Plasma Sheath Around Long Conductors with Elliptic Cross-sections

L. Chiabò, G. Sánchez-Arriaga

Universidad Carlos III de Madrid, Spain

APS-DPP 2020, 9-13 November

INDEX

- Introduction
- Kinetic Model for 2D Emissive Probes with Elliptic cross-section
- Numerical Results
- Conclusions

INTRODUCTION

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- Goal: Kinetic analysis of plasma structure and currents around long electron emitting objects with elliptical cross-sections

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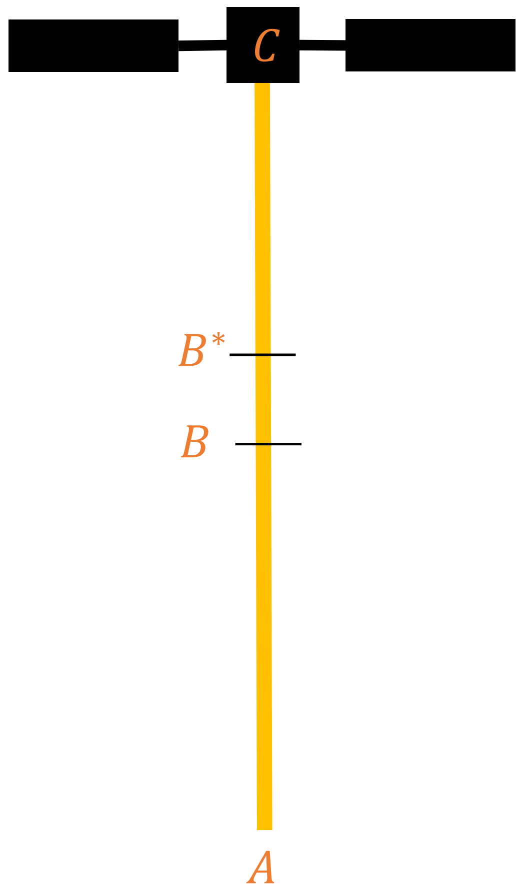
  - Low Work-function Tethers (E.T.PACK)

Plasma-Tether interaction



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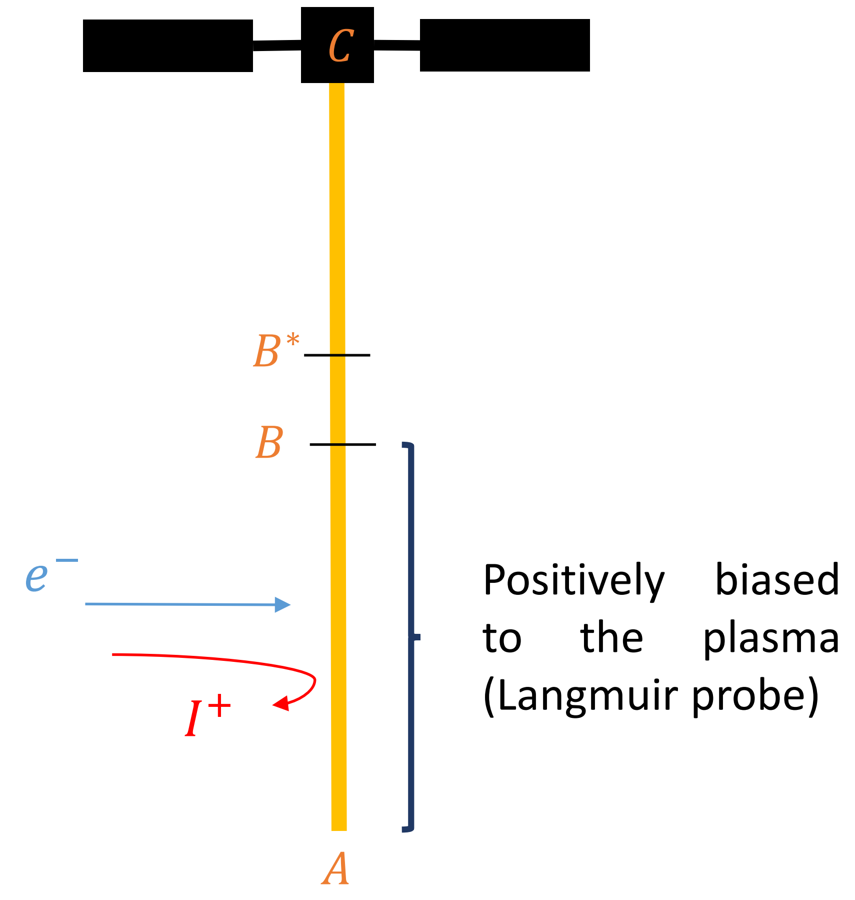

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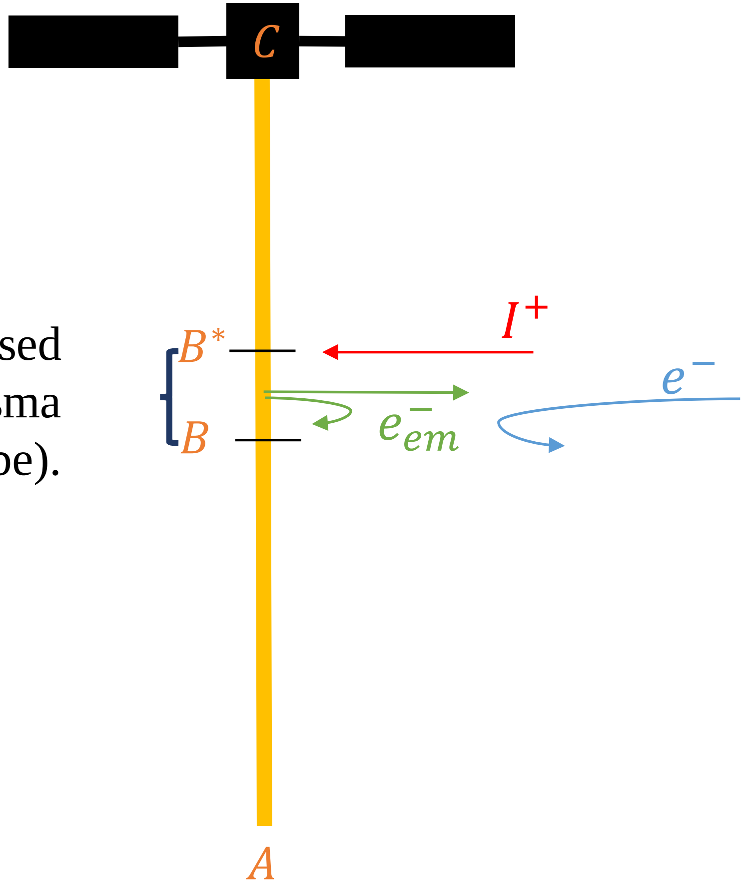
Negatively biased to the plasma (Emissive* probe).



*Space Charge Limited (SCL): a potential dip reflects part of the emitted electrons back to the tether

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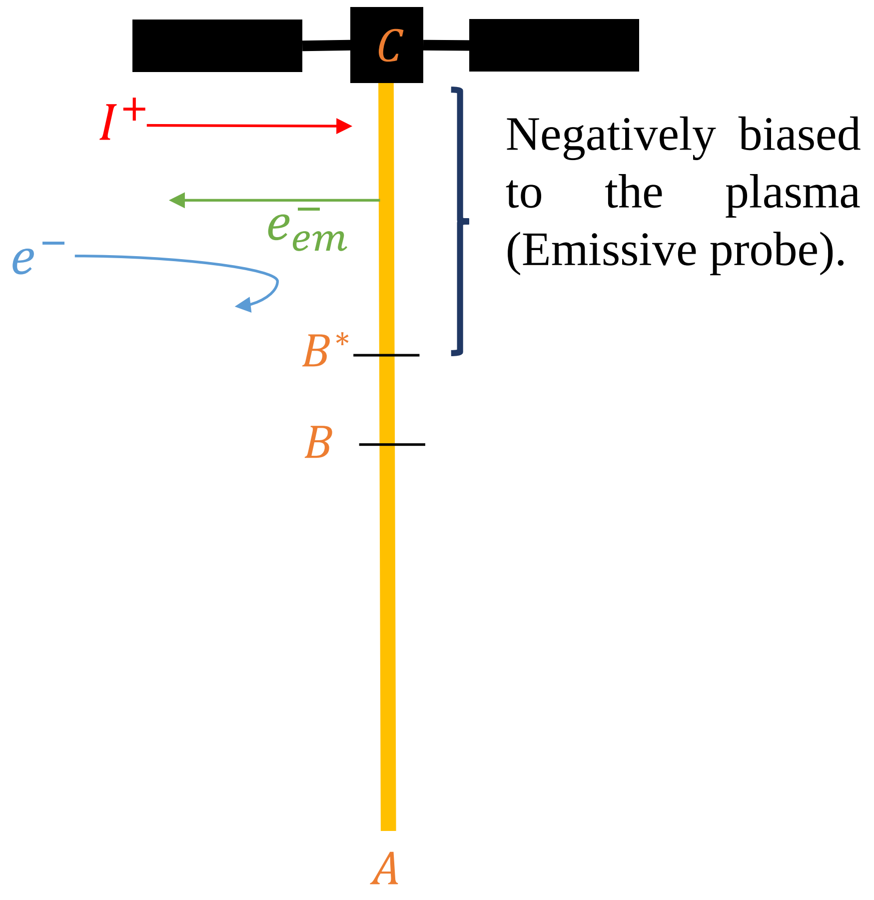

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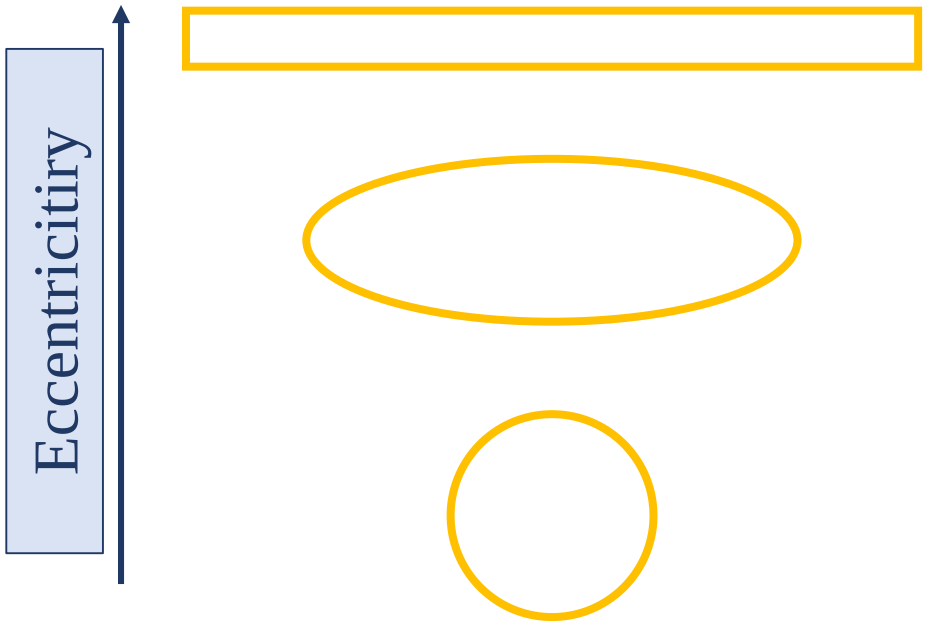
- Tape geometry: favourable for tethers applications
- Ellipse (eccentricity = 1) ≈ Tape



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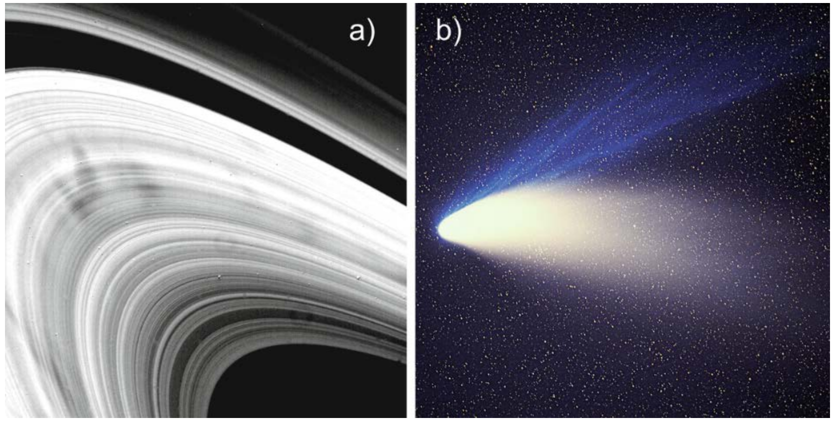
  - Probe theory
  - Dusty plasmas
  - Spacecraft charging



Melzer A. (2019) Introduction. In: *Physics of Dusty Plasmas. Lecture Notes in Physics*, vol 962. Springer, Cham.

