Beam experiments in the magnetosphere: how do we get the charge off the spacecraft?

Gian Luca Delzanno

T-5

Collaborators: J.E. Borovsky, M.F. Thomsen, J. D. Moulton, E.A. MacDonald

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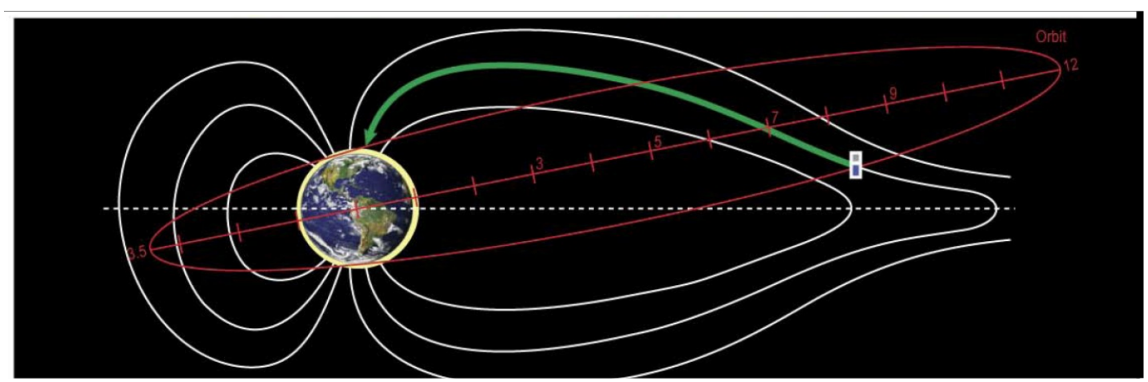
Outline:

- Motivation
- Some introductory remarks
- An electron collection strategy
    - Simulation results
- An ion emission strategy:
    - Simulation results
- Conclusions

Motivation: ConnEx mission concept

- Goal: establish connectivity of magnetic field lines from the magnetosphere to the ionosphere
- Emit high-power electron beam from magnetospheric spacecraft
- (Previously done for spacecraft in the ionosphere)
- Spacecraft charging big problem: I_e~μA, I_B~.1 A
- Contactor technology to mitigate spacecraft charging
  - Contactor cloud ~km size: very multiscale!

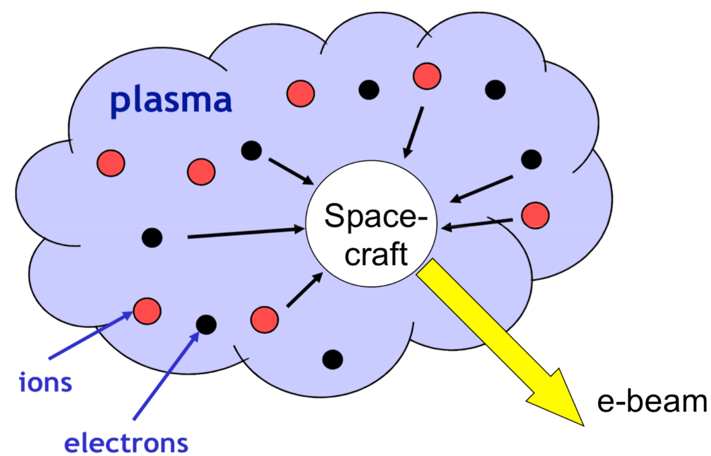


E. Munch,
The scream (1893)

The spacecraft charging equation

- $$\frac{dQ_{sp}}{dt} = \underbrace{I_b^e}_{\text{Beam current}} + \underbrace{I_e^{bg} + I_i^{bg}}_{\text{Background currents}} + \underbrace{I_e^{cont} + I_i^{cont}}_{\text{Contactor currents}}$$

- $$Q_{sp} = \mathcal{C}_{sp}\phi_{sp} = 4\pi\varepsilon_0 r_{sp}\phi_{sp}$$ Net charge on the spacecraft



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A beam emitted in vacuum returns to the spacecraft

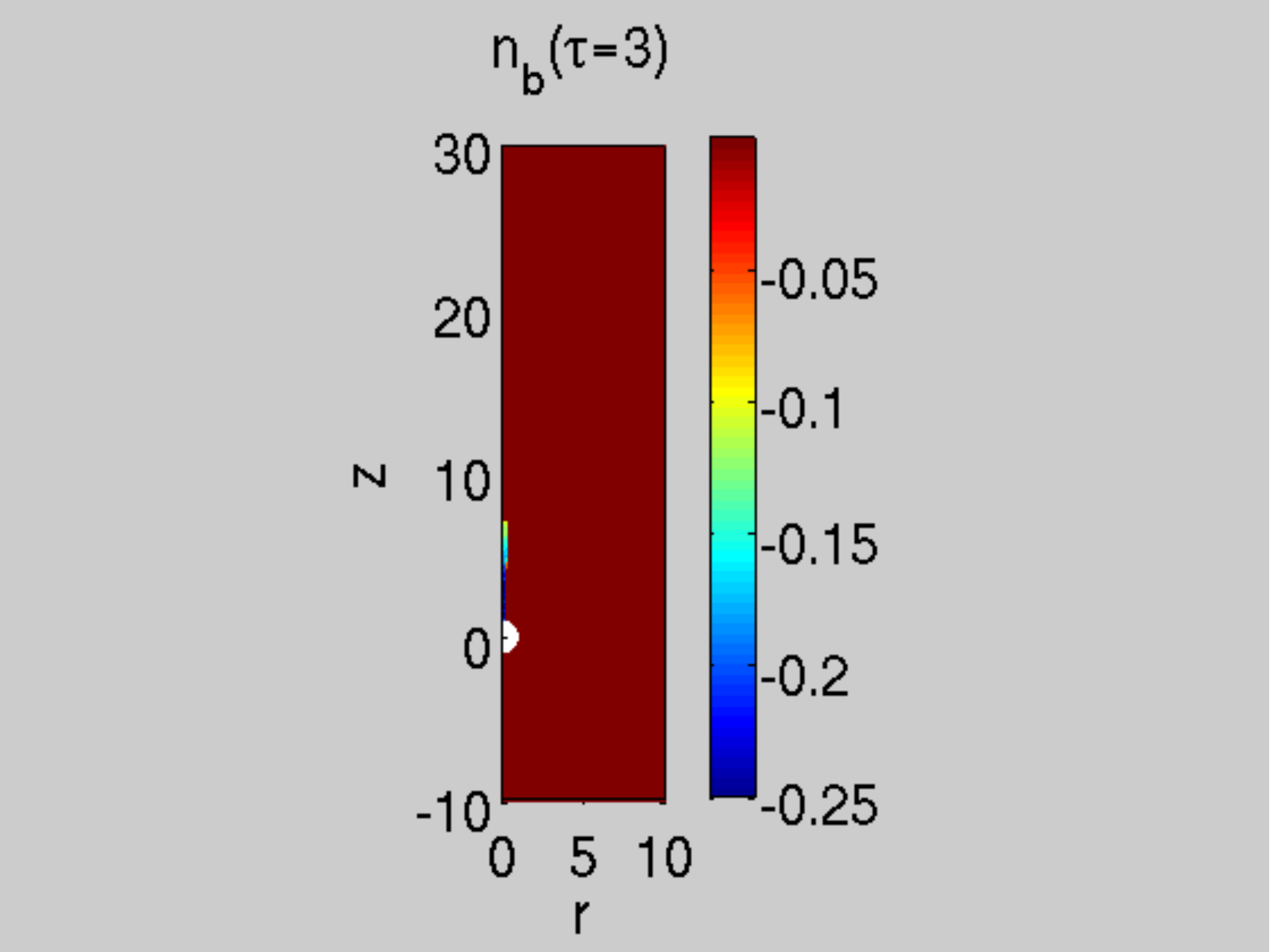
- $$\frac{dQ_{sp}}{dt} = I_b^e \qquad\qquad Q_{sp} = \mathcal{C}_{sp}\phi_{sp} = 4\pi\varepsilon_0 r_{sp}\phi_{sp}$$

