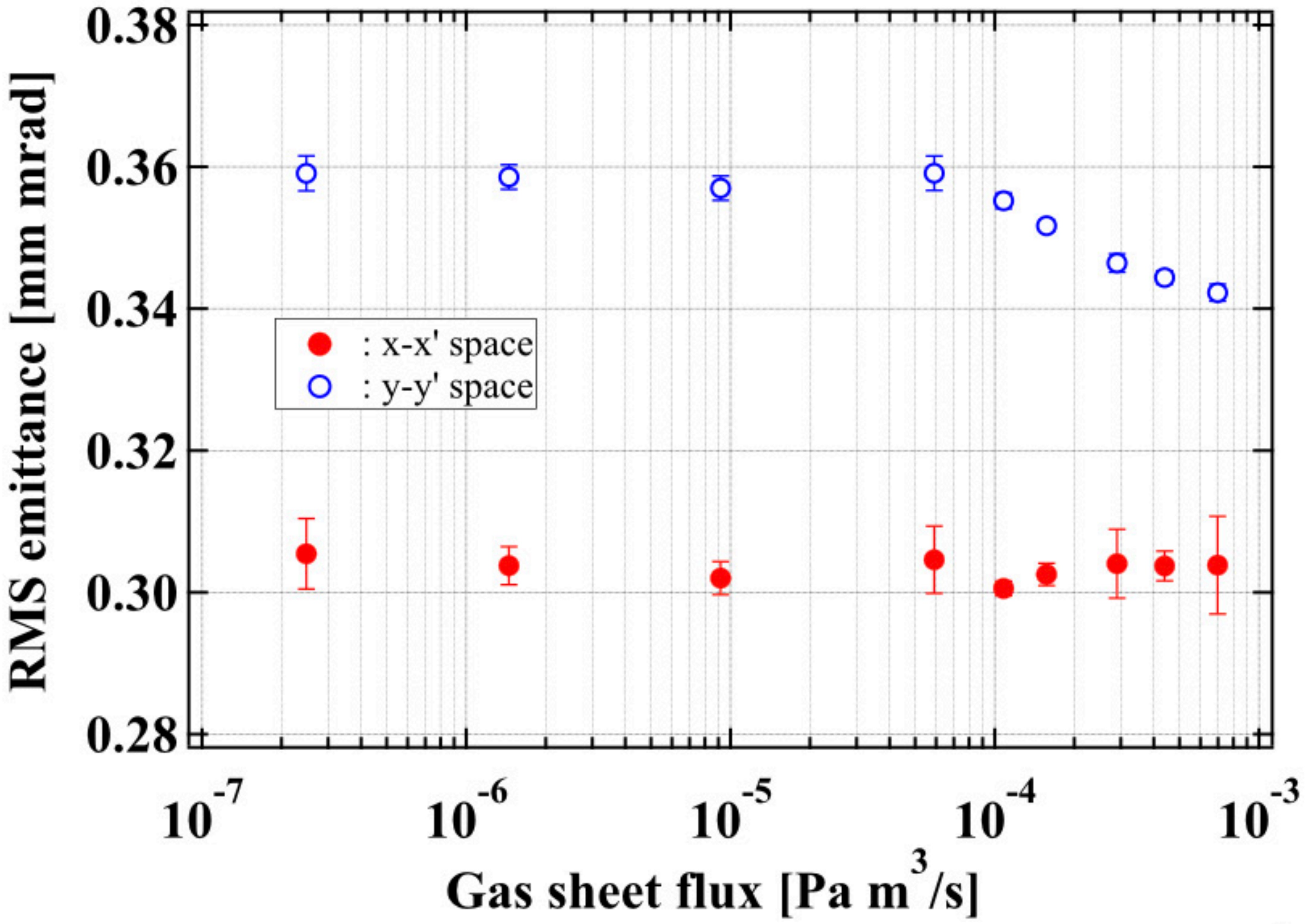
❖ **Invasiveness: phase space distribution (emittance)**