Plasma-Tether interaction

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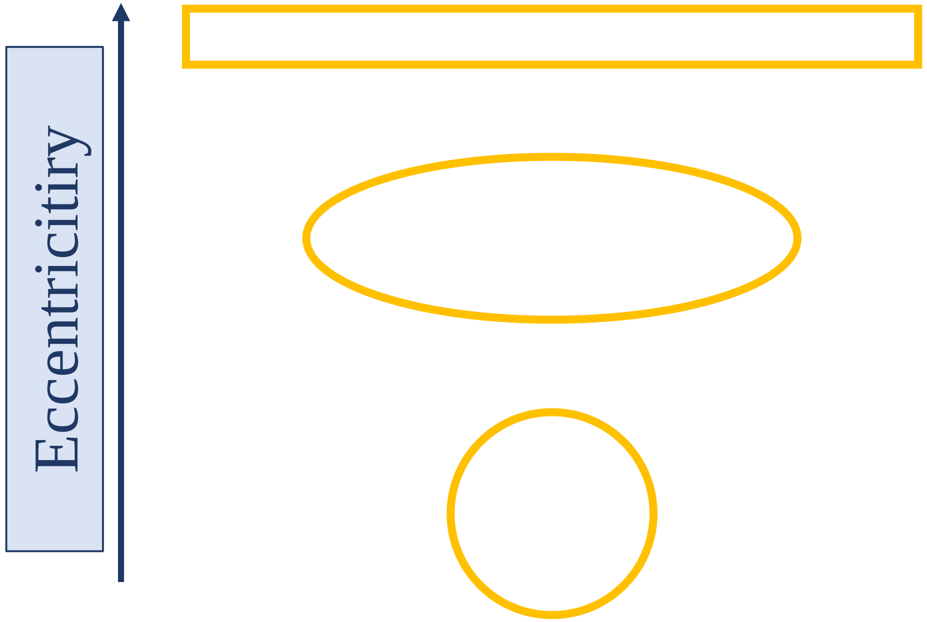

KINETIC MODEL FOR 2D EMISSIVE PROBES WITH ELLIPTIC CROSS-SECTION

KINETIC MODEL FOR 2D EMISSIVE PROBES

Hypotheses

- Stationary solution

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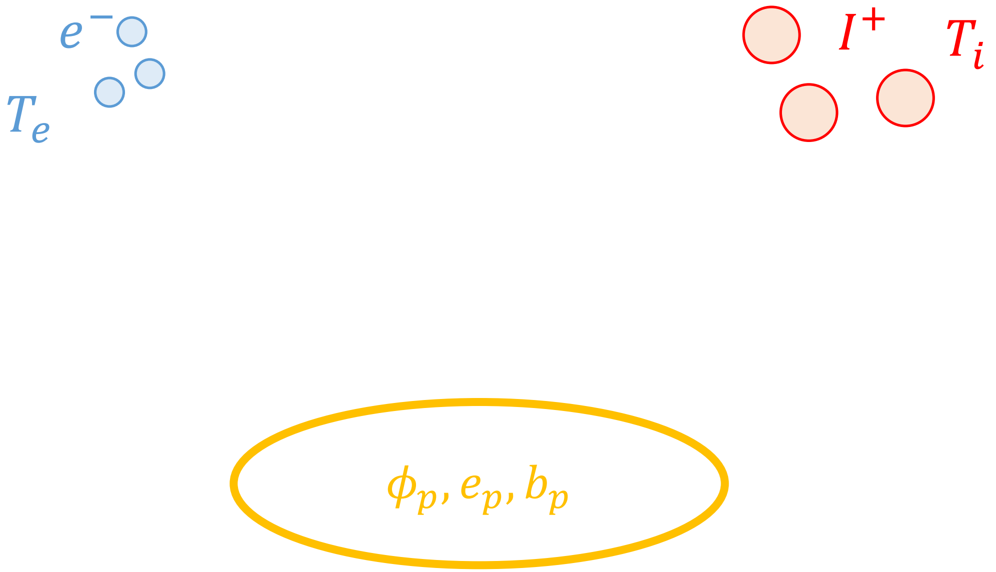

KINETIC MODEL FOR 2D EMISSIVE PROBES

Hypotheses

- Stationary solution
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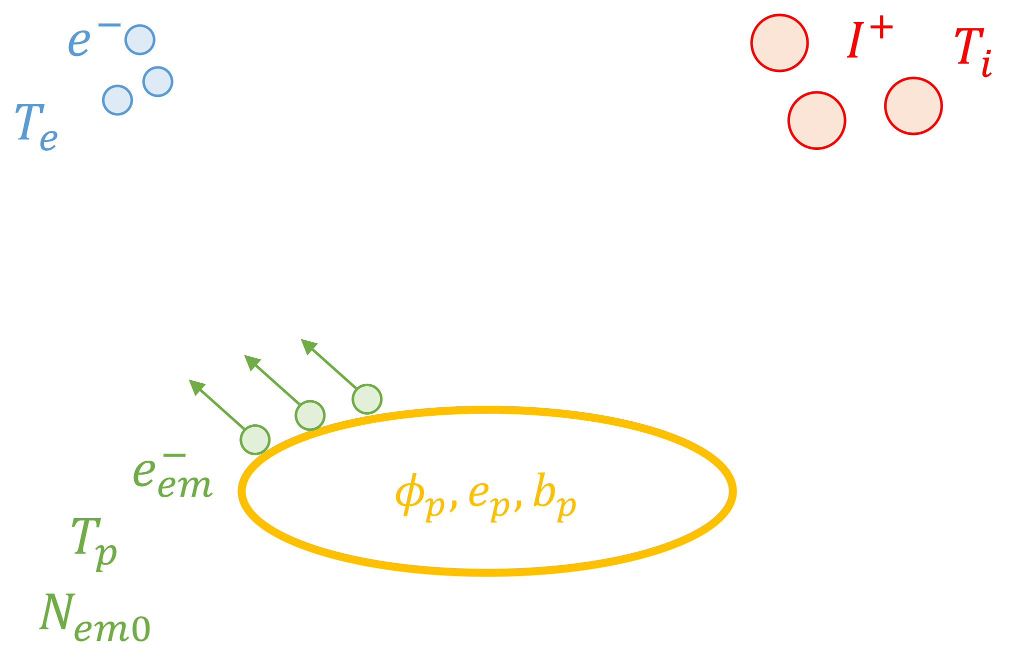
- Singly charged I^+
- Half-Maxwellian e^-_{em}
- Emission follows Richardson-Dushman law

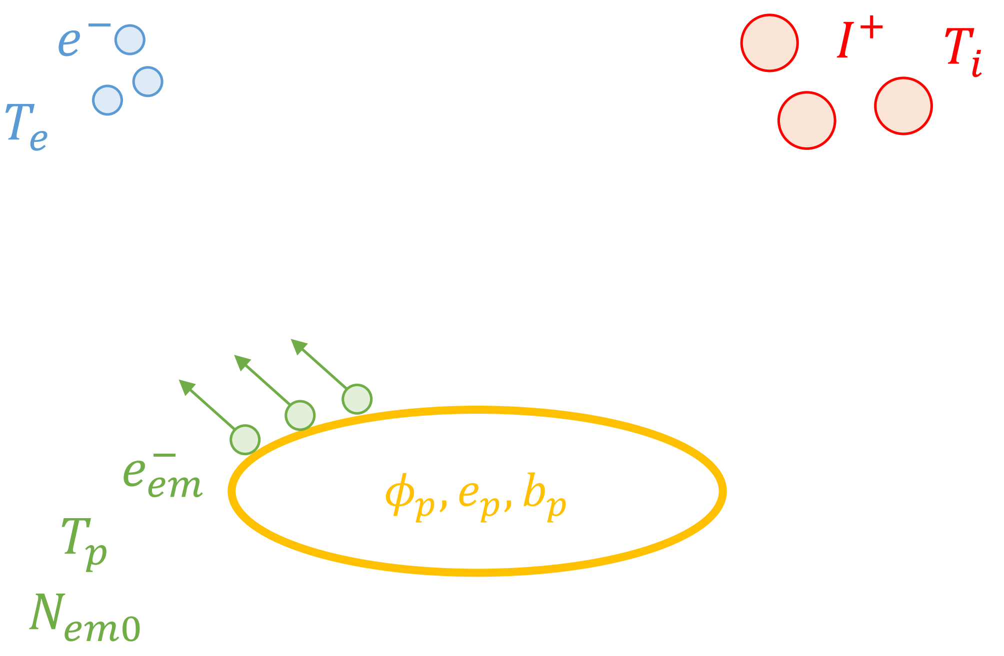


KINETIC MODEL FOR 2D EMISSIVE PROBES

Hypotheses

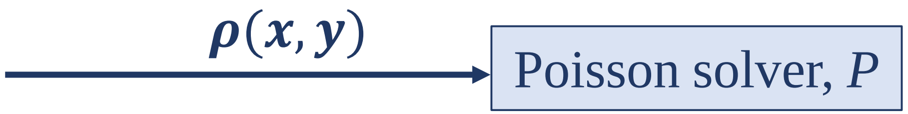
- Stationary solution
- Probe at rest in an unmagnetized, collisionless, Maxwellian plasma with background density N_0
- Singly charged I^+
- Half-Maxwellian e_{em}^-
- Emission follows Richardson-Dushman law
- No trapped particles
- Our solutions depend on 6 parameters:

$$e_p: probe\ eccentricity$$
$$b_p: semi\ minor\ axis/Debye\ length$$
$$\phi_p: normalized\ probe\ bias$$
$$\delta_p \equiv T_p/T_e$$
$$\delta_i \equiv T_i/T_e$$
$$\beta \equiv \frac{N_{em0}}{N_0} = emission\ level$$