- Condition for beam return:

$$\boxed{e\phi_{sp}^{ret} = \frac{m_e}{2}V_b^2} \qquad\qquad t_r = \frac{2\pi\varepsilon_0 r_{sp} m_e V_b^2}{eI_b^e}$$

- I^e_b=0.1 A, r_{sp}=1 m, 1 keV beam: t_r~0.6 µs, L~7 m

A beam emitted in vacuum returns to the spacecraft



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The background cannot provide the return current needed

- $$\frac{dQ_{sp}}{dt} = I_b^e + I_e^{bg} + I_i^{bg}$$

- Background currents given by Orbital Motion Limited theory

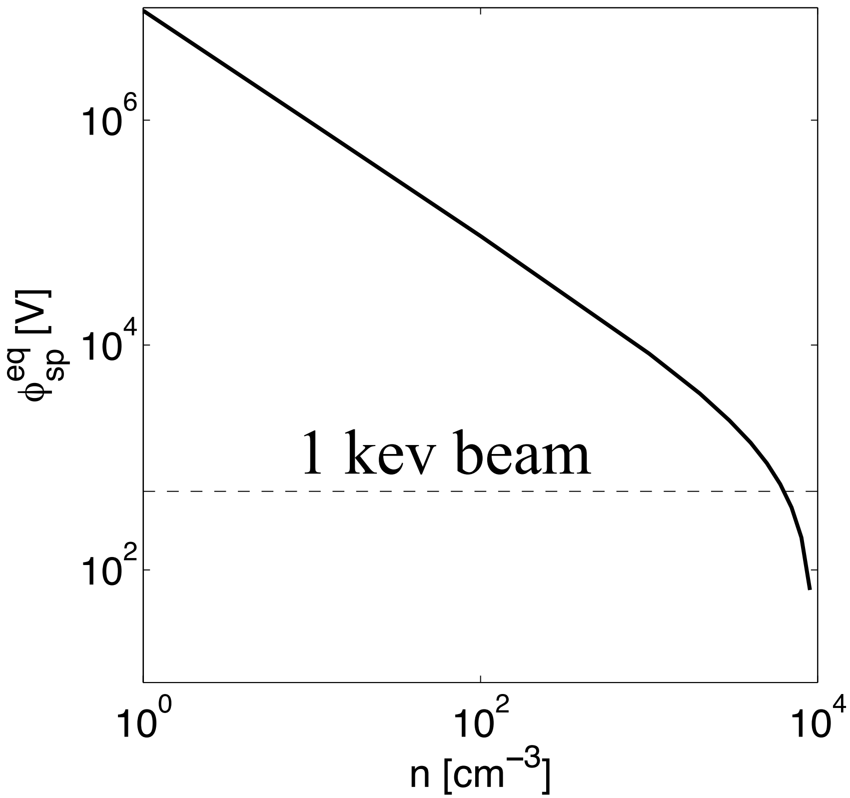
$$I_e^{bg} = -e\sqrt{8\pi}r_{sp}^2 n_e \sqrt{\frac{T_e}{m_e}} \left(1 + \frac{e\phi_{sp}}{T_e}\right)$$

$$I_i^{bg} = e\sqrt{8\pi}r_{sp}^2 n_i \sqrt{\frac{T_i}{m_i}} \exp\left(-\frac{e\phi_{sp}}{T_i}\right)$$

- I^e_b=0.1 A, r_{sp}=1 m, 1 keV beam, n_e=n_i=1 cm^{-3}, T_e=T_i=1 keV, hydrogen

$$\boxed{\phi_{sp}^{eq} = 9.4 \cdot 10^6\ \mathrm{V}}$$

The background cannot provide the return current needed



Needs density $>10^3$ cm^{-3} to work!