Beam RMS emittances in transverse were measured



< Prediction >

Emittance should increase due to scattering



< Results >

- X-X' plane: no significant change
- Y-Y' plane: **decreased at high flux!!**

Background: Space-Charge Neutralization

❖ **Space-Charge Neutralization (Compensation)**

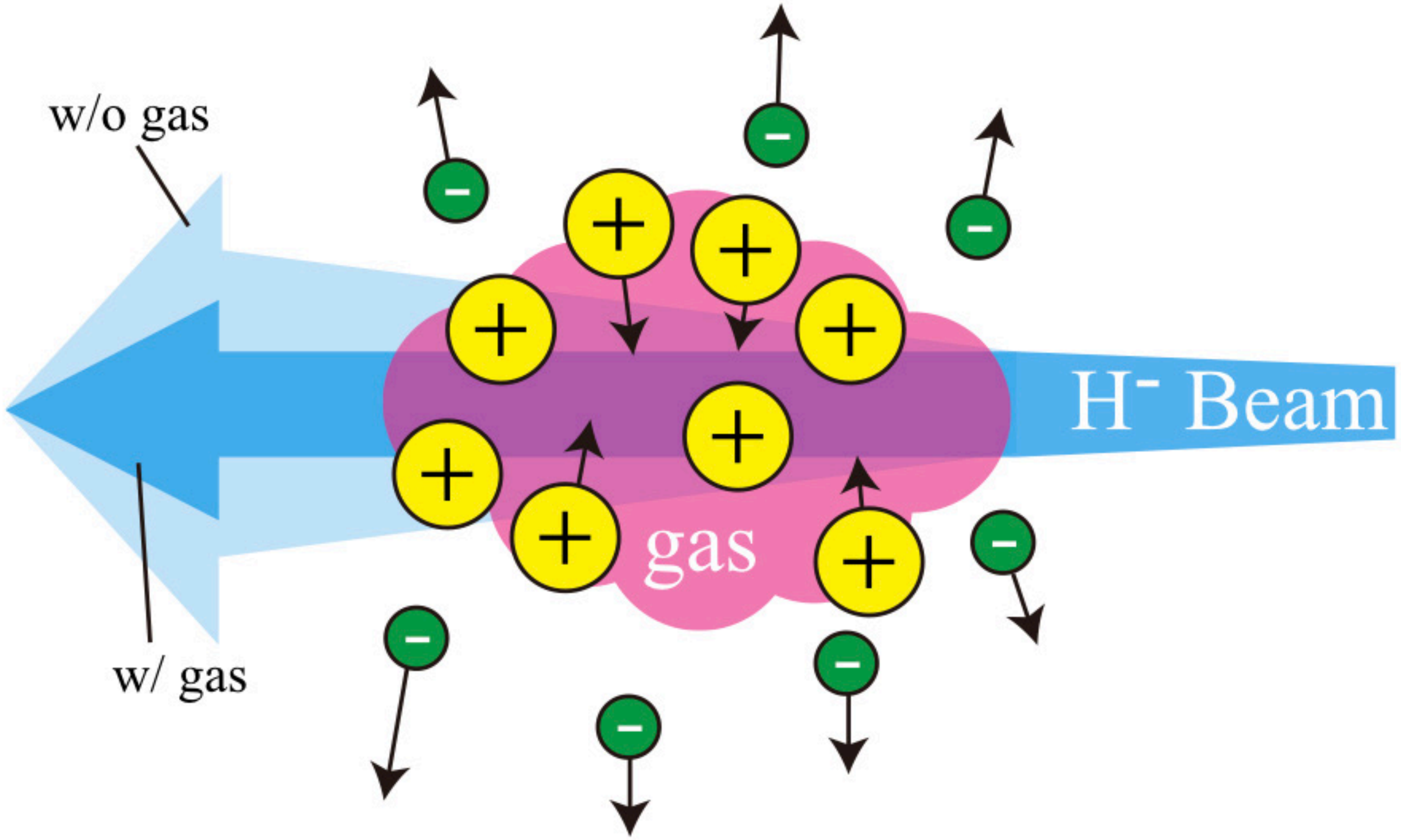
Beam-Gas interaction produces **plasma** as well as photons

=> Ions in plasma are integrated by H^- beam's potential and neutralize space charge

=> Non-linear force inducing emittance growth disappears

=> Emittance **relatively** decreases

Does use of Gas Sheet Monitor improve beam quality, rather than disturb beam!?



Objectives & Methods

❖ **Objectives**

Understanding and Modeling neutralization in terms of beam dynamics for developing a beam profile monitor having relative cooling function

❖ **Methods**

- Check code with simple model
- Simulate GSM experiment to evaluate measured emittance reduction
- Clarify SCN and emittance reduction and their conditions/limitations

Methods: Particle-in-Cell Simulation Model

❖ Simulation Code

WARP code developed in LBNL: one of Particle-in-Cell code
—> Calculating time development of beam and plasma motions

❖ Simulation Model

Beam : H^-

assumed rapidly eliminated by beam potential

Plasma : N_2^+ ions w/o electrons

Production probability = $n_{\mathrm{gas}}\sigma_{\mathrm{ion}}(\beta c\Delta t)$: $\sigma_{\mathrm{ion}} = 6 \times 10^{-21}\ \mathrm{m}^2$

- distribution in trans.) same as beam
- distribution in long.) proportional to gas distribution
- distribution in velocity) thermal motion (300 K)
- time structure) uniform = produced in each time step

