**RPC2024**

XVII International Conference on
Resistive Plate Chambers and Related Detectors

# Microscopic and fluid modelling of RPCs under LHC-like conditions

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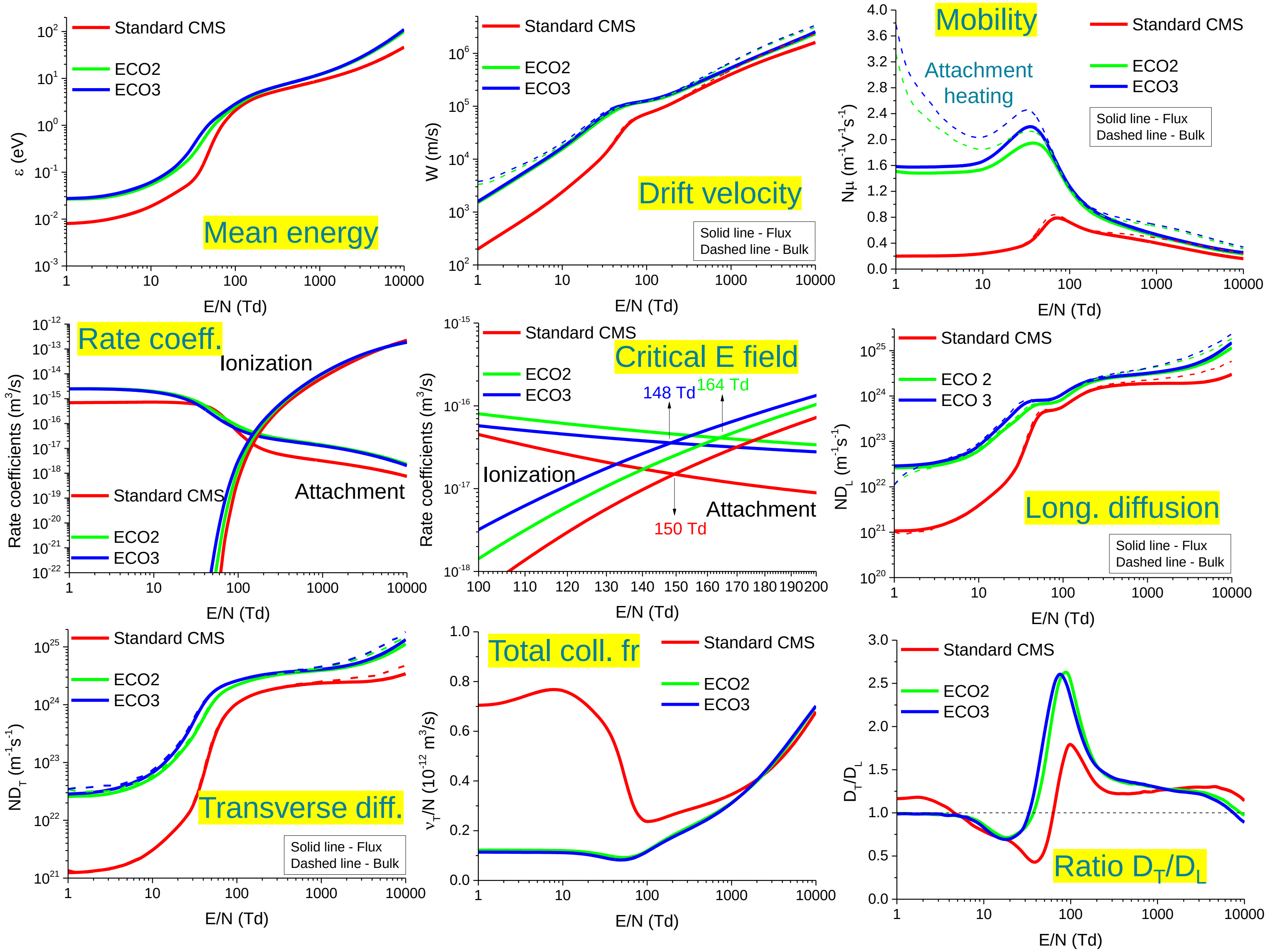
EGWIn

# Simulation and modelling of RPCs

| Model(s) | Advantages | Disadvantages |
| --- | --- | --- |
| **Analytical** | • can provide general conclusions | • often approximate |
| **Fluid equations** | • space charge effects, photoionization and recombination can be relatively easily included<br>• computationally efficient | • provide average quantities (deterministic) |
| **Macroscopic stochastic** | • provide stochastic quantities such as efficiency, timing resolution and charge spectra<br>• computationally efficient | • based on different models of avalanche fluctuations (e.g. Legler, Polya) which can be approximate |
| **Microscopic stochastic** | • provide stochastic quantities<br>• accurate | • computationally demanding |

# Input data




We focus on these **gas mixtures*** :

**Standard**
$R134a/i\text{-}C_4H_{10}/SF_6$ 95.2/4.5/0.3

**ECO2**
$HFO1234ze/CO_2/i\text{-}C_4H_{10}/SF_6$ 35/60/4/1

**ECO3**
$HFO1234ze/CO_2/i\text{-}C_4H_{10}/SF_6$ 29/65/5/1

*Abbrescia *et al.* (2024) *Eur. Phys. J. C* (2024) 84:300

**Cross sections** for electron scattering in R134a and HFO1234ze gases were developed by our group. The complete cross section sets were normalized using measured Pulsed Townsend data.