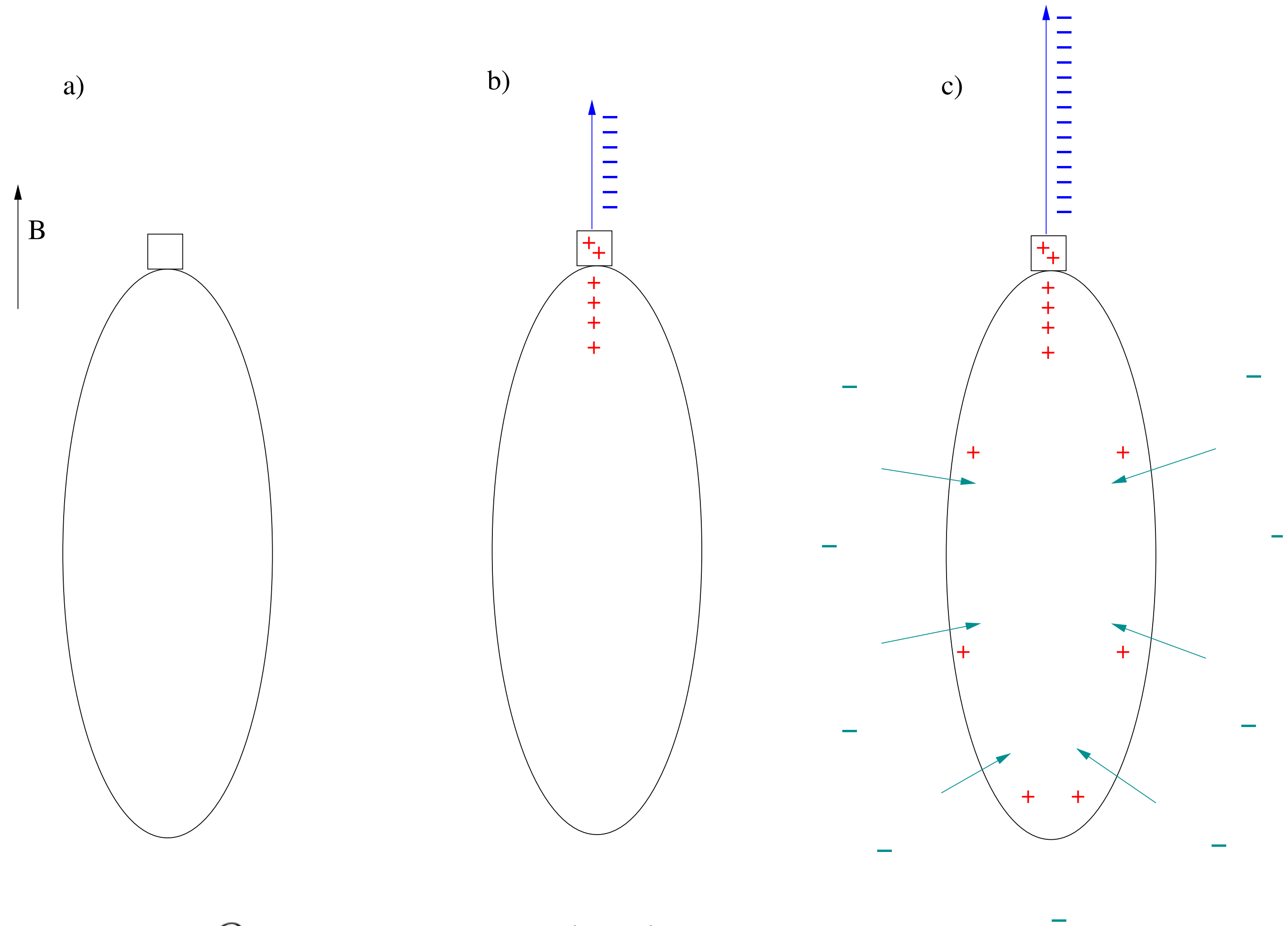
Explains why beam experiments were successful in the ionosphere.

$$I_e^{bg} = -e\sqrt{8\pi}\,\boxed{r_{sp}^2 n_e \sqrt{\frac{T_e}{m_e}}}\left(1 + \frac{e\phi_{sp}}{T_e}\right)$$

An electron collection strategy: ConnEx

- Plasma contactor: provides a high density plasma reservoir

Km-sized cloud



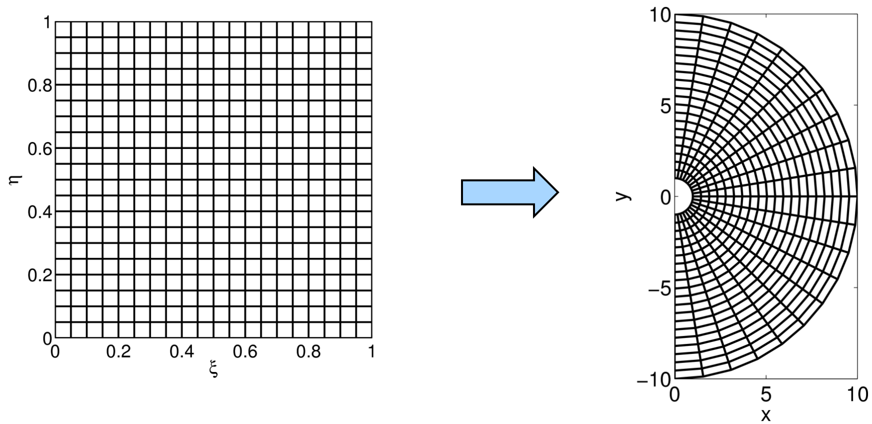
$$R = \frac{Q}{4\pi\varepsilon_0\phi} \xrightarrow{\text{Q=0.25 C, 1 keV beam}} R \gtrsim 8 \cdot 10^3 \text{ km}$$

Particle-In-Cell (PIC) simulations

- Curvilinear PIC (CPIC) Delzanno et al., IEEE (2013).
- Solves collisionless Vlasov-Poisson equations for a plasma

$$\frac{\partial f_\alpha}{\partial t} + \mathbf{v} \cdot \nabla_{\mathbf{x}} f_\alpha + \frac{q_\alpha \left(-\nabla \phi + \mathbf{v} \times \mathbf{B_0} \right)}{m_\alpha} \cdot \nabla_{\mathbf{v}} f_\alpha = 0 \qquad \nabla^2 \phi = \int (f_e - f_i)\, d\mathbf{v}$$

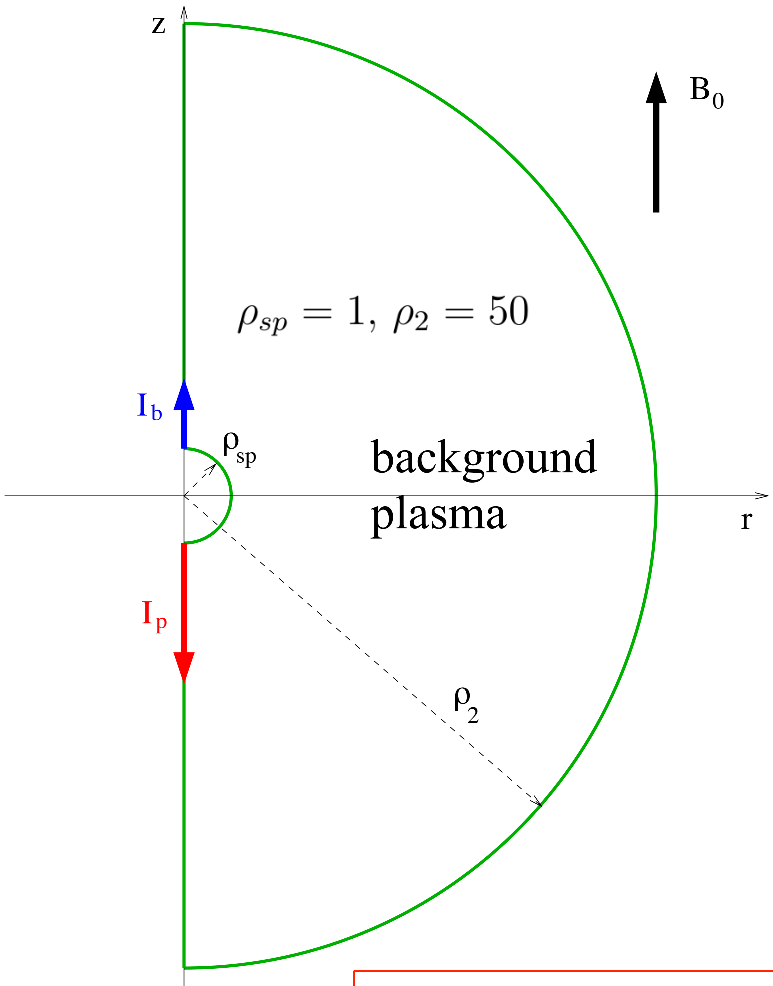
- Conforms to objects of arbitrary shape (geometry independent)