Elimination: collision with wall

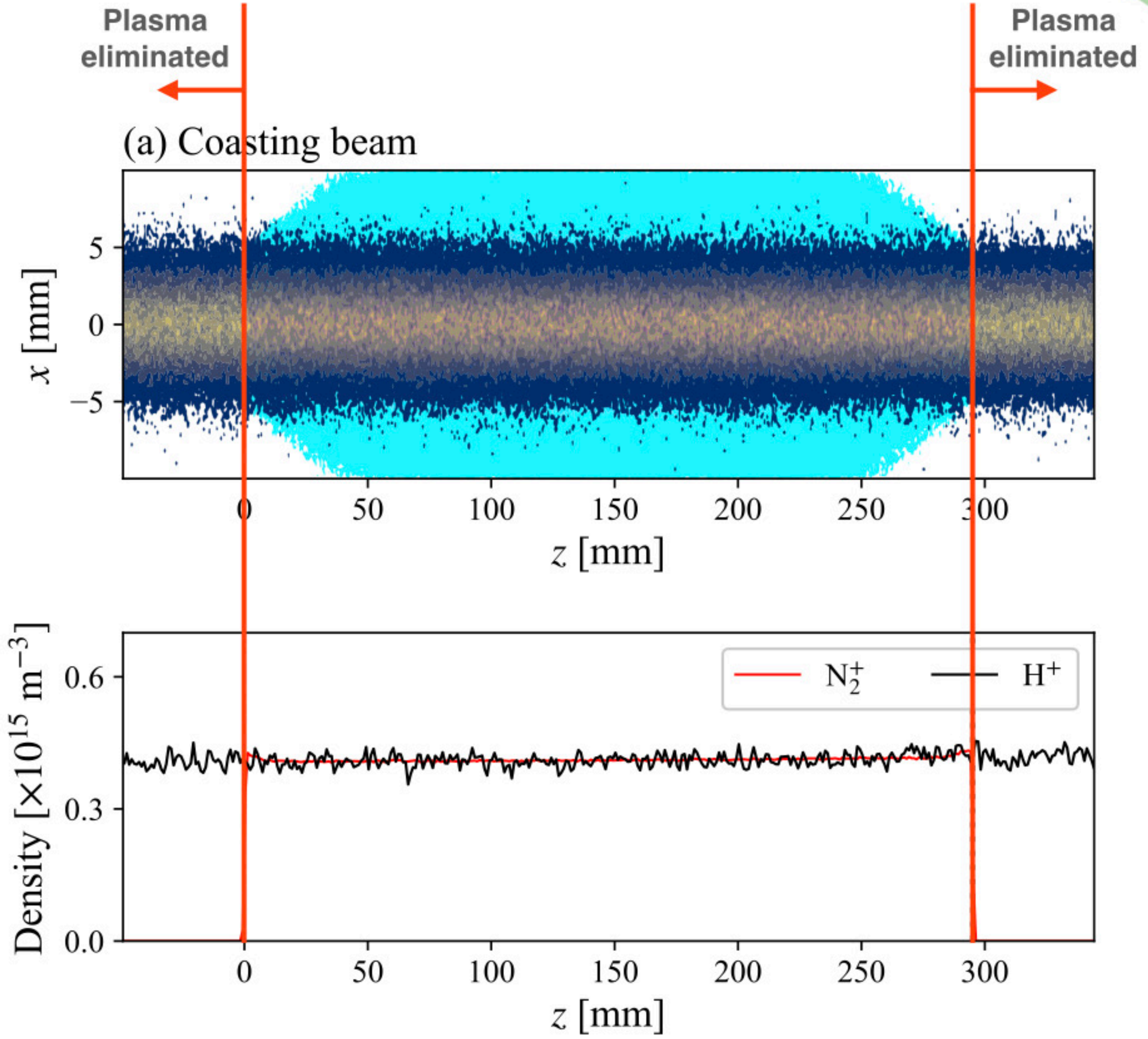
Result: Checking code

❖ **Coasting Beam Model**

For coasting beam,
SCN degree may reach 1 at steady state
—> Code evaluation

< Conditions >

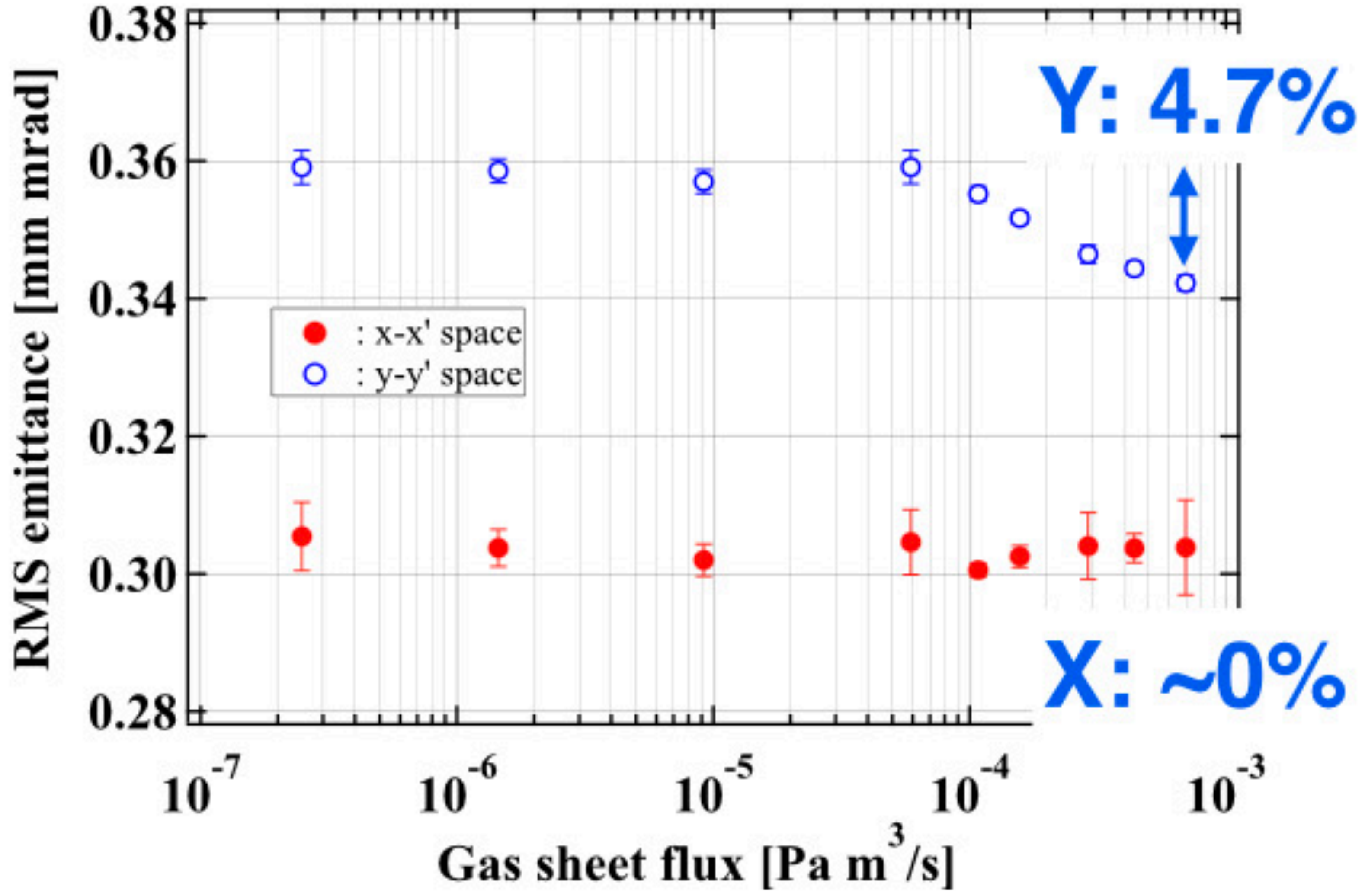
- Beam: 3 MeV, 60 mA, Gaussian(trans.)+uniform(long.)
- External Force: uniform focusing
- Gas density: 10^{-3} Pa, uniform



< Result >

Plasma density has a steady state
where SCN degree took 1 as expected
=> WARP code can simulate space-charge neutralization