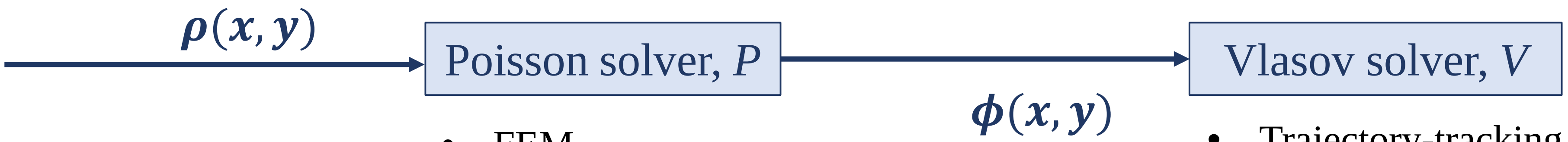
Vlasov-Poisson system

NUMERICAL SCHEME



- FEM
- *Choiniere (2004)*

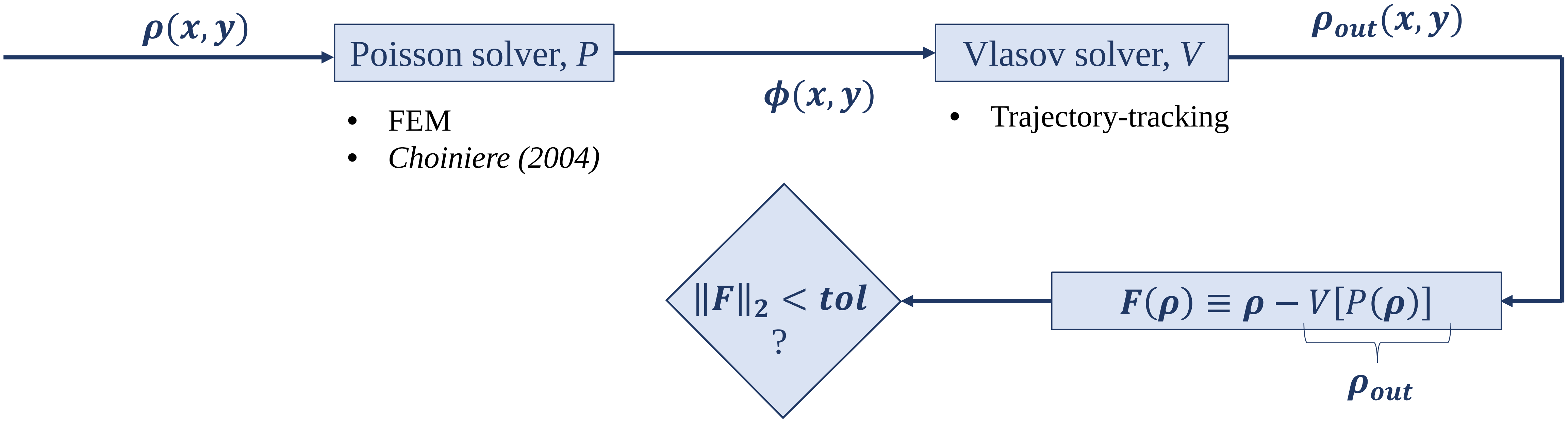
NUMERICAL SCHEME



- FEM
- *Choiniere (2004)*

- Trajectory-tracking

NUMERICAL SCHEME



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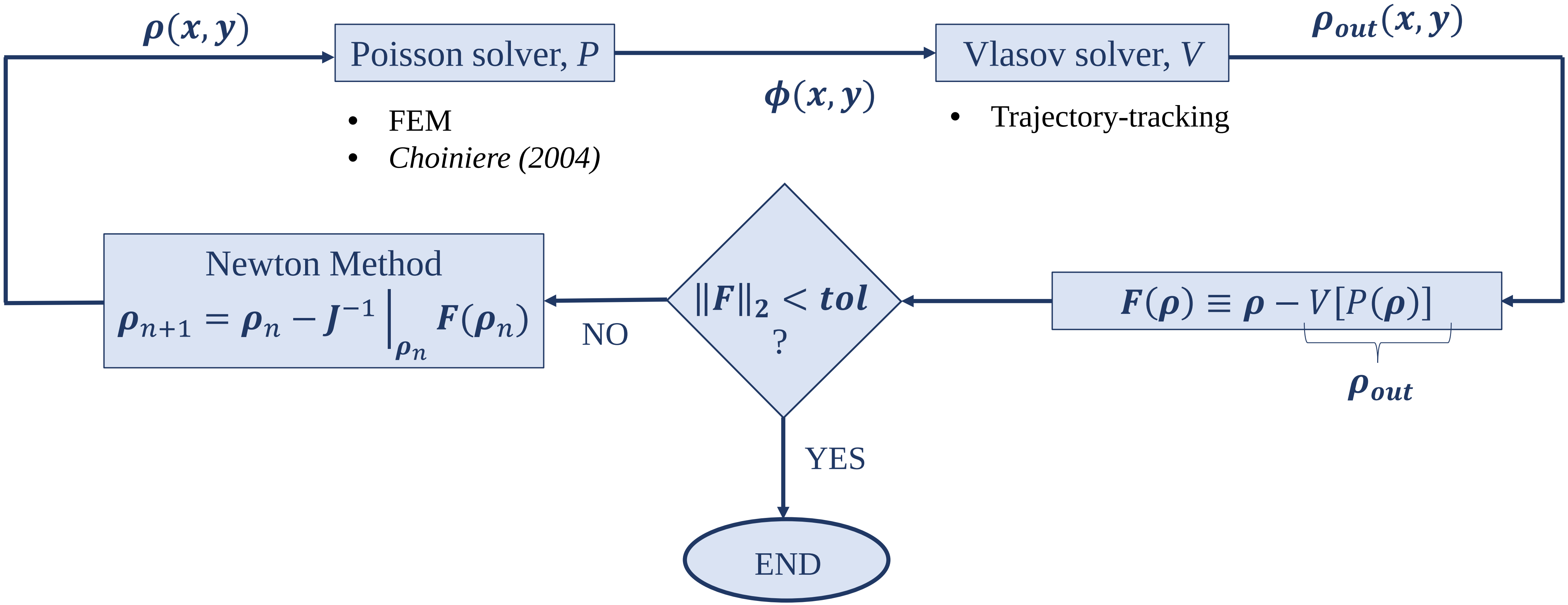

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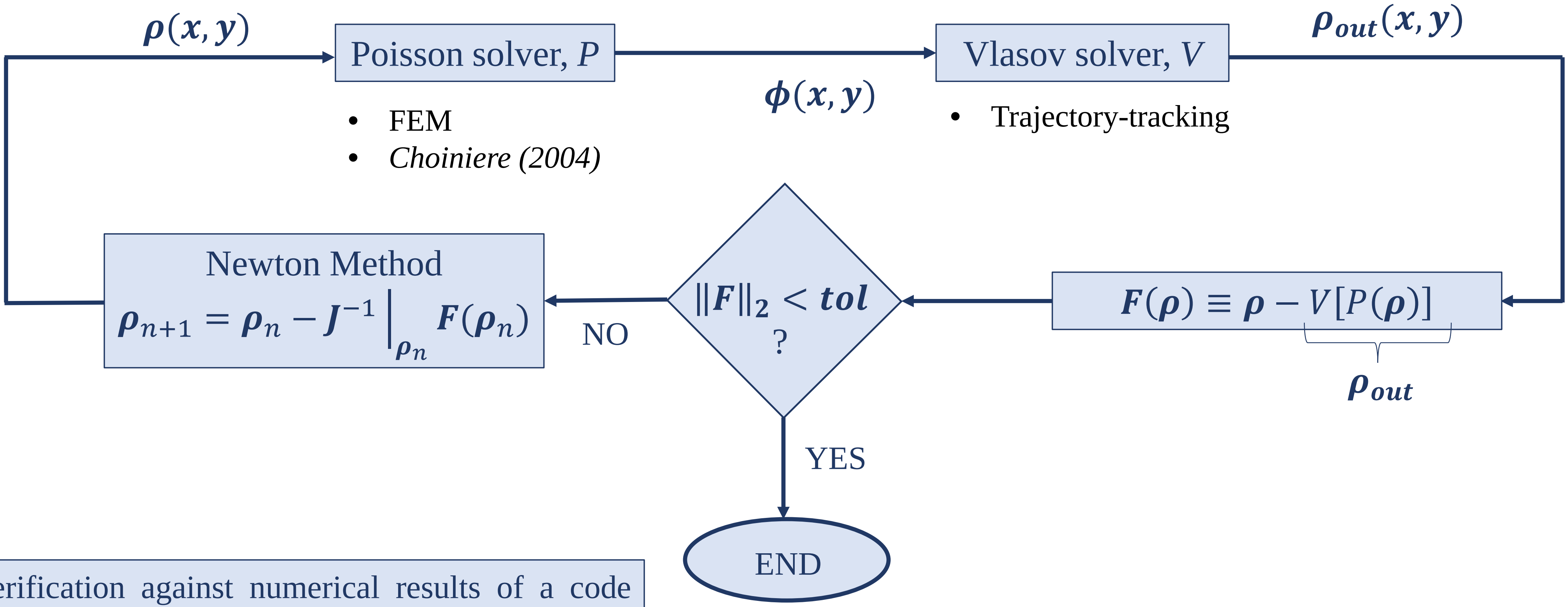


Verification against numerical results of a code for cylindrical emissive probes by *Chen, Sánchez-Arriaga (2017)*

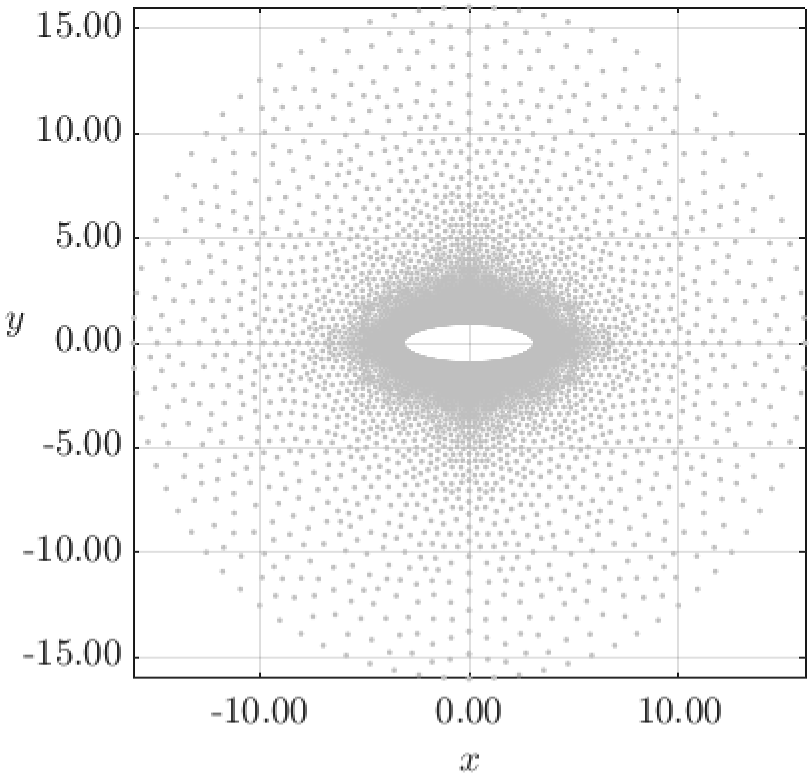
NUMERICAL SCHEME

Vlasov solver

- Computes the density of each species (ϕ as input)
- Collisionless plasma: $df_\alpha/d\tau = 0$
- Backward integration of particles orbits

NUMERICAL SCHEME

Trajectory-tracking algorithm



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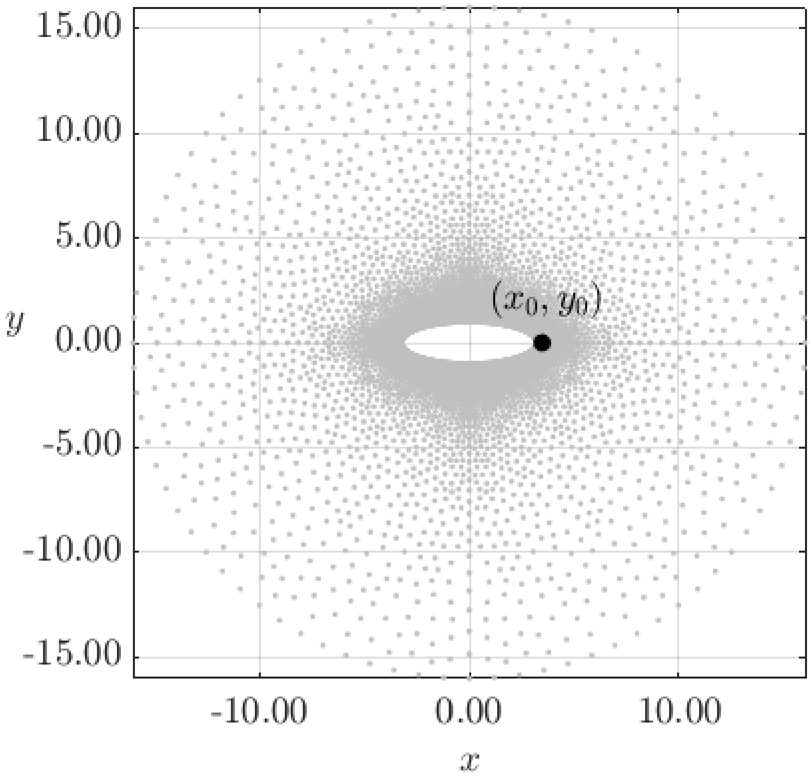
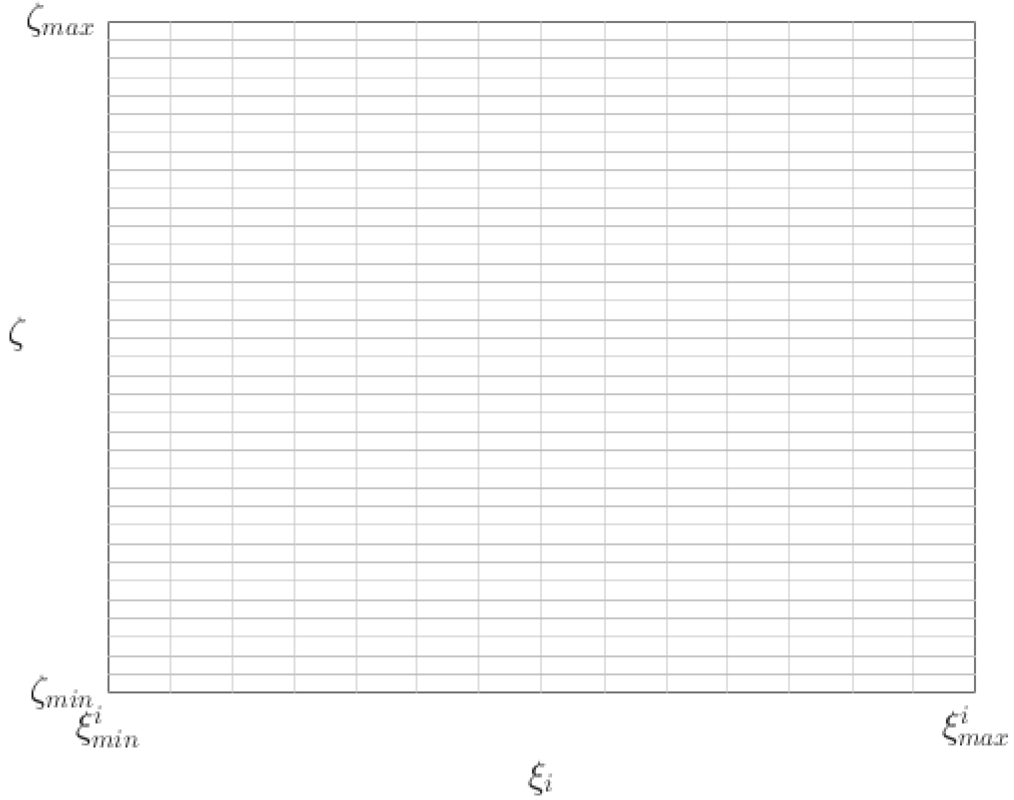