$$\nabla_{\mathbf{x}}^2 \Phi(\mathbf{x}) = \frac{1}{J} \frac{\partial}{\partial \xi^\alpha} \left(J g^{\alpha\beta} \frac{\partial \Phi(\boldsymbol{\xi})}{\partial \xi^\beta} \right)$$

- Optimal solver (Black Box multigrid), efficiently parallelized

PIC simulation campaigns: details



- 2D, cylindrical geometry
- Contactor fired before beam
  - 3 initial configurations for beam emission with different size of contactor cloud
- Fire electron beam
  - with contactor on
  - with contactor off
  - in vacuum or with bg plasma
- Diagnostic: spacecraft potential
- Normalized units:
  - T_{ref}=1 keV, n_{ref}=10^4 cm^{-3}

$$\hat{n}_e^{cont} = \hat{n}_i^{cont} = 100,\ \hat{V}_i^{cont} = 0.01,\ \hat{T}_e^{cont} = \hat{T}_i^{cont} = 0.01,\ \hat{I}_i^{cont} = 0.187$$

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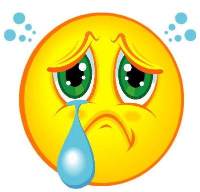
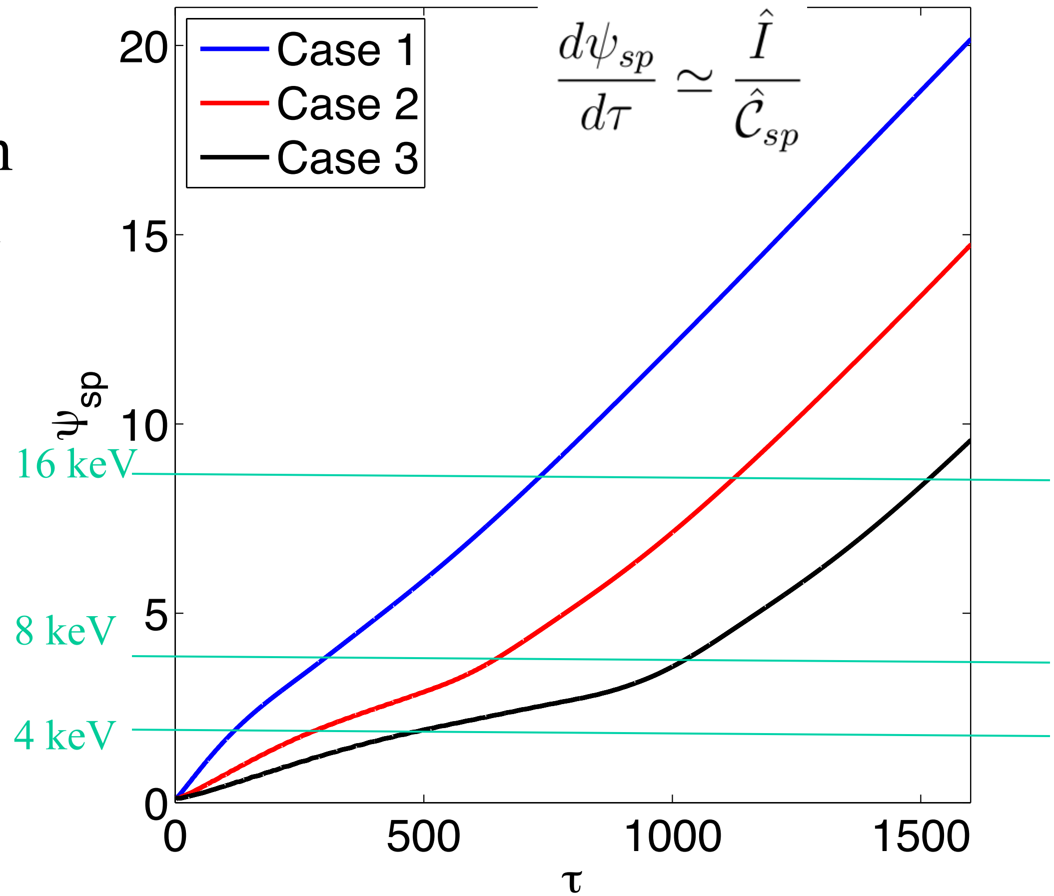
Electron collection route: $I_b/I_{cont}=2$ ($I_b=0.4$, $I_{cont}=0.2$)

- Contactor kept on with beam
- Connection between ion and contactor cloud maintained
- As bad as before:

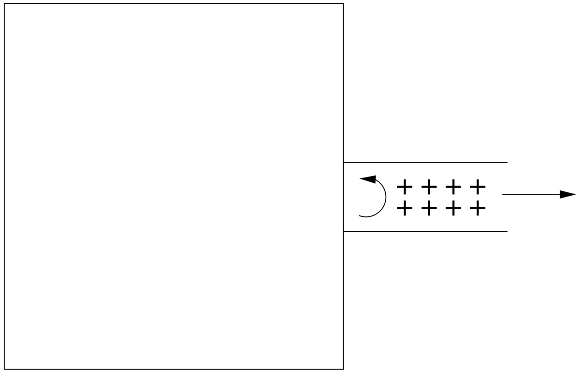
  Contactor fails to draw a large current from bg





PLAN B: How about balancing the electron beam with ion emission?