Result: Emittance Reduction with Gas Sheet Monitor

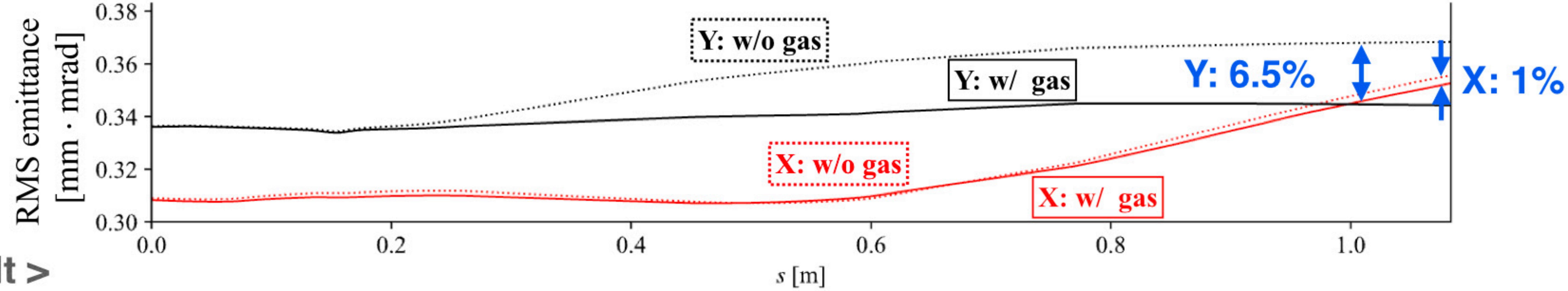


❖ Simulating Gas Sheet Monitor Experiment

Reproducing the GSM evaluation experiment

< Conditions >

- Beam: 3 MeV, 60 mA, bunched (with 324 MHz RFQ), phase space distr. measured by double-slit monitor
- Lattice: RFQ test stand
- Gas: realistic distribution simulated with measured pressures 10^{-5}-10^{-3} Pa



< Result >

Simulation reproduced the experimental emittance reduction

=> **GSM has potential to reduce emittance through SCN when measuring beam profile**

✓ WARP code can simulate SCN
✓ GSM can induce SCN

⬇

Modeling SCN

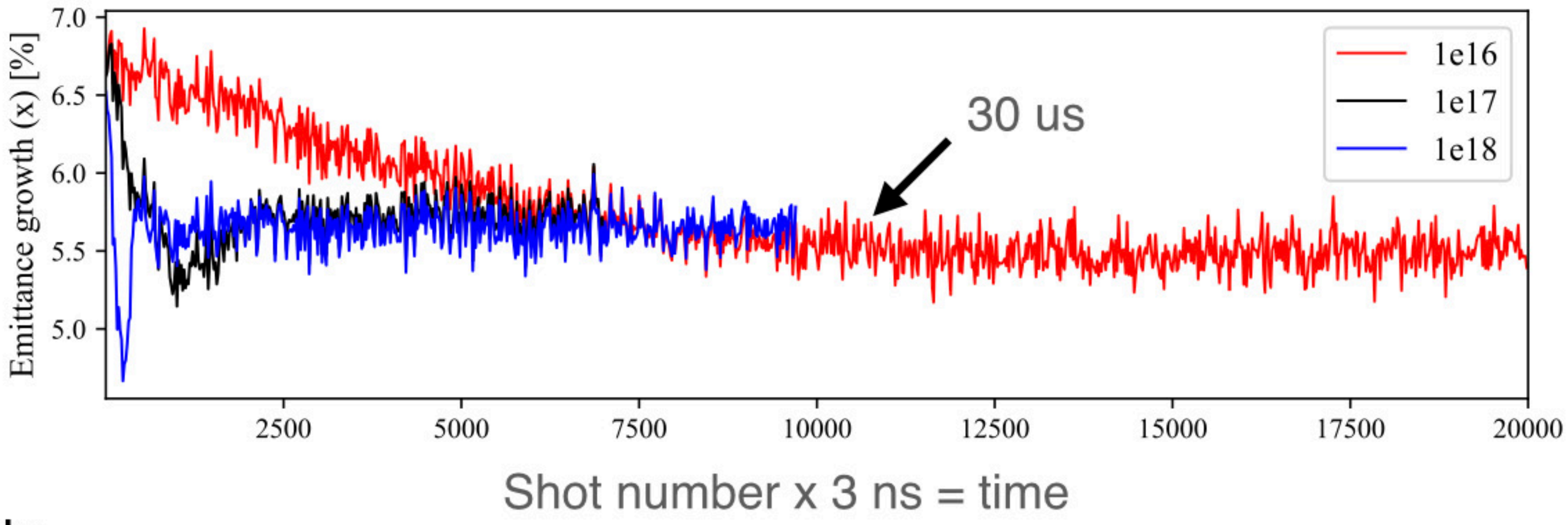
Result: Gas density enough to reduce emittance

❖ **Time evolution dependance on gas density**

To find enough gas density to reduce emittance,
time dependance of the emittance change was evaluated

< Conditions >

- Beam : 6D Gaussian
- Lattice: RFQ-TS
- Gas : uniform



< Result >

- 10^{16} [m^{-3}] ~ 10^{-4} [Pa] is enough
  => GSM case reached steady state
- Lower than 10-4 Pa does not lead to steady state because plasma disappears among pulses
  (even thermal motion at 300 K --> 500 m/s x 40 ms = 20 m)
- Denser gas leads to over relaxation?