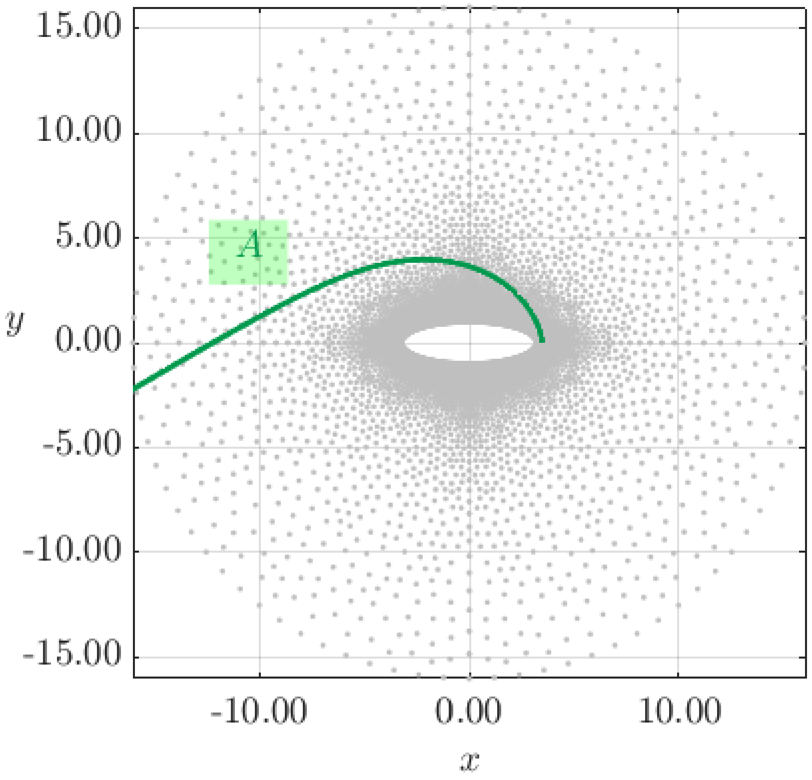
Plasma ions around a negatively polarized probe

ξ_i ≡dimensionless energy, ζ ≡velocity angle

NUMERICAL SCHEME

Trajectory-tracking algorithm

- ● Finite value (Maxwellian)
- ○ Null value



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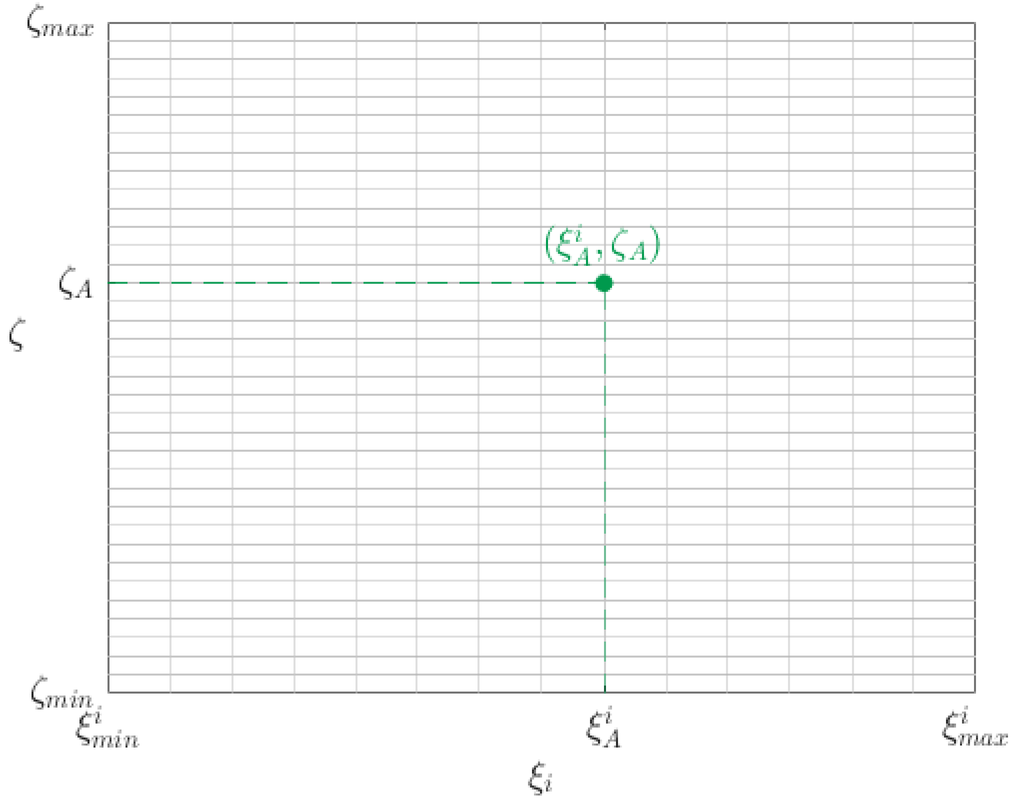

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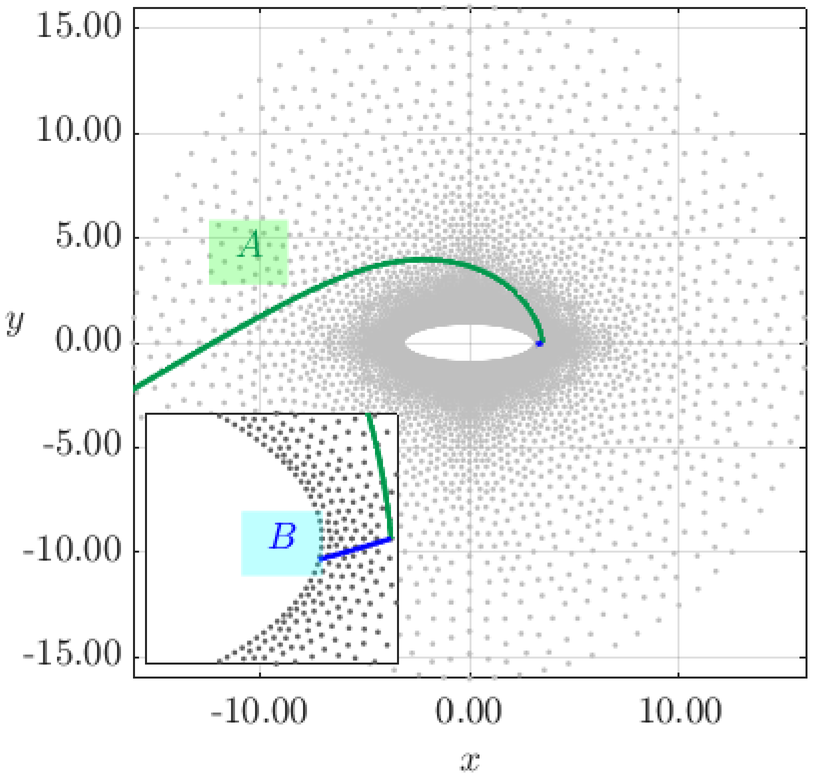

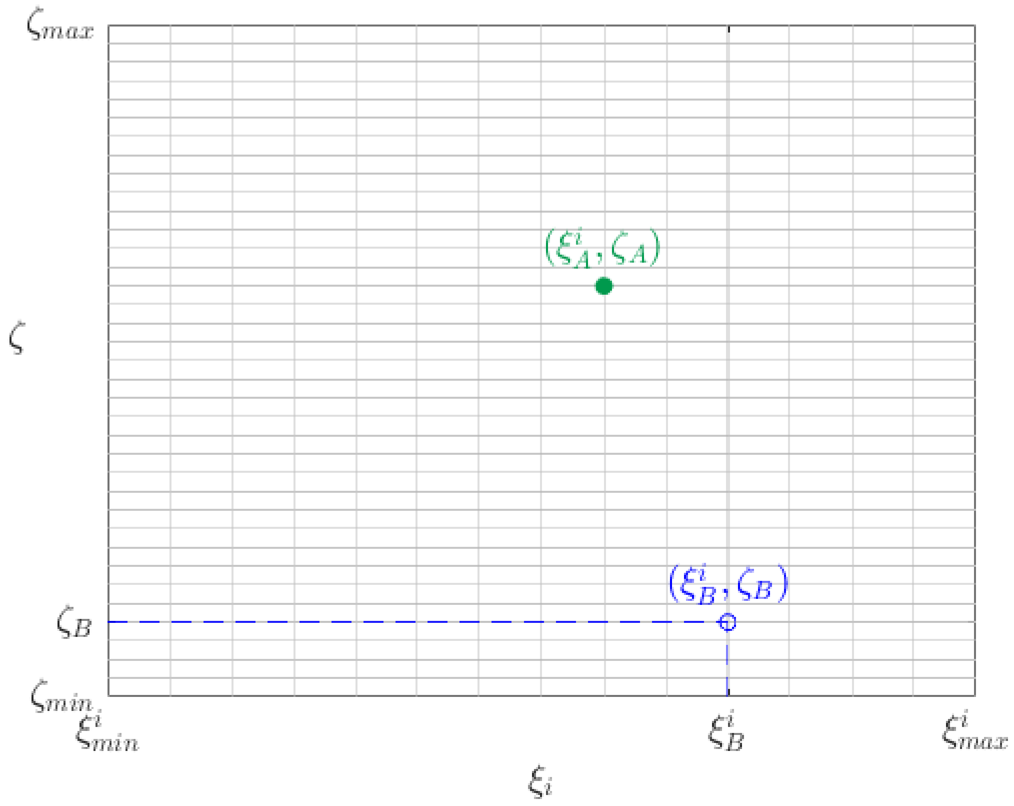

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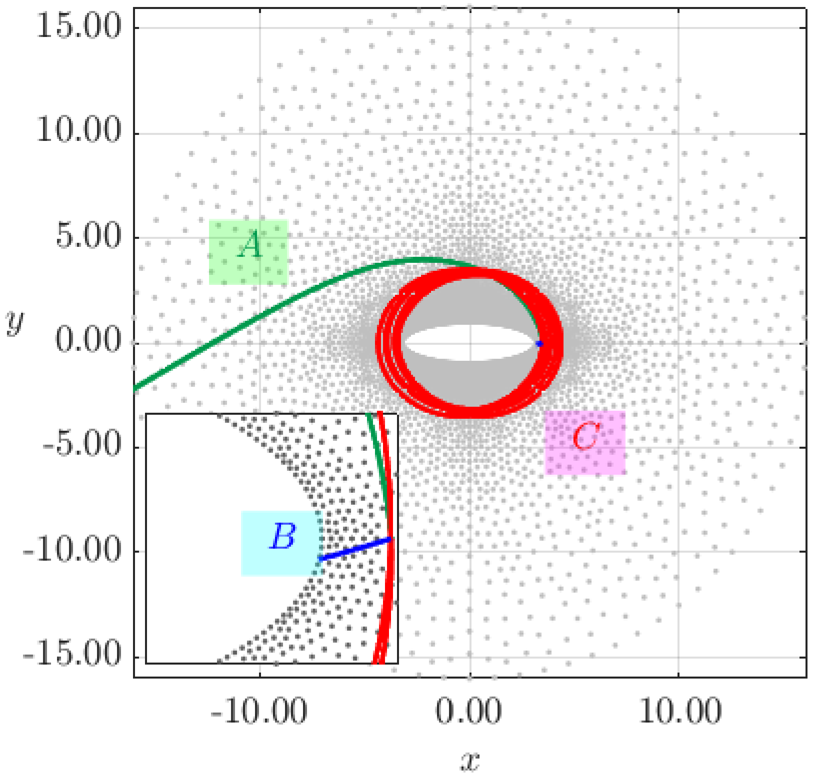