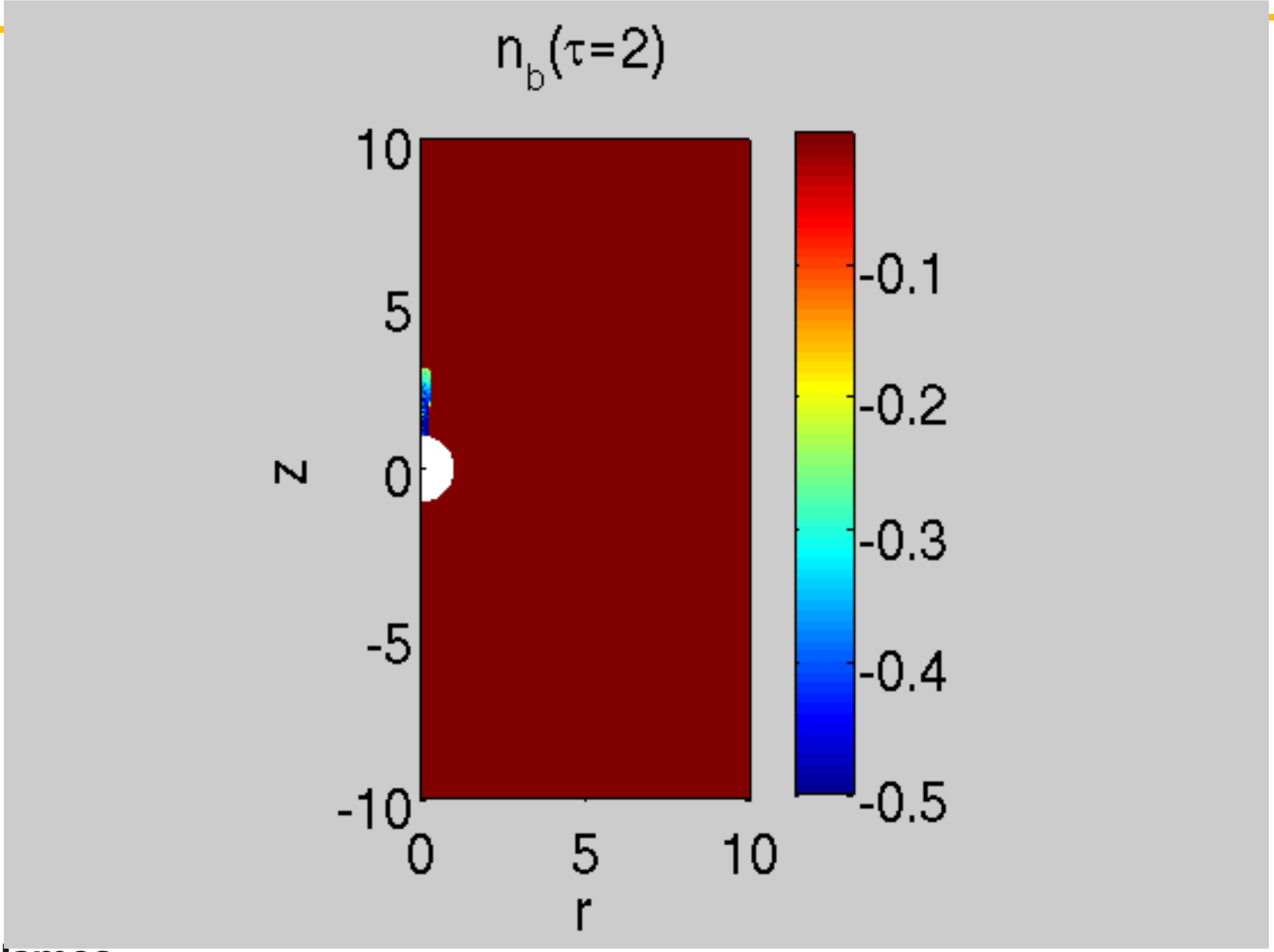
- $$\frac{dQ_{sp}}{dt} = I_b^e + I_b^i$$ Ion beam emission
- Notoriously difficult: space charge Child-Langmuir (CL) limits, planar geometry



$$\mathcal{E} = \frac{1}{2}\frac{m_i}{m_e}V_i^2 \qquad J_{CL}^{planar} = \frac{4}{9}\frac{\mathcal{E}V_i}{(\rho_2-\rho_{sp})^2}\left(\sqrt{1+\frac{\psi_{sp}}{\mathcal{E}}}-1\right)\left(\sqrt{1+\frac{\psi_{sp}}{\mathcal{E}}}+2\right)^2$$

only a tiny ion current is emitted!

Ion beam emission: electron density



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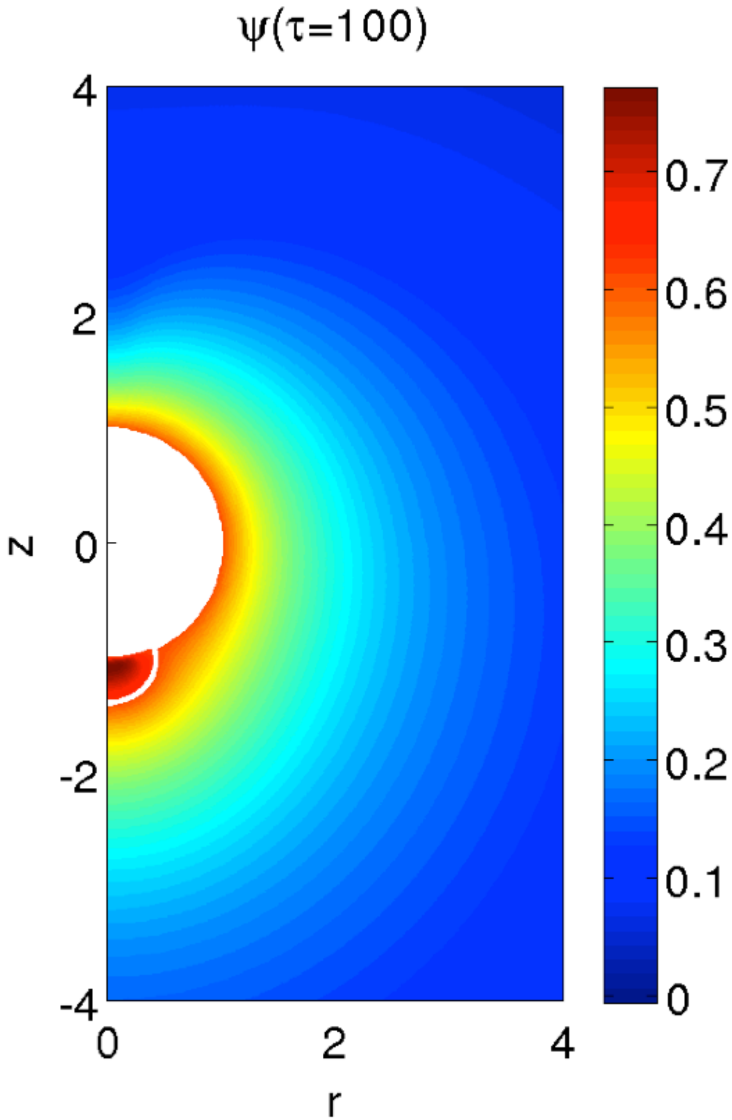
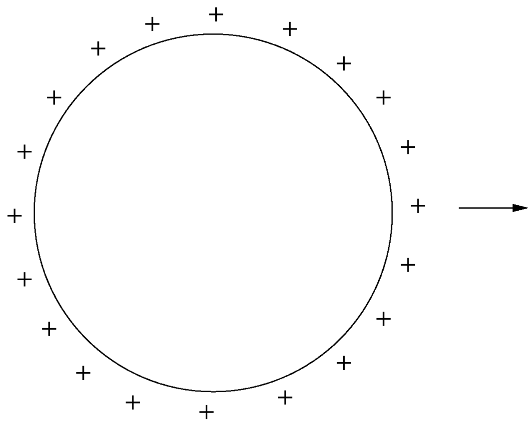
Ion beam emission: virtual anode