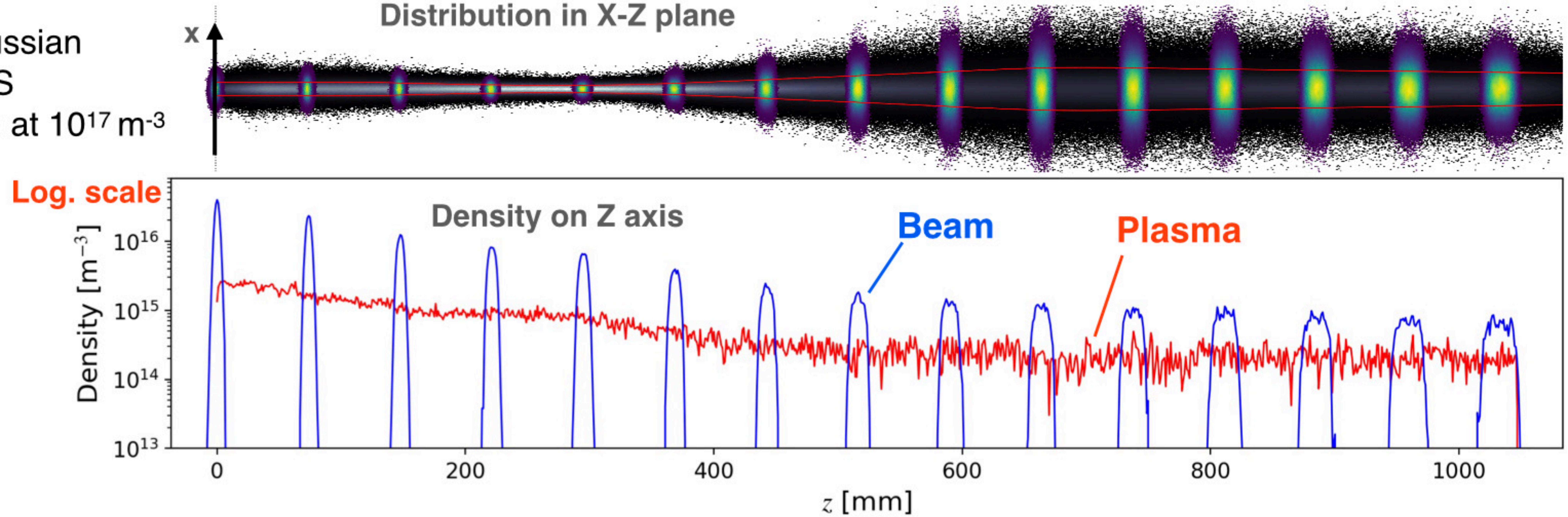
Result: Comparison of densities

❖ **Densities of bunched beam and plasma at steady state**

To understand the details of SCN, comparing densities of beam and plasma

< Conditions >

- Beam : 6D Gaussian
- Lattice: RFQ-TS
- Gas : uniform at 10^{17} m^{-3}



< Result >

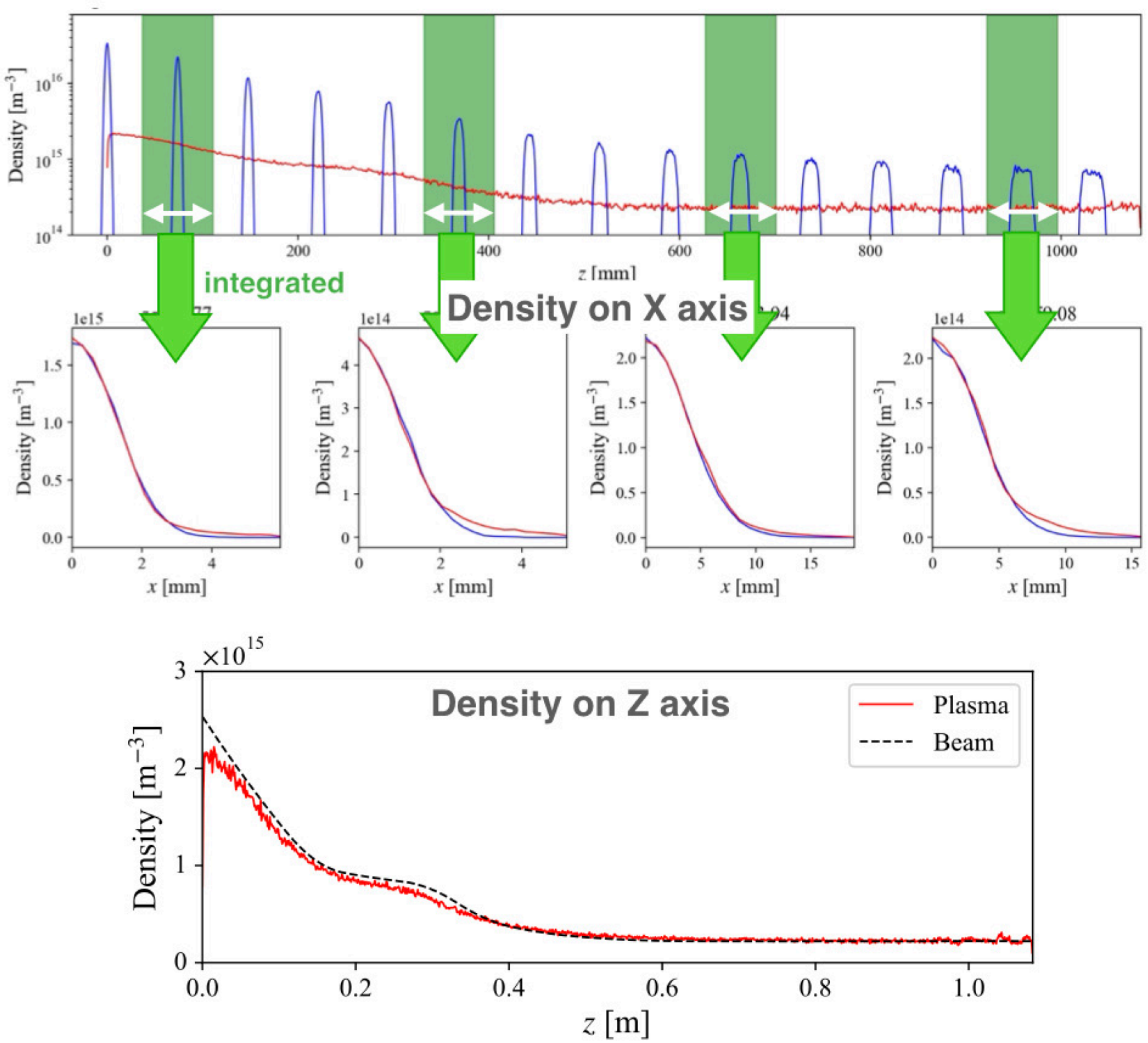
- Plasma density is 10 times lower even in steady state
  => SCN degree does not reach 1

=> Can plasma not respond to the beam passing and feel time-averaged field of the beam?