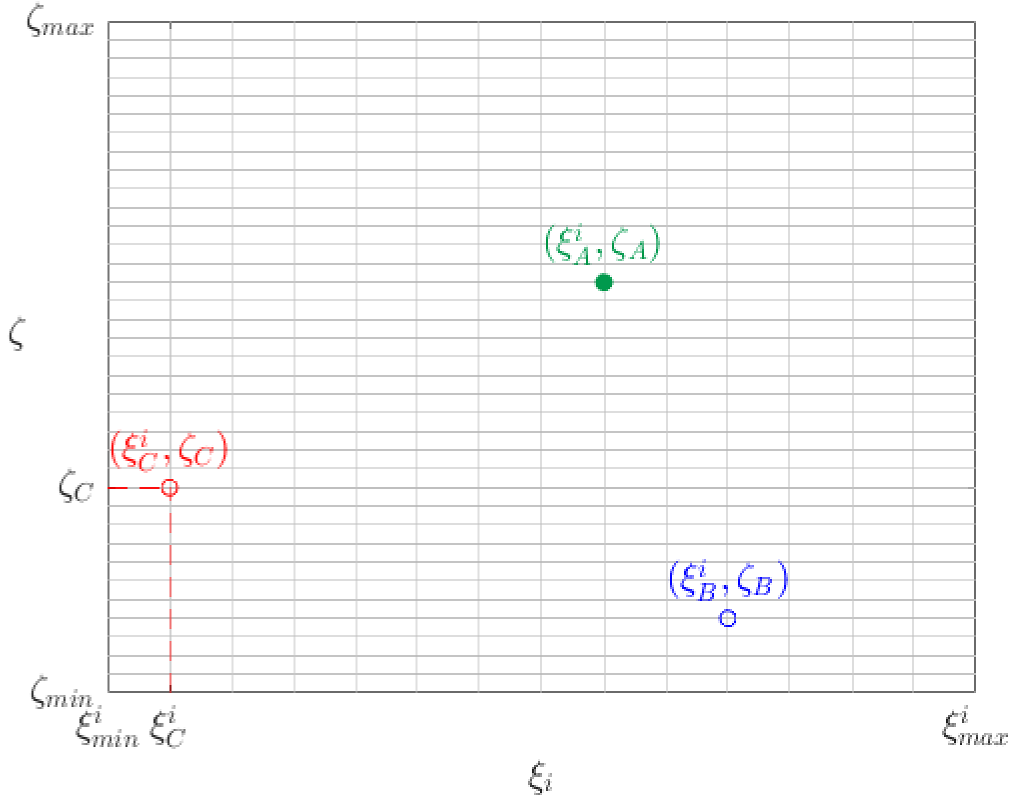

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- Computes the density of each species (ϕ as input)
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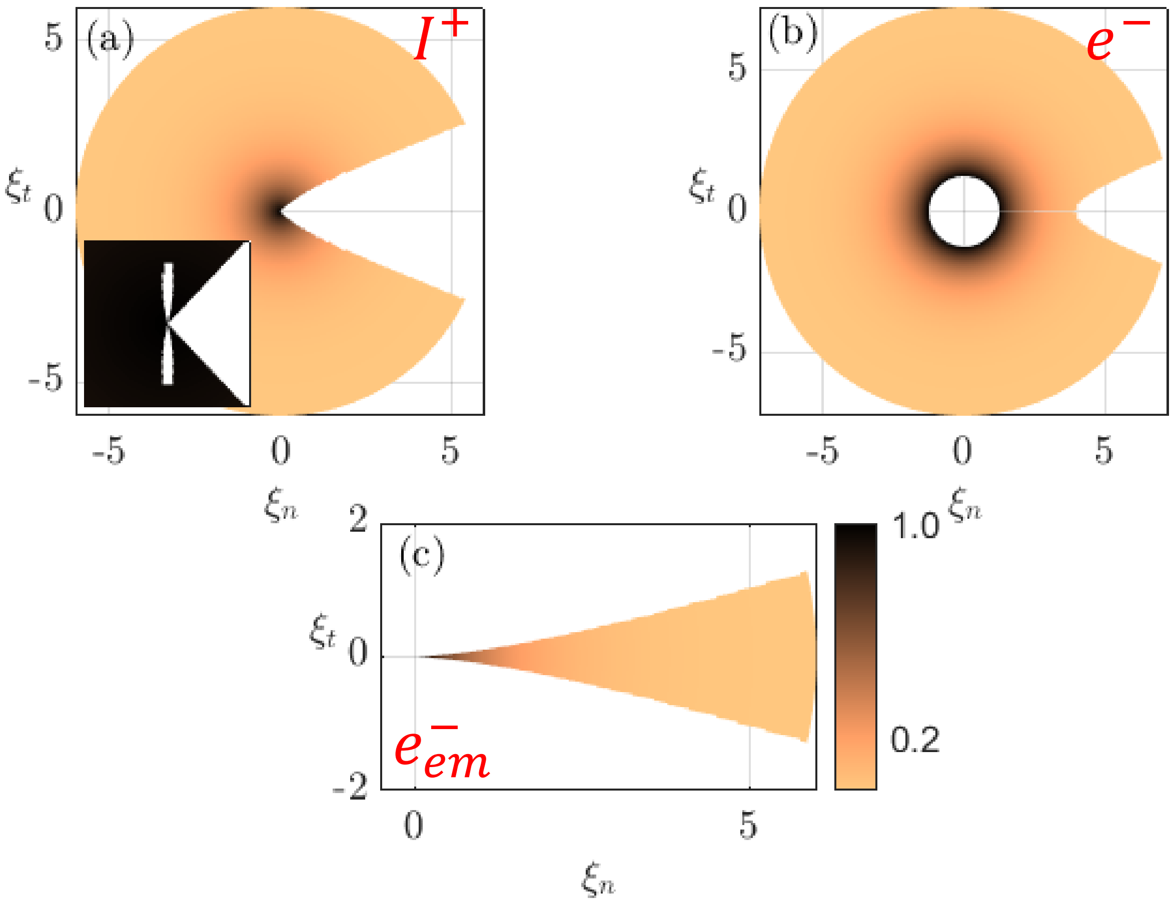
- Backward integration of particles orbits
- Numerical integration:

$$n_\alpha(x_0, y_0) = \sum_{i=1}^{N_\xi} \sum_{j=1}^{N_\zeta} f_\alpha(x_0, y_0, \xi_i^\alpha, \zeta_j)\Delta\zeta_j\, \Delta\xi_i^\alpha$$

$$\xi_n = \xi_\alpha \cdot \cos\zeta \qquad \xi_t = \xi_\alpha \cdot \sin\zeta$$



NUMERICAL RESULTS

LIMITATIONS OF STATIONARY VP-SOLVERS

"Limitations of Stationary Vlasov-Poisson Solvers in Probe Theory" (under review)

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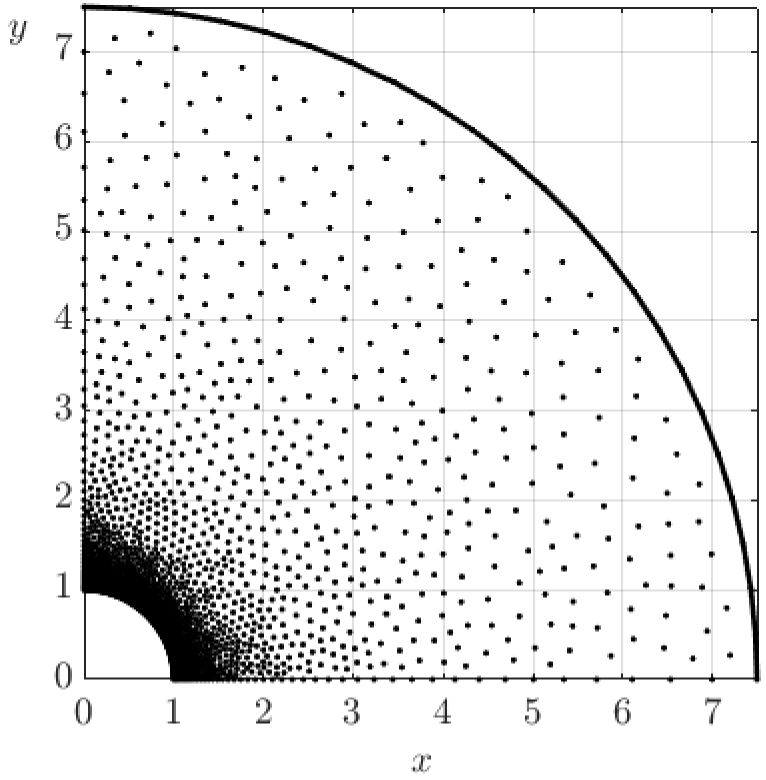
$\phi_p = -4, e_p = 0, b_p = 1, \delta_i = 1$

Numerical

- Angular momentum and energy are physical invariants for cylindrical probes



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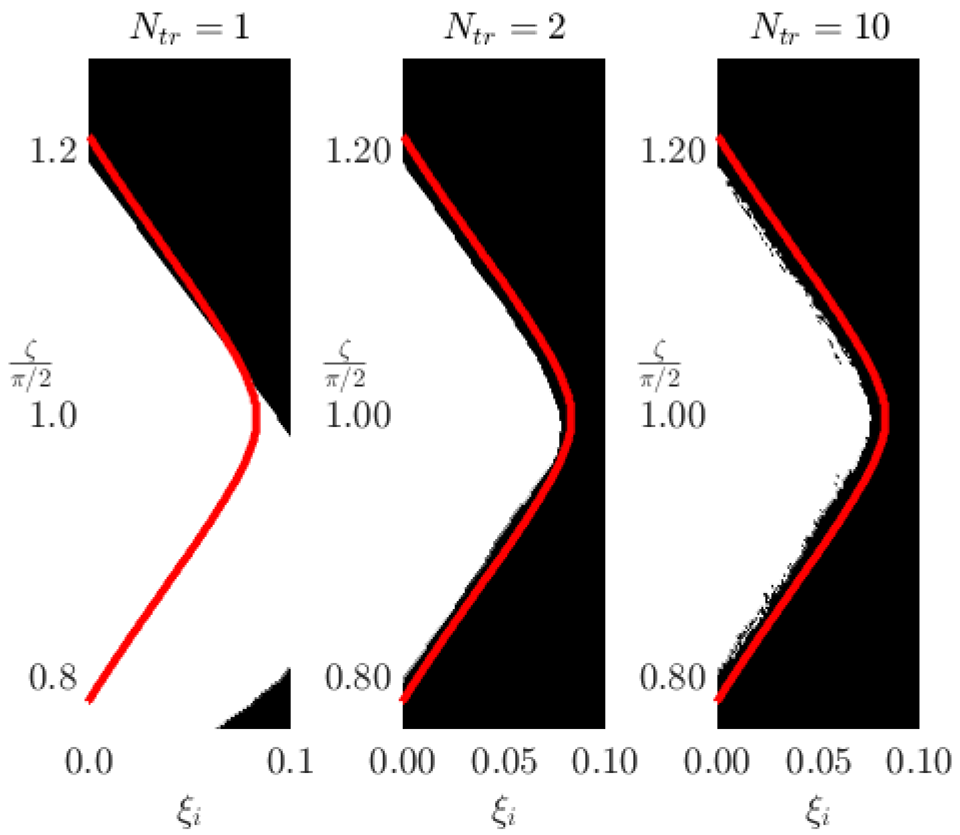
N_{tr} ≡number of complete turns a around the probe for trapped particles



Red boundary: computed analytically with code by *Chen, Sánchez-Arriaga(2017)*

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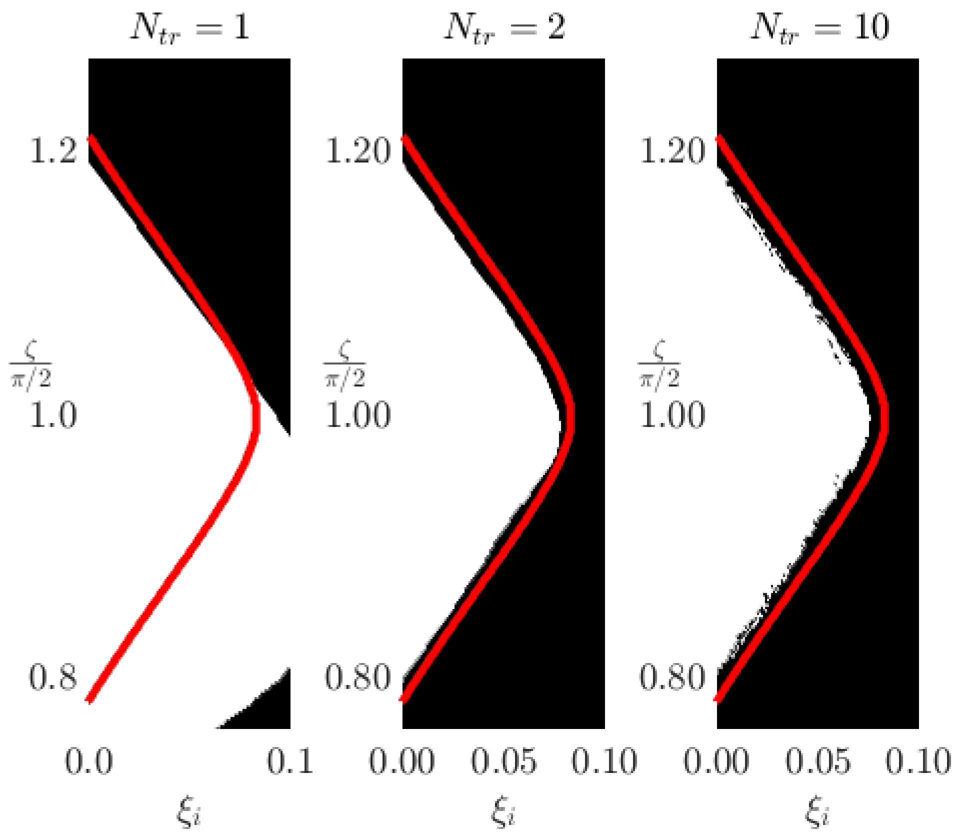
Numerical

- Angular momentum and energy are physical invariants for cylindrical probes
- Spatial discretization of the electric field: angular momentum & total energy are <u>not</u> perfectly conserved by the algorithm
- Boundary between trapped (white) and non-trapped (black) particles becomes jagged as N_{tr} increases