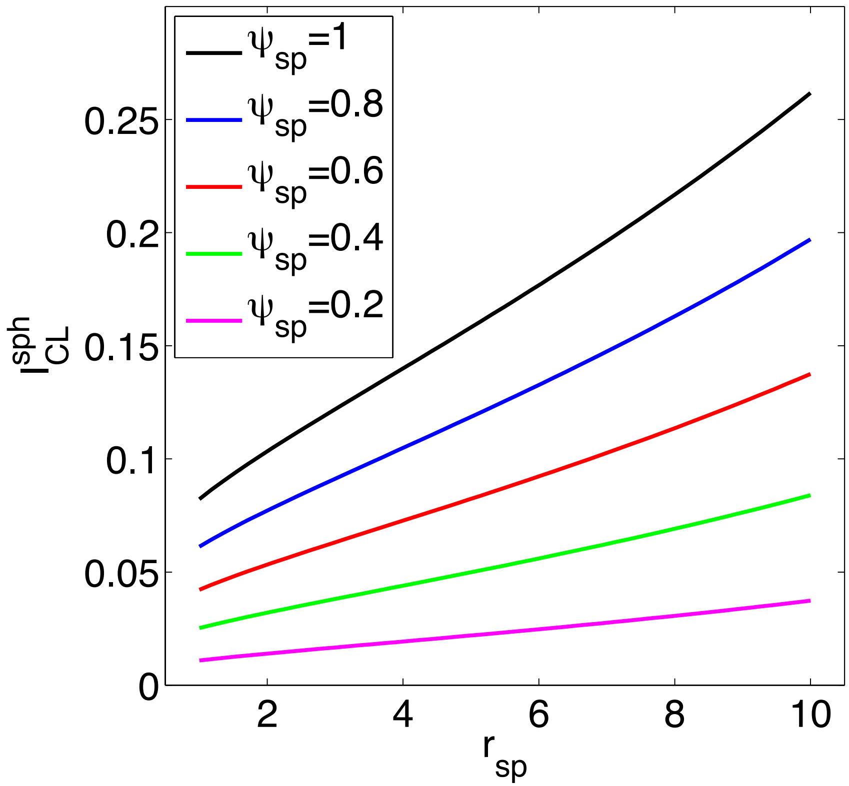


The virtual anode returns most ions to the spacecraft

Detour: Child-Langmuir law in spherical geometry

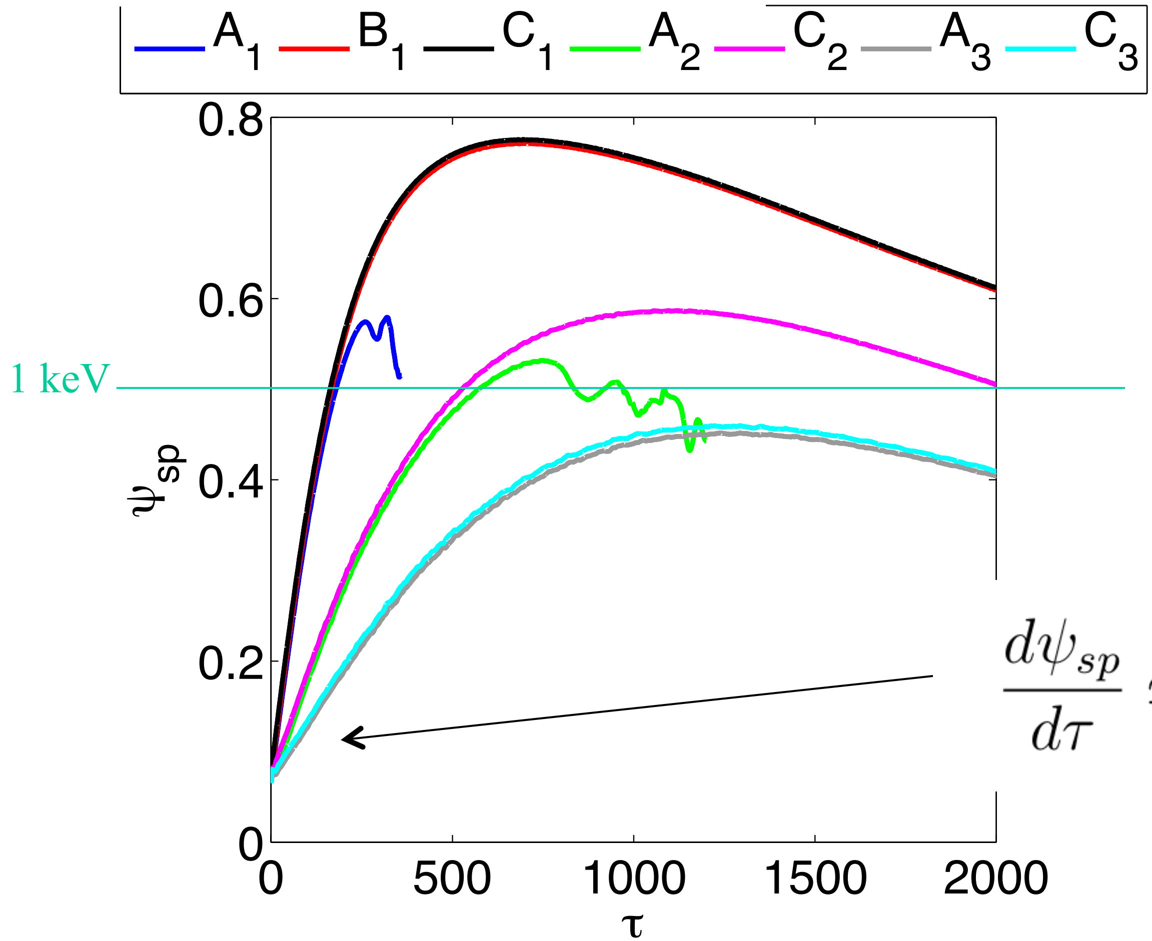


The geometry helps!