Result: Time-averaged beam density

❖ **Time average**

Plasma feels time average field
=> Plasma density may reach time average density of beam



< Result >

- Plasma density distribution well agreed with time-averaged beam distribution

=> SCN degree for bunched beam is limited by bunch compression ratio

- Over neutralization caused at denser gas is understandable because plasma density can exceed the one at steady state before steady state

Discussion: Proposal of SCN term for envelop equstion

❖ **Space-Charge Neutralization Term in Envelop Equation**

For steady state, we propose space-charge neutralization model for envelop eq.
(we are trying to improve it for time evolution & consideration of gas density)

< Conventional >

- Arbitrary parameter: f
- (perhaps) Only for continuous beam

$$\frac{\mathrm{d}^2\sigma_x}{\mathrm{d}s^2} + k(s)\sigma_x - \frac{{\varepsilon_x}^2}{{\sigma_x}^3} - \frac{K_{\mathrm{sc,2D}}(1-f)}{\sigma_x + \sigma_y} = 0$$

< Proposal >

- For bunched beam
- No arbitrarity
-

$$K_{\mathrm{sc}} = \frac{qI}{4\pi\sqrt{2\pi}\epsilon_0 m\beta^2 c^2 \gamma^3 f_{\mathrm{RF}}}$$

$$K_{\mathrm{scn}} = \frac{qI}{4\pi\epsilon_0 m\beta^3 c^3 \gamma}$$

$$\frac{\mathrm{d}^2\sigma_x}{\mathrm{d}s^2} + k(s)\sigma_x - \frac{{\varepsilon_x}^2}{{\sigma_x}^3} - \frac{K_{\mathrm{sc}}}{(\sigma_x + \sigma_y)\sigma_z} + \frac{K_{\mathrm{scn}}}{\sigma_x + \sigma_y} = 0$$

$$\frac{\mathrm{d}^2\sigma_z}{\mathrm{d}s^2} + k(s)\sigma_z - \frac{{\varepsilon_z}^2}{{\sigma_z}^3} - \frac{K_{\mathrm{sc}}}{\sigma_x\sigma_y} = 0$$

* in case of uniform beam

Discussion: SC and SCN terms

❖ Comparison between SC and SCN terms

SCN term is

- bigger in factor of $\gamma^2/\beta > 1$
  => Plasma is in Lab frame <—> Beam is in CM frame

- smaller in factor of $\sigma_z/\lambda_{\mathrm{RF}}$
  => Bunch compression ratio against continuous beam reduces SCN effect

$$-\frac{K_{\mathrm{sc}}}{\sigma_z(\sigma_x+\sigma_y)}+\frac{K_{\mathrm{scn}}}{\sigma_x+\sigma_y}=-\frac{K_{\mathrm{sc}}}{\sigma_z(\sigma_x+\sigma_y)}\left\{\boxed{1}-\boxed{\sqrt{2\pi}\frac{\gamma^2}{\beta}\frac{\sigma_z}{\lambda_{\mathrm{RF}}}}\right\}$$