N_{tr} ≡number of complete turns a around the probe for trapped particles



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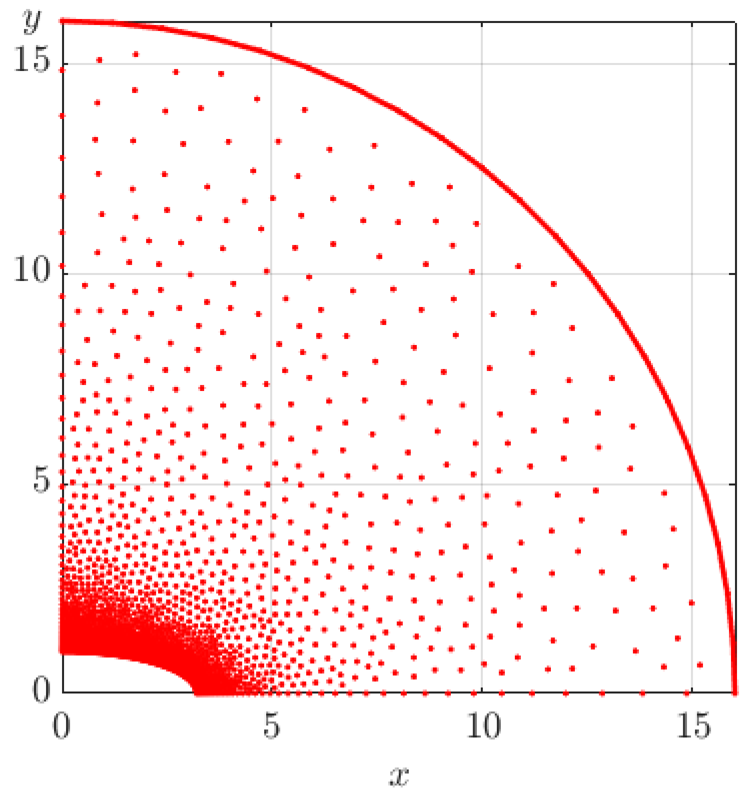
$\phi_p = -4, e_p = 0.95, b_p = 1, \delta_i = 1$

Physical limitations for elliptic probes



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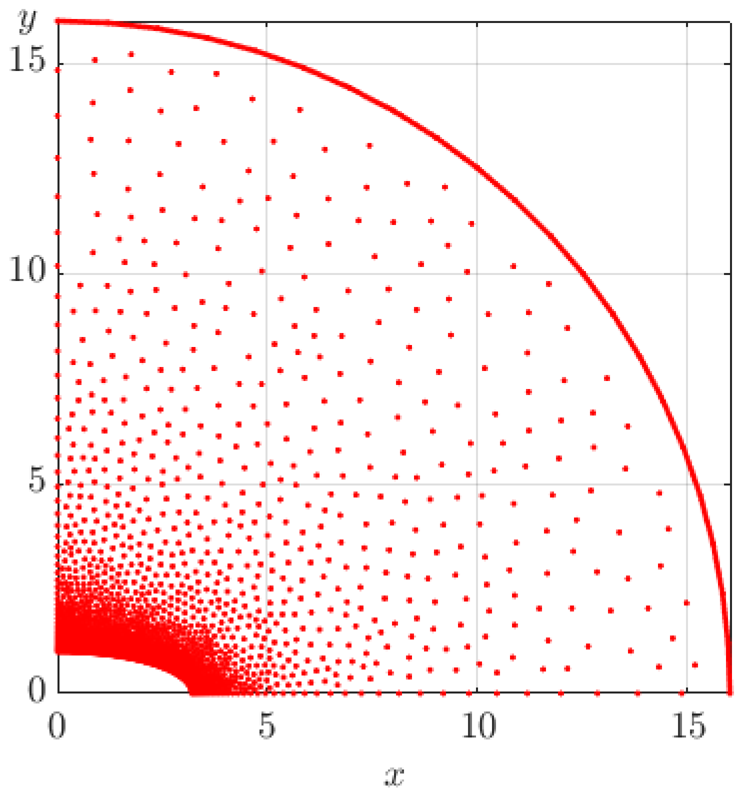
Physical limitations for elliptic probes

- Angular momentum is not conserved
- Chaotic orbits appear



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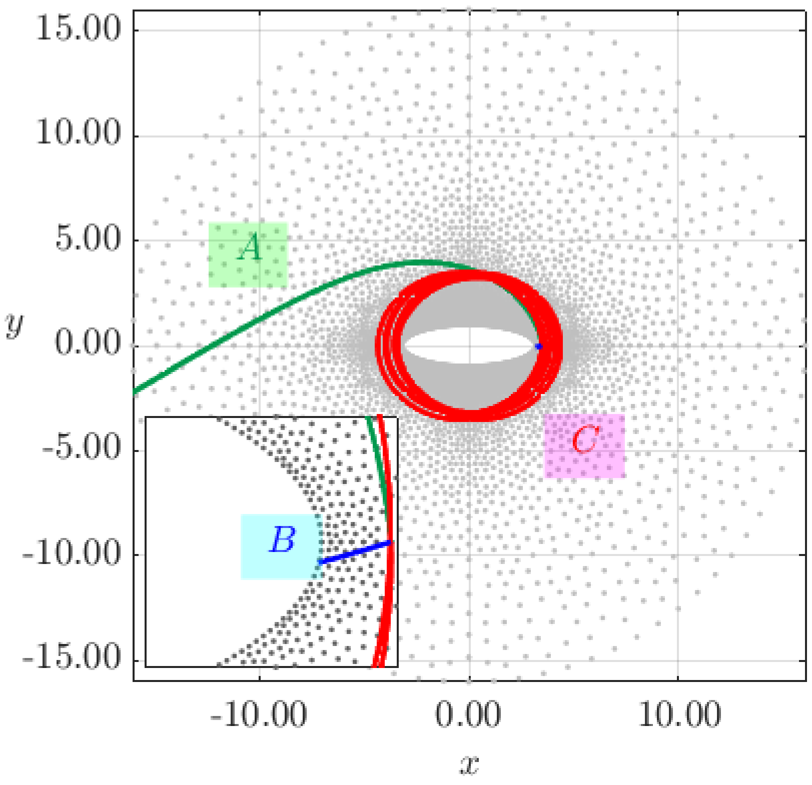

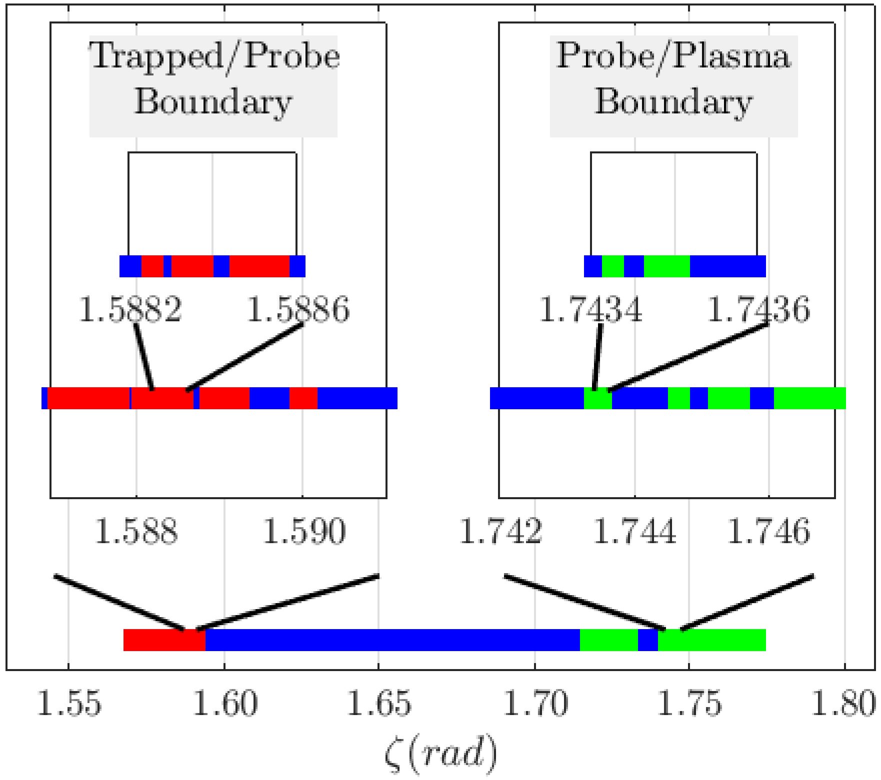

$\xi_i \approx 0.062, \zeta$ varies

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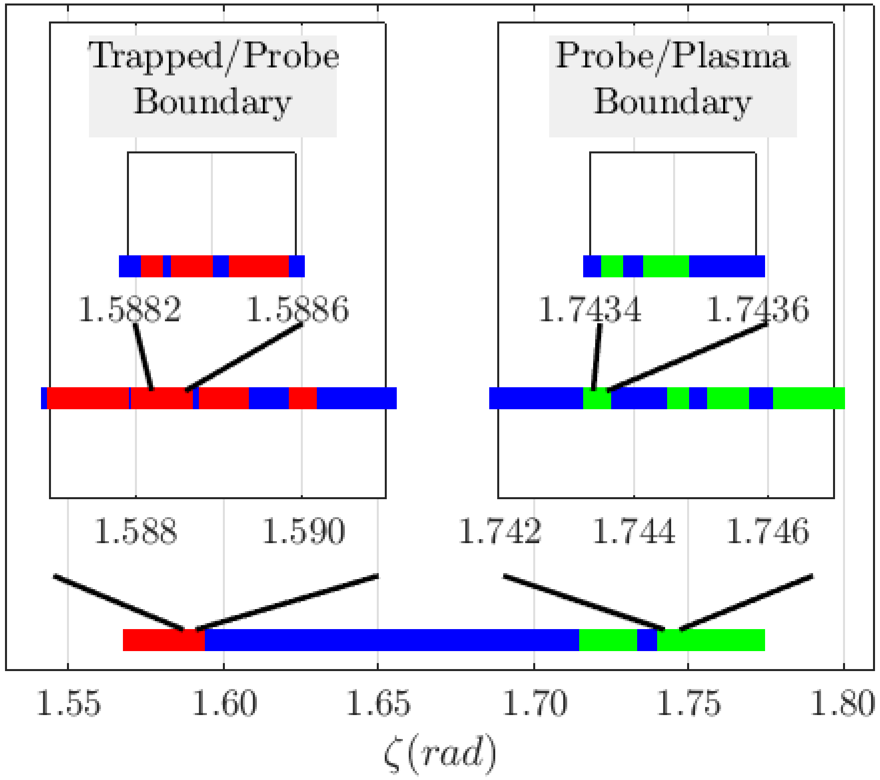
$\phi_p = -4, e_p = 0.95, b_p = 1, \delta_i = 1$

Physical limitations for elliptic probes

- Angular momentum is not conserved
- Chaotic orbits appear
- Boundaries in velocity space reveal the distribution function is filamented



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SPACE CHARGE LIMITED (SCL) TRANSITION

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$\phi_p = -4, e_p = 0.75, b_p = 1, \delta_i = 1, \delta_p = 0.32, \beta \in [0,30]$

- Impact of the emission level

$$\beta \propto exp\left(-\frac{eW}{k_B T_P}\right)$$

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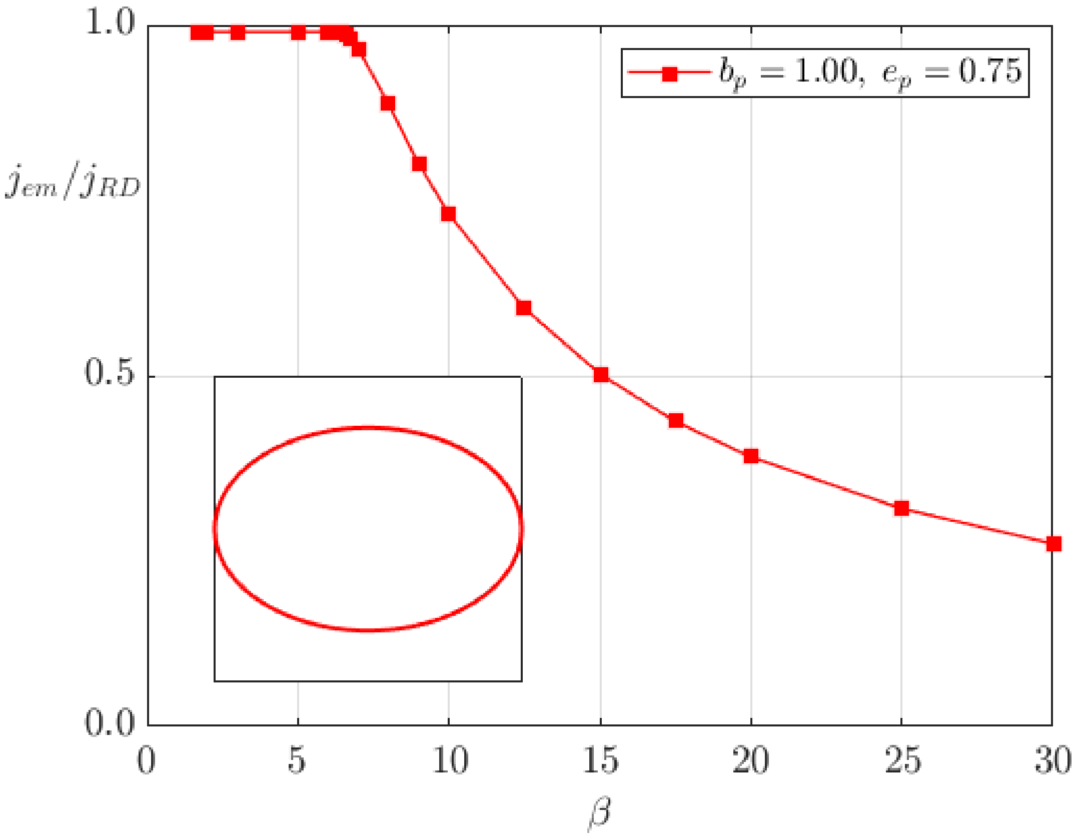