Ion emission route: $I_b/I_{cont}=0.5$

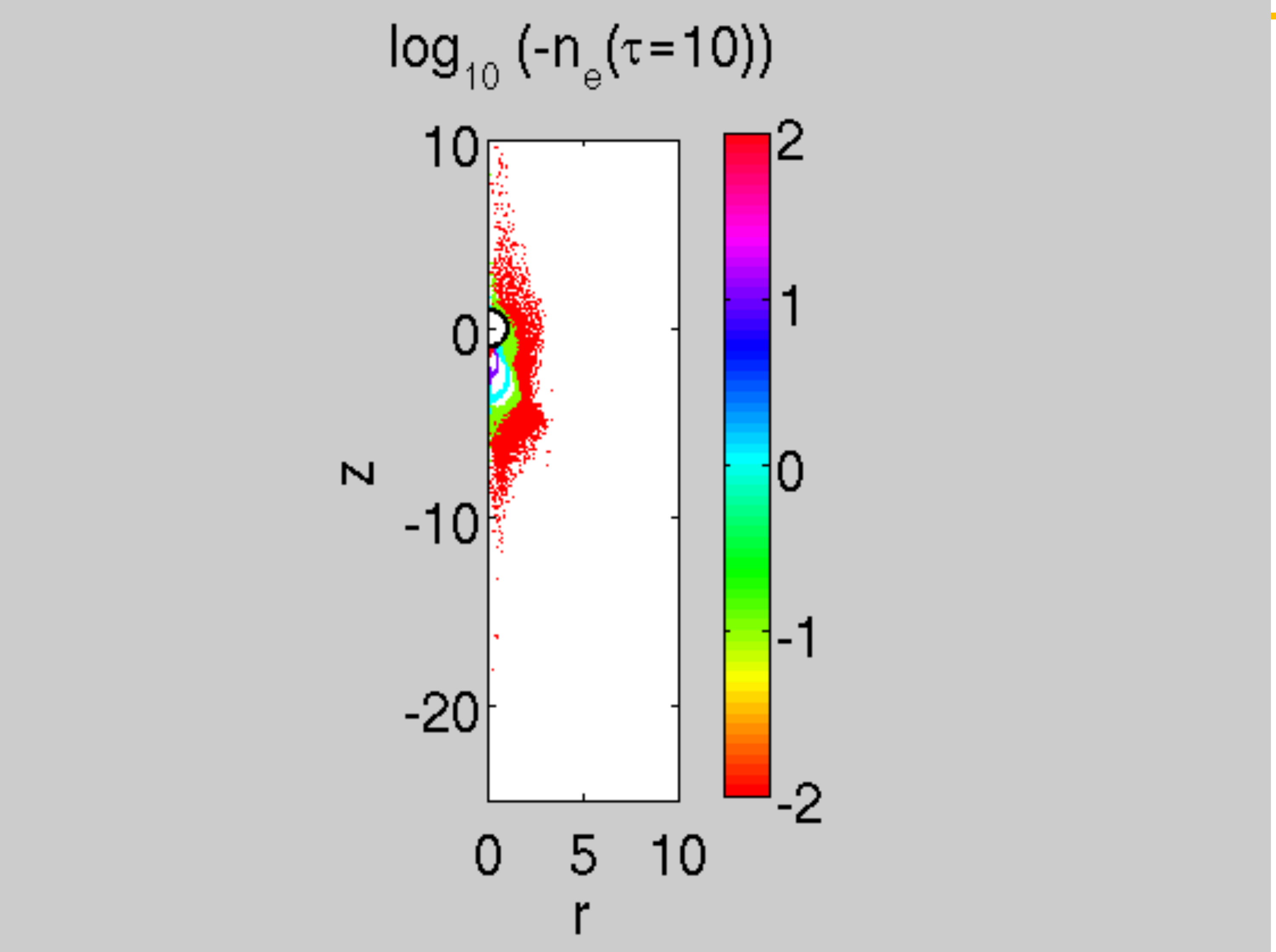
$$\frac{dQ_{sp}}{dt} = I_b^e + I_e^{bg} + I_i^{bg} + I_e^{cont} + I_i^{cont}$$



$$\frac{d\psi_{sp}}{d\tau} \simeq \frac{\hat{I}_b}{\hat{\mathcal{C}}_{cont}}$$

Different parameter regime: I_b/I_{cont}=0.5, e⁻ density

Case 1



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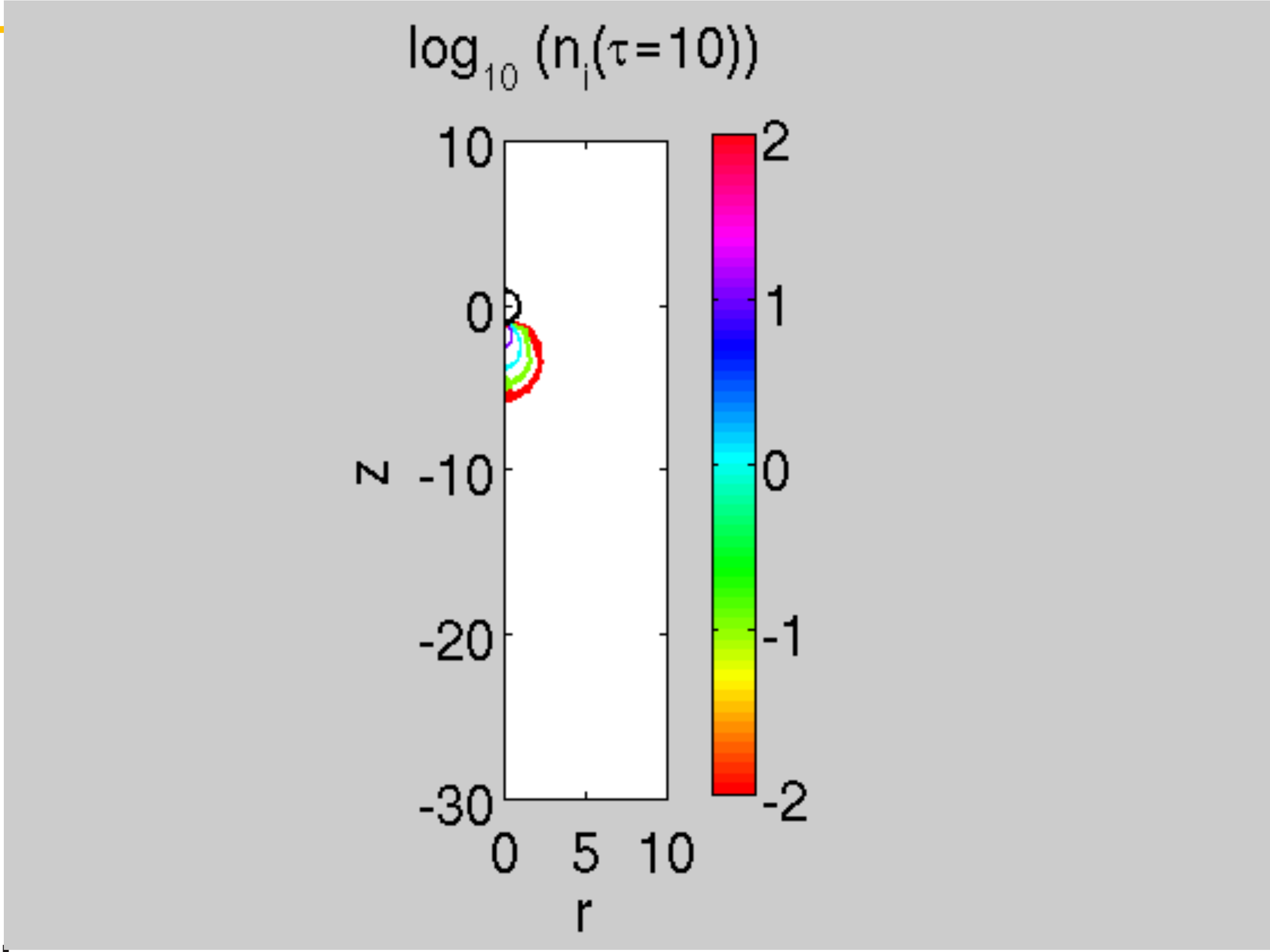
Different parameter regime: I_b/I_{cont}=0.5, i density