**Transport data** were calculated using a multiterm theory for solving Boltzmann equation and Monte Carlo simulations.

Dujko *et al.* unpublished

# Our “microscopic” Monte Carlo model of RPC

Based on **tracking of each electron and its collisions** with the background gas in a bounded space between the cathode and absorbing anode.

Includes **primary ionization** and **signal induction**.

Collisions are determined by **electron scattering cross sections**.

Electron path is determined using an analytical solution for the equation of the electron motion.

## Time and nature of a collision

$$t_c = -\ln(1 - r_1)/\nu_{max}$$

null-collision method is used to determine the time until collision

$$p_i = \sigma_i(\varepsilon)/\sigma_{tot}(\varepsilon)$$

relative probabilities of collisional processes

$$\sum_{j=1}^{k-1} p_j < r_2 < \sum_{j=1}^{k} p_j$$

check if collisional process *k* occurred

## Collision dynamics

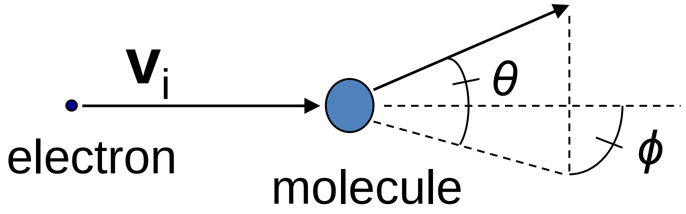
- anisotropic scattering: Okhrimovskyy, Capitelli-Longo or arbitrary angle distribution
- isotropic scattering:

$$\phi = 2\pi r_3$$

azymuthal angle $\phi$

$$\theta = \cos^{-1}(1 - 2r_4)$$

polar angle $\theta$




Change in the electron energy after an elastic collision:

$$\Delta\varepsilon = \varepsilon_0 \left(1 - 2\frac{m\,M(1 - \cos\theta)}{(m + M)^2}\right)$$

Bošnjaković et al., J. Instrum. **9** (2014) P09012

# Primary ionization

Primary ionization is implemented by grouping initial electrons in clusters.

The distance *x* between neighbouring clusters is exponentially distributed:

$$P(x) = \lambda^{-1} e^{-x/\lambda}$$

Average number of clusters per mm and cluster size distributions are calculated using HEED (assuming minimum ionizing particles):

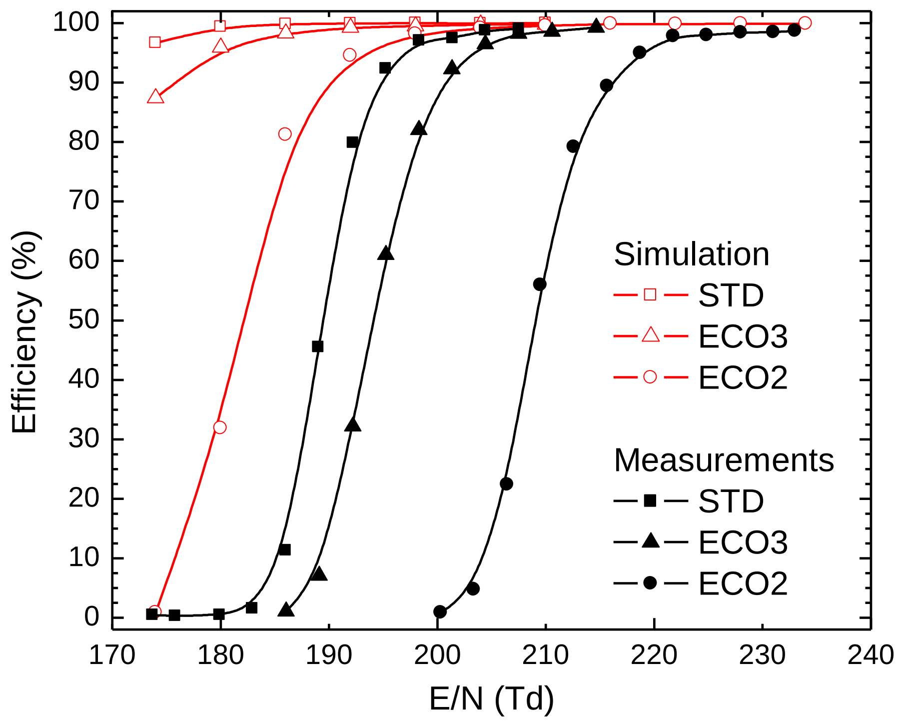
| | |
|---|---|
| STD | 8.24917 clusters/mm |
| ECO2 | 5.84578 clusters/mm |
| ECO3 | 5.33172 clusters/mm |

# Signal induction (Ramo's theorem)

Induced current: $i(t) = e_0 \frac{\mathbf{E}_w}{V_w} \sum_{i=1}^{N} \mathbf{v}_i = e_0 \frac{\mathbf{E}_w}{V_w} N(t) \langle \mathbf{v} \rangle$ — mean electron velocity "flux drift velocity"