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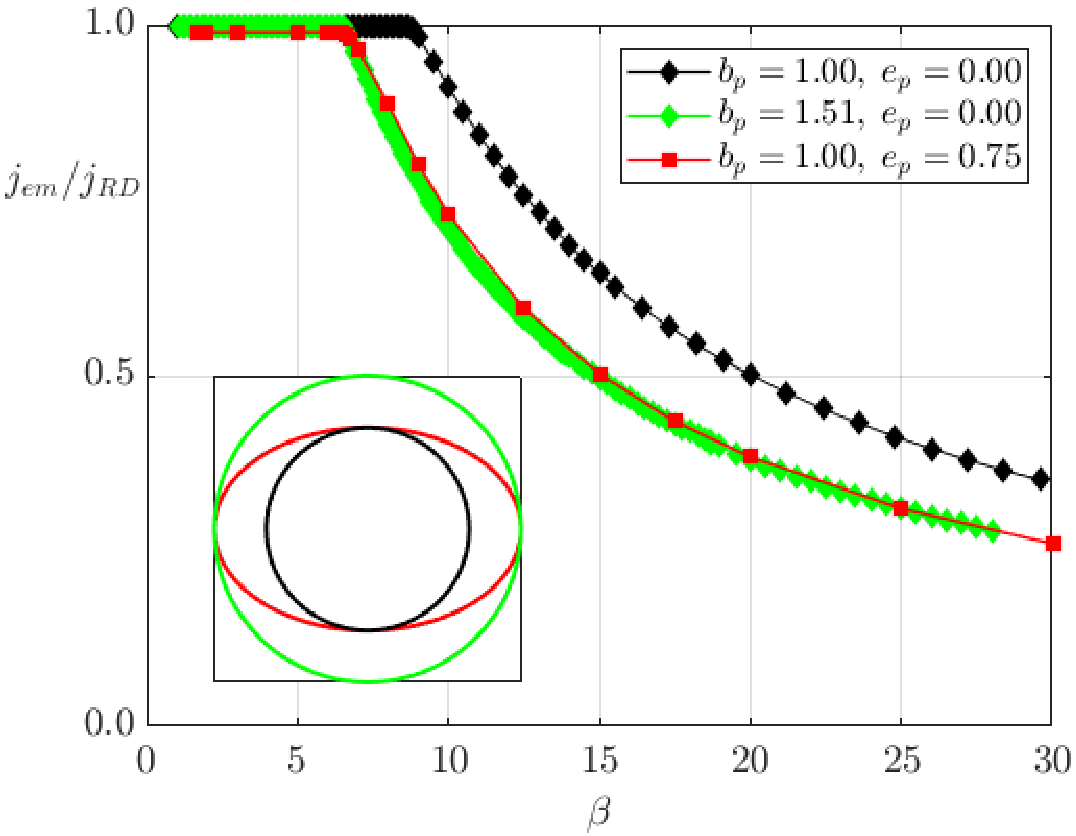
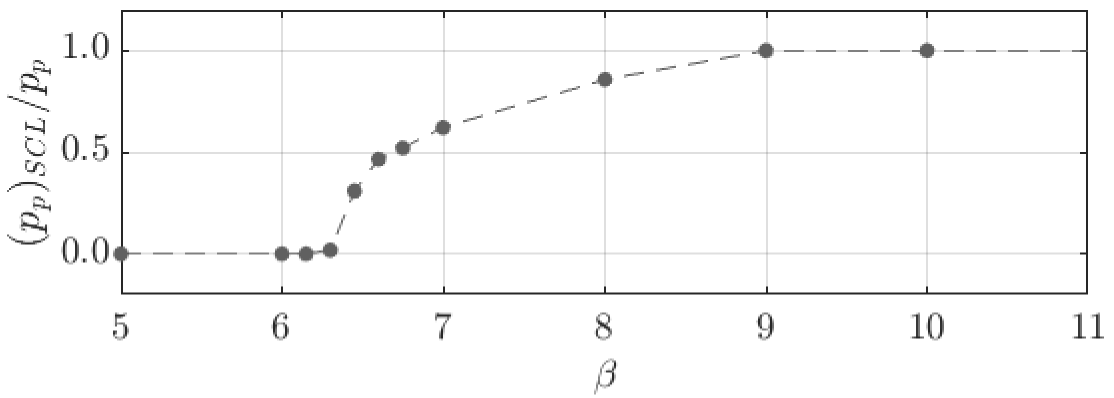
Elliptical probe ≈ Round probe with radius equal to the semi-major axis



SPACE CHARGE LIMITED (SCL) TRANSITION

$$\frac{(p_p)_{SCL}}{p_p} = \frac{Perimeter\ under\ SCL}{Total\ perimeter}$$



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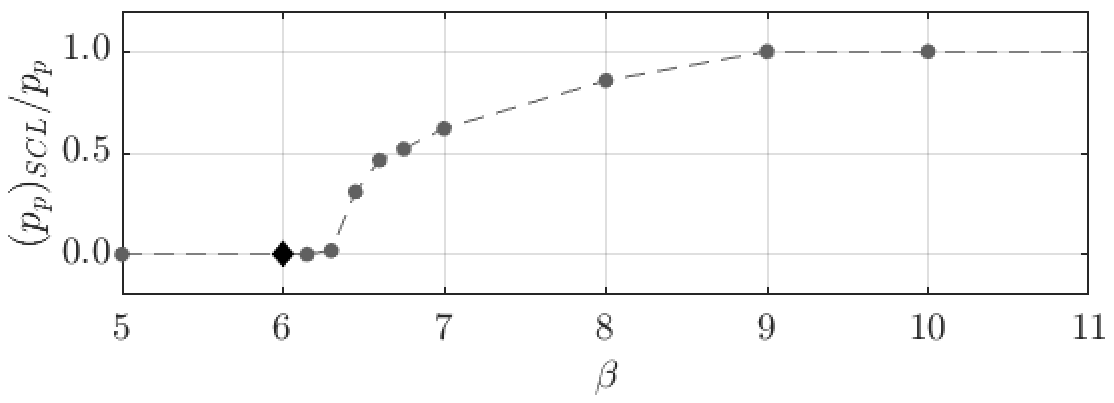
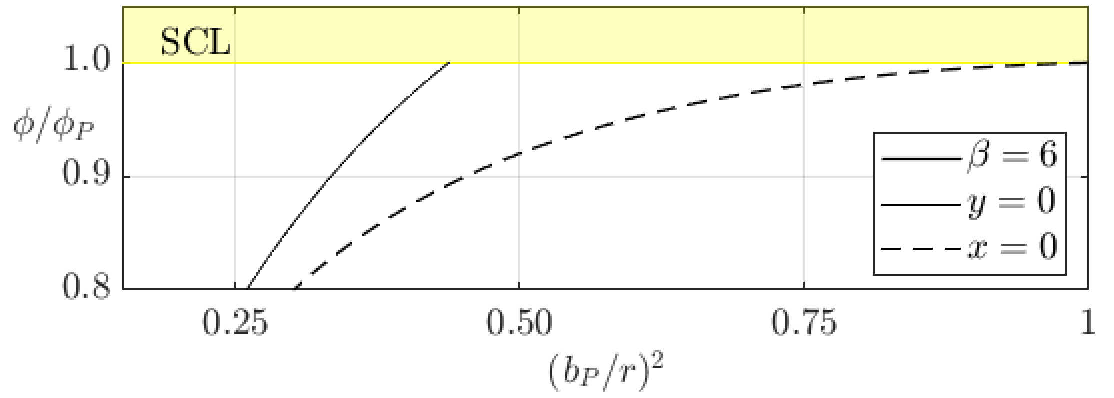
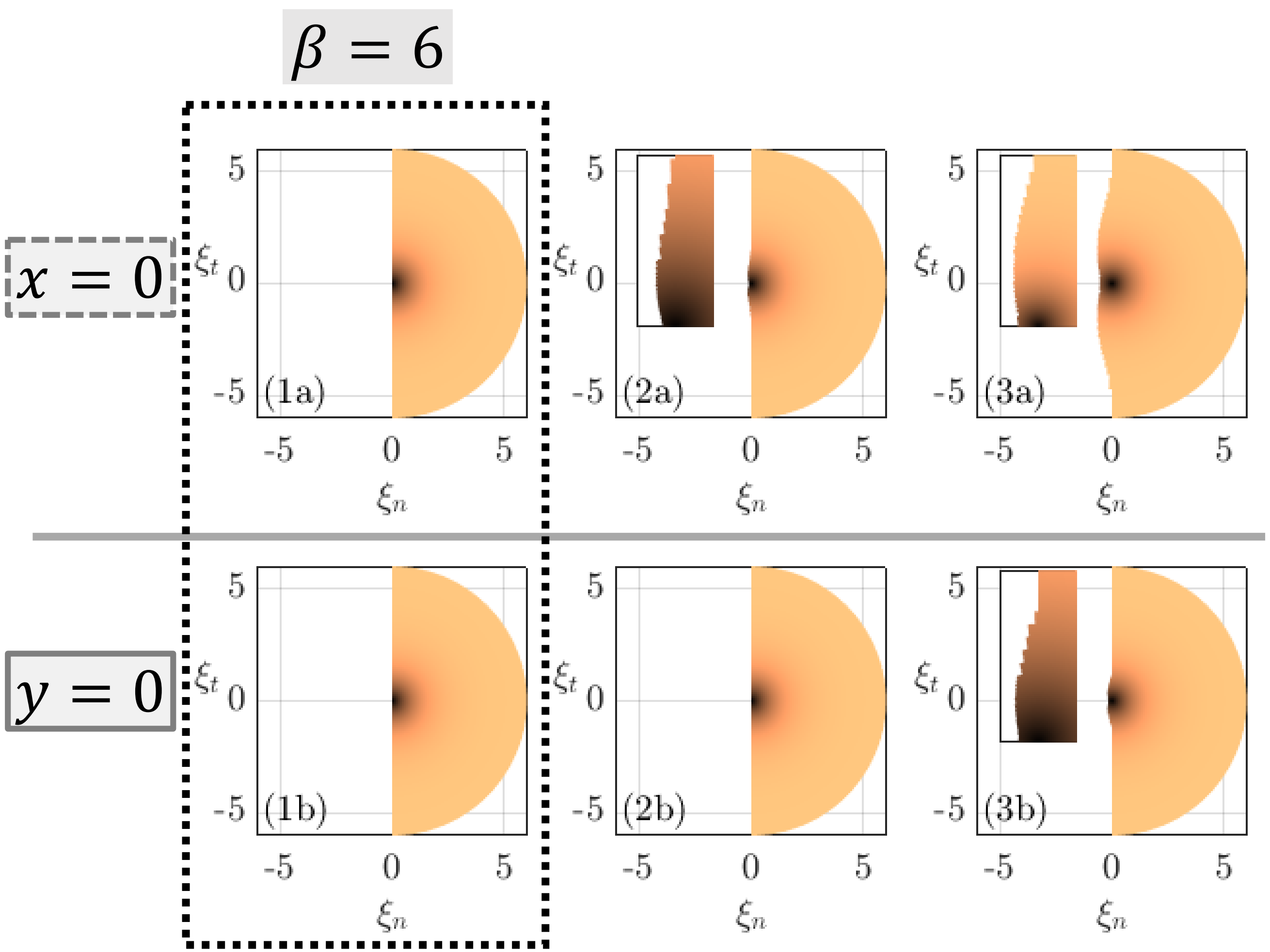




Distribution function of emitted electrons



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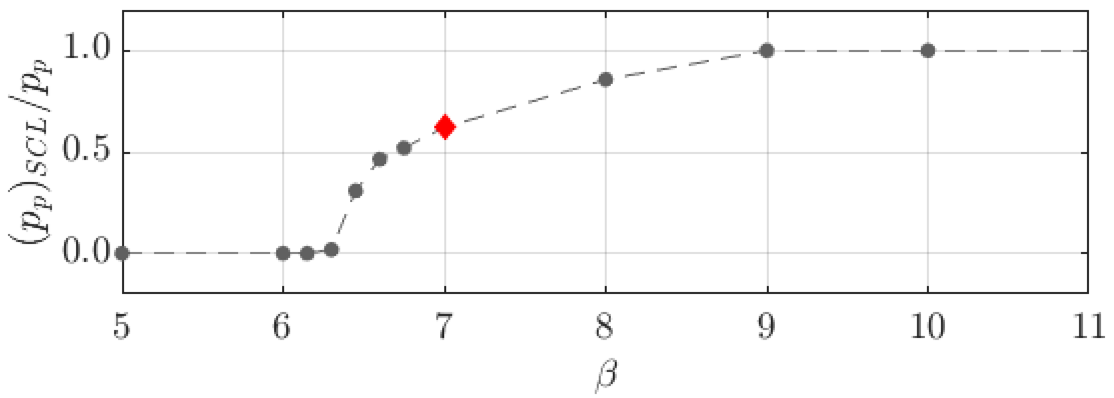