SC term SCN term

β, γ: Lorentz factor
σ_z: Bunch length
λ_{RF}: RF acceleration wavelength

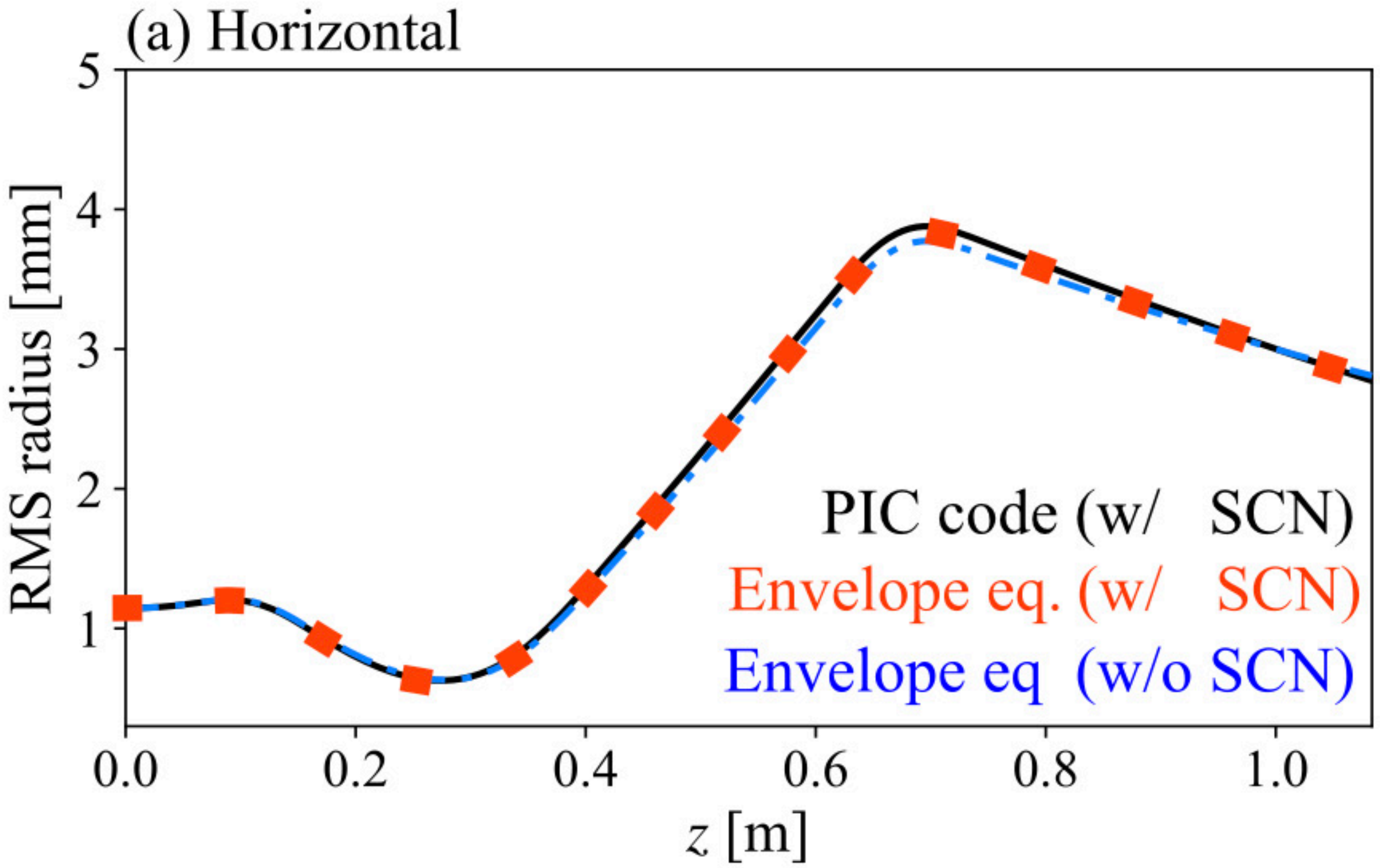
Discussion: Effect of SCN term

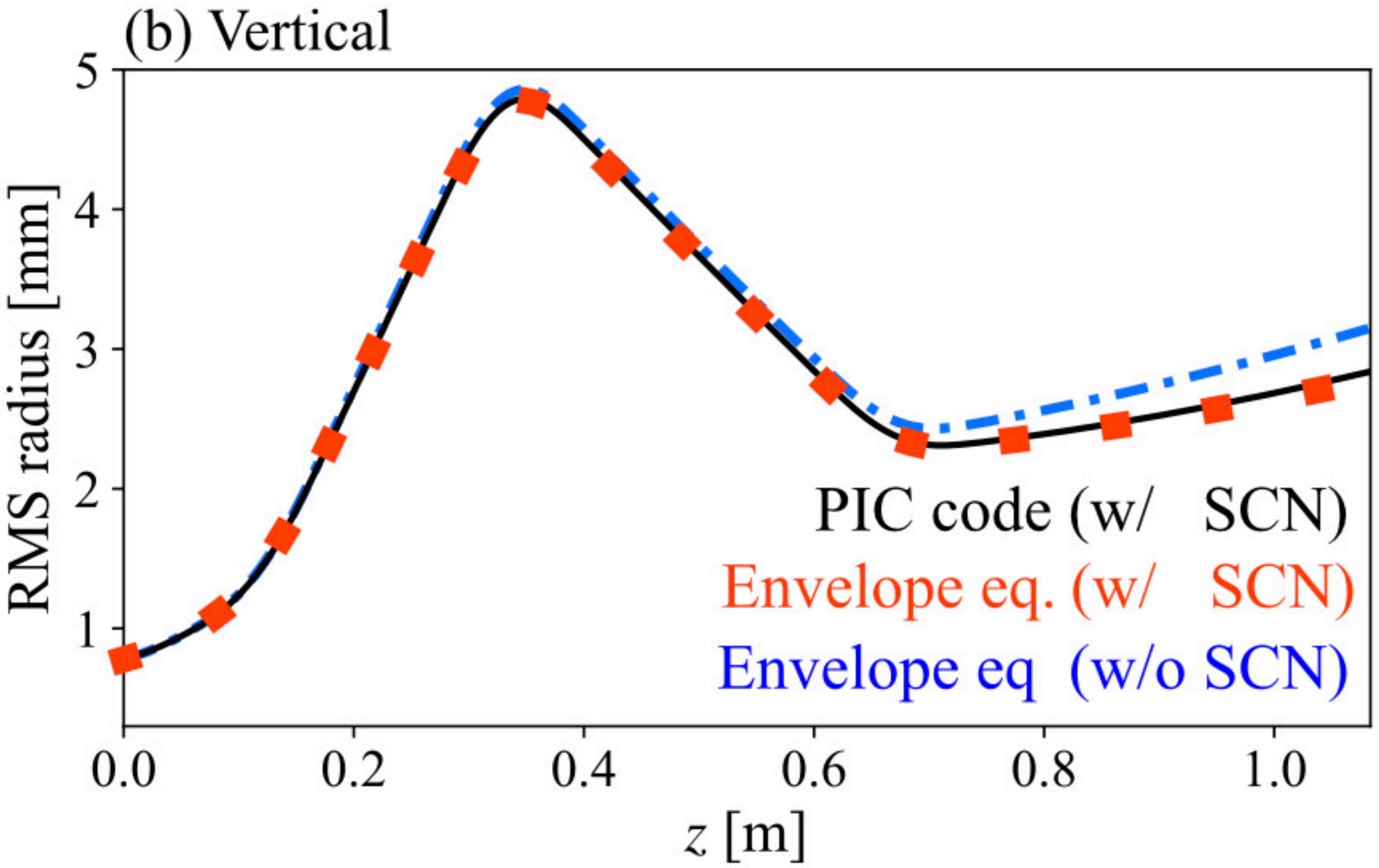
❖ **Evaluation Env. eq. with PIC code**

Beamline : RFQ test stand

Beam profile: 6D Gaussian => solve Poisson eq. in each time step for SC terms

Result: **SCN term** could improve the RMS evolution to match the **PIC code**

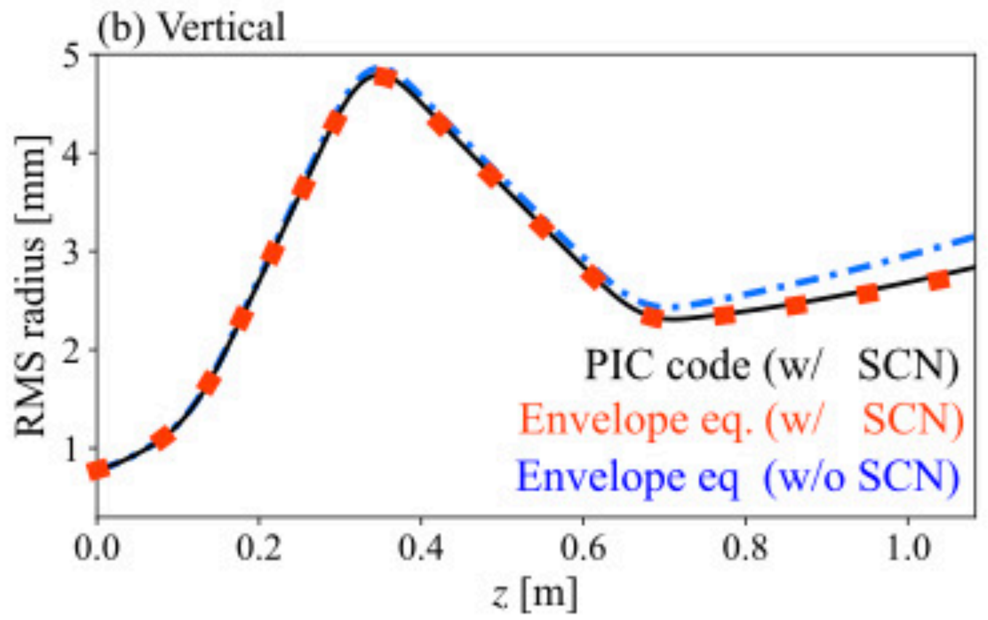


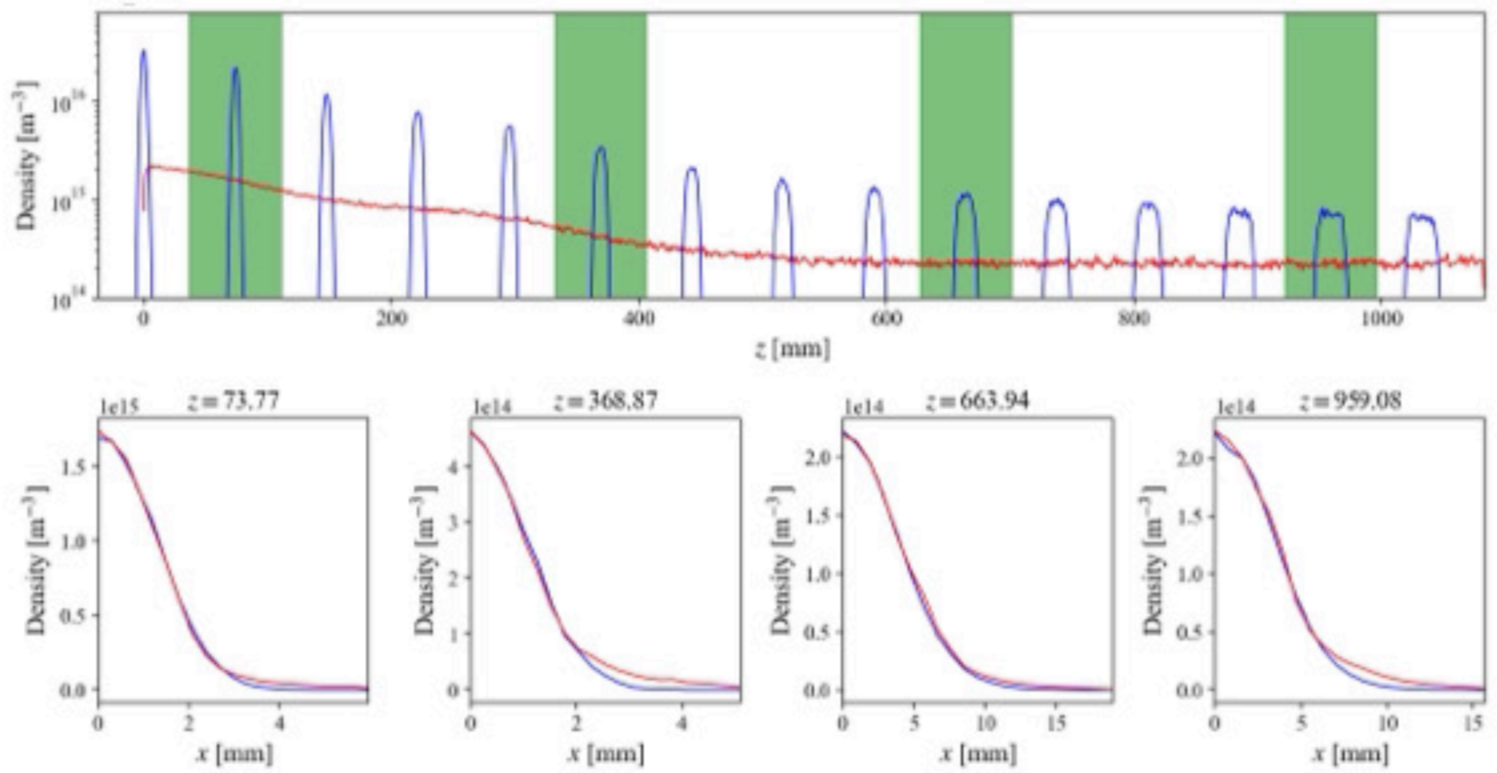


Summary

< Summary >

- Gas-sheet beam profile monitor can induce space-charge neutralization and emittance reduction even for bunched beam
- Plasma density reaches to beam density corresponding to continuous beam
  => Space-charge neutralization for bunched beam is limited by bunch compression ratio
- SCN term at steady state can be described by perveance for continuous beam and improves envelop equation to match PIC code





< Next Plans >

Improve SCN term by taking into consideration of

- Time evolution
- Gas density dependance