Case 1



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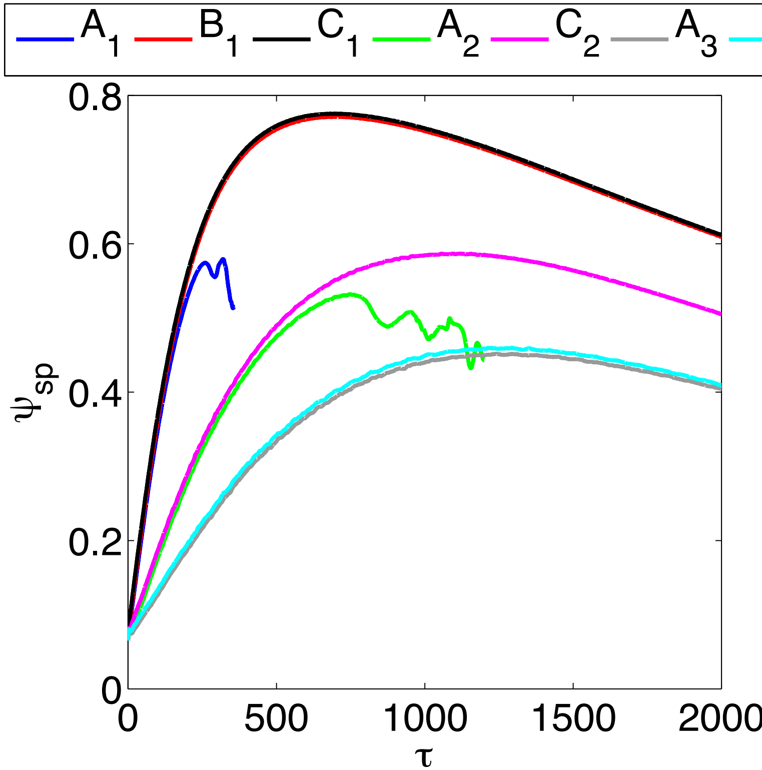
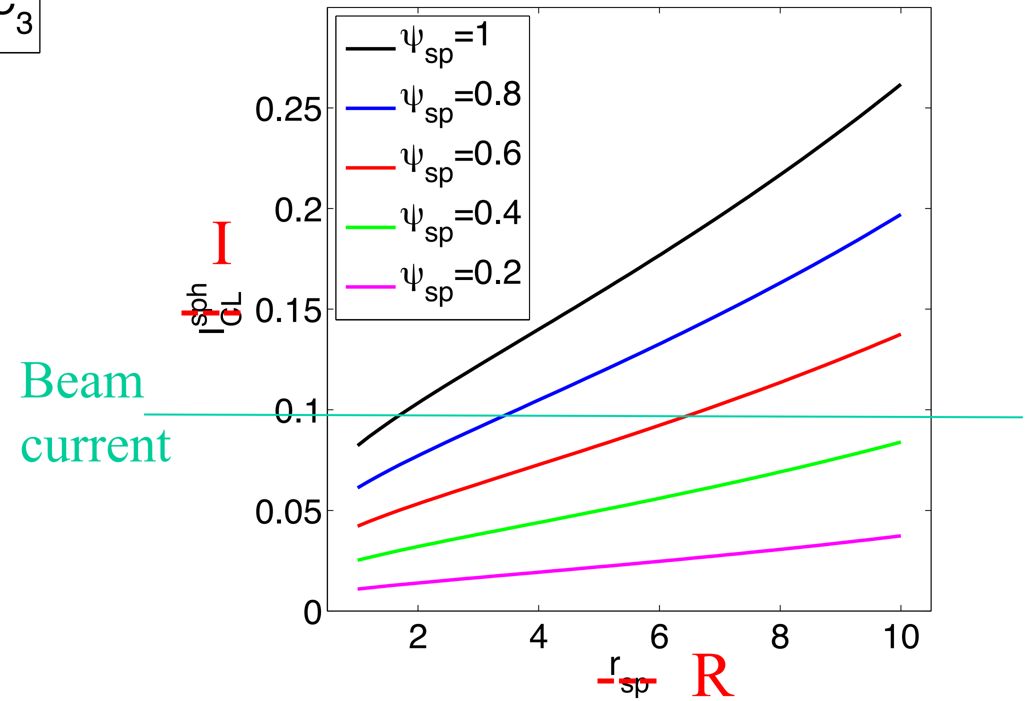
Physics interpretation in terms of CL law: an ion emission route!





Initial transient: space charge limited

Asymptotic behavior: NOT space charge limited

The simulation results confirm this interpretation!

Conclusions

- Studied emission of high-power electron beam from a spacecraft mediated by a plasma contactor
- Two strategies compared
  - Electron collection route: not viable
  - Ion emission route offers path forward
- Physics interpretation in terms of CL law: Ions can be emitted off the surface of the quasi-neutral contactor cloud. When the cloud reaches a certain size, space charge no longer limits emission. In a nutshell: the contactor turns the spacecraft and cloud into an ion emitter
- Identified a path forward for high-power e-beam experiments in the magnetosphere