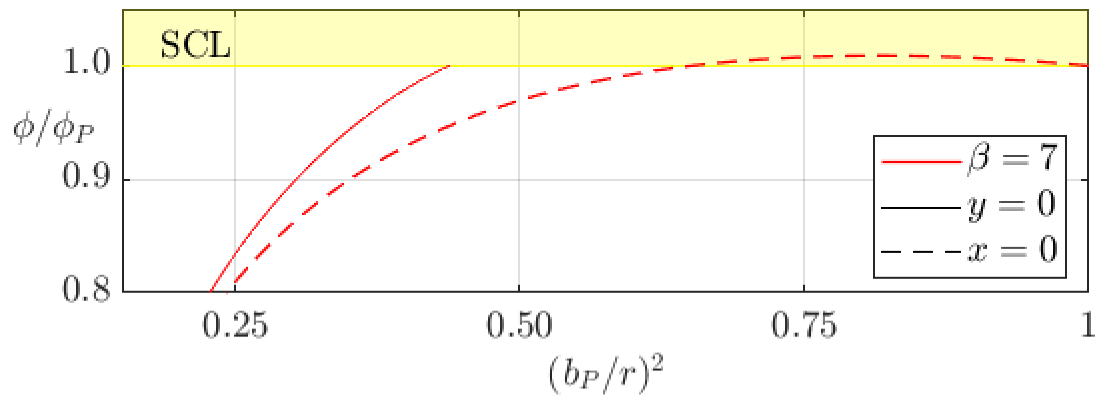

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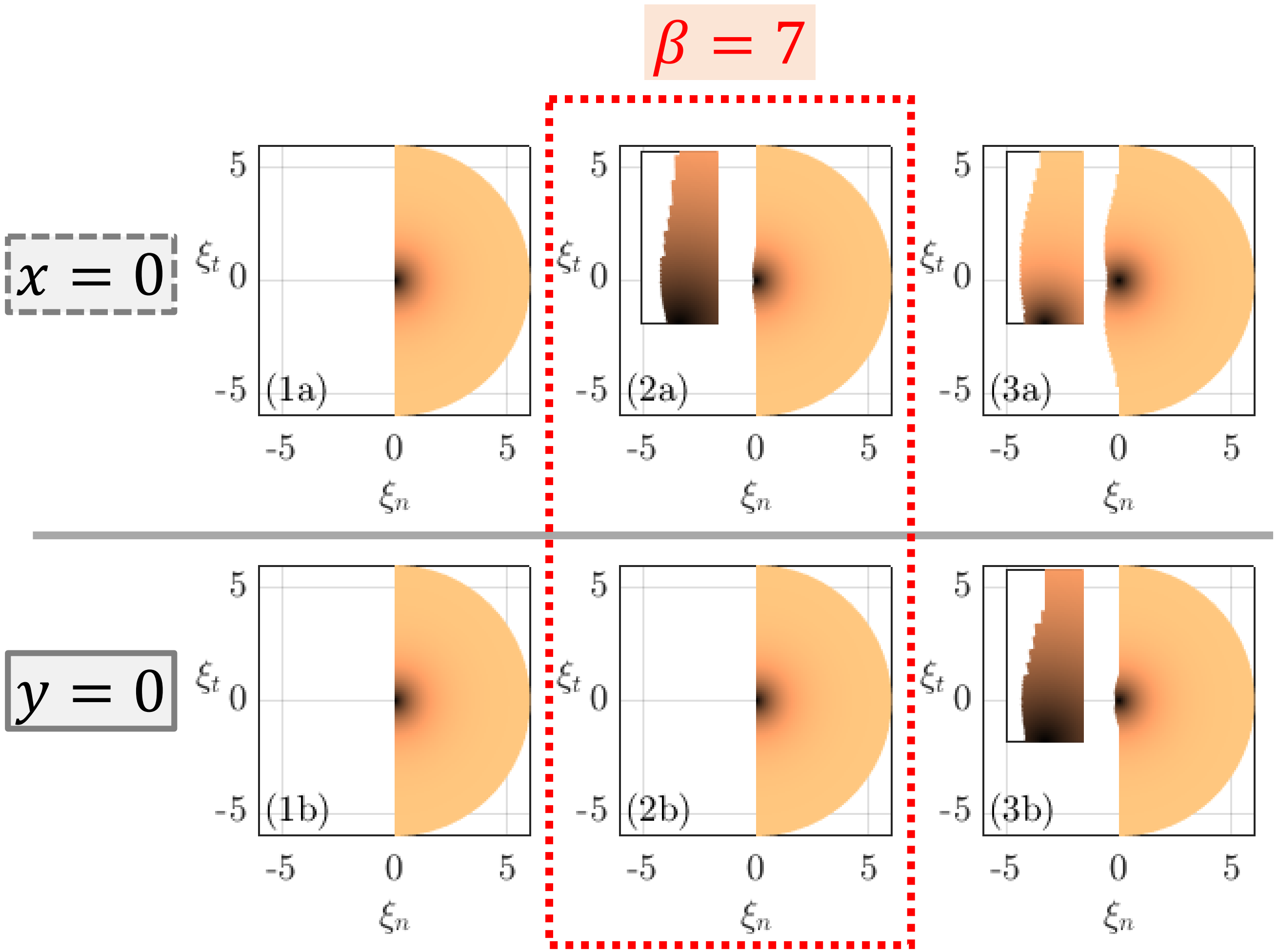

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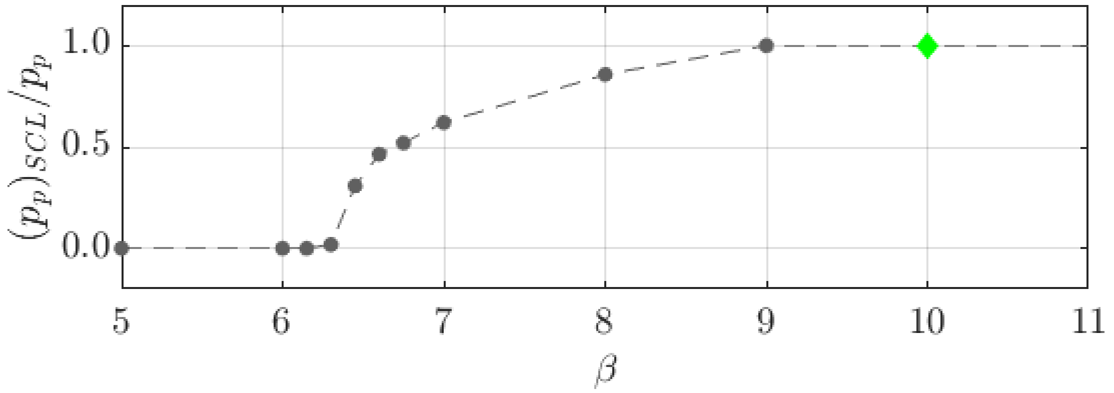
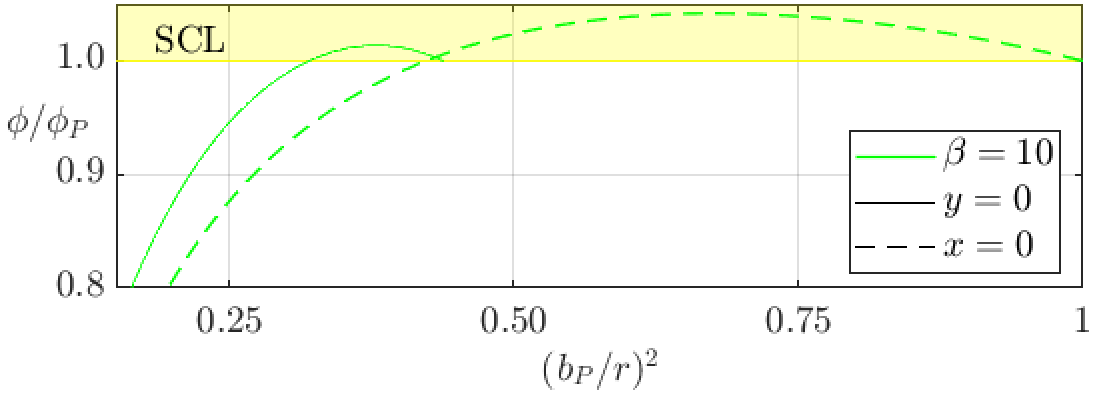
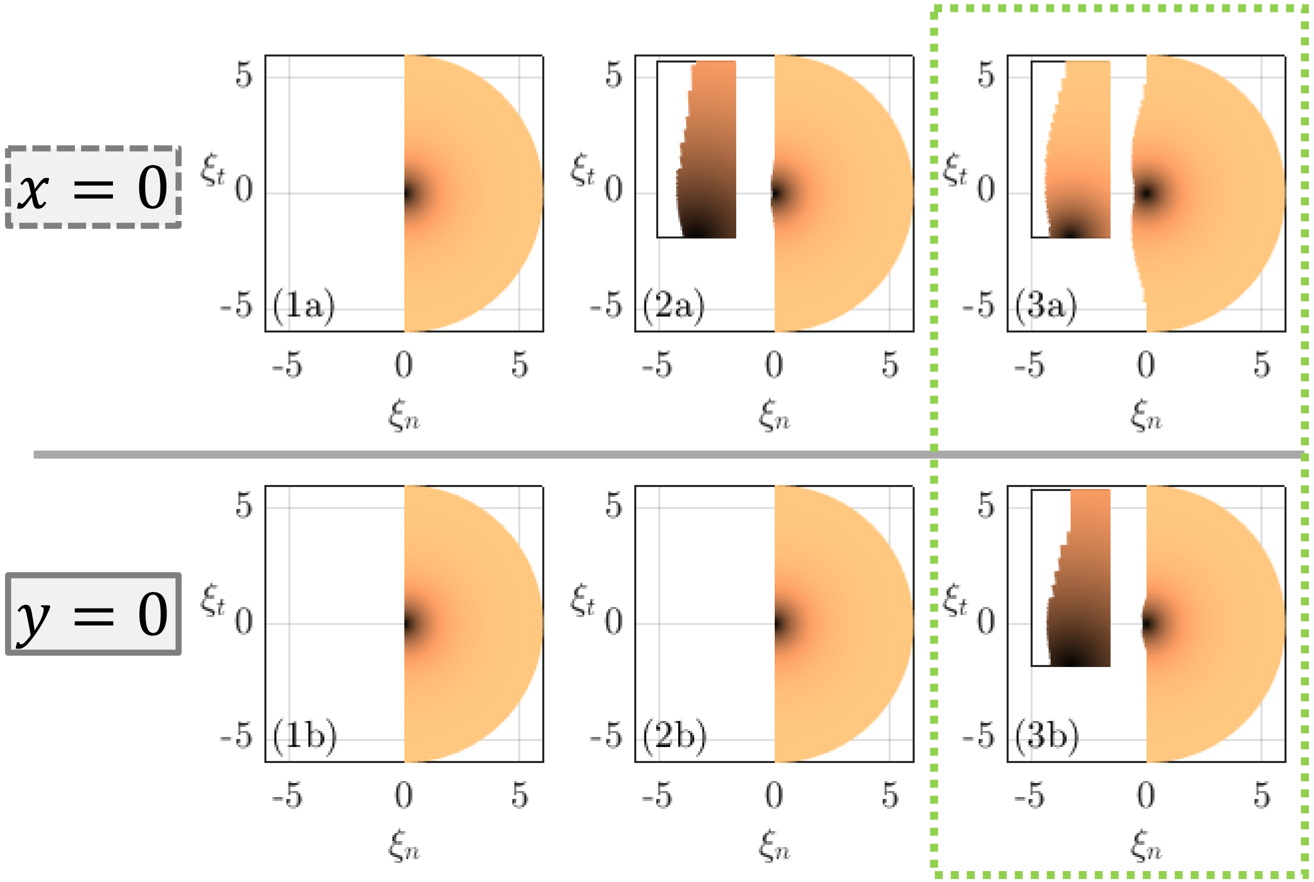




Distribution function of emitted electrons

$\beta = 10$



CONCLUSIONS

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- We developed a 2D stationary Vlasov-Poisson solver for the kinetic analysis of emissive objects with elliptical cross-sections
- Numerical and physical limitations of the implementaiton were discussed (chaotic dynamics, filamentation)
- Transition to SCL regime as a function of the emisison level was investigated
- Elliptical probes resemble cylindrical ones with radius equal to the semi-major axis

Find more details at:

- *L. Chiabò, G. Sánchez-Arriaga, "Limitations of Stationary Vlasov-Poisson Solvers in Probe Theory"* (currently under review)
- *L. Chiabò, S. Shahsavani, G. Sánchez-Arriaga, "Kinetic Analysis of Elliptical Emissive Probes Immersed in Maxwellian Plasmas"* (in preparation)

THE END

Thank you for your attention!

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Universidad Carlos III de Madrid, Spain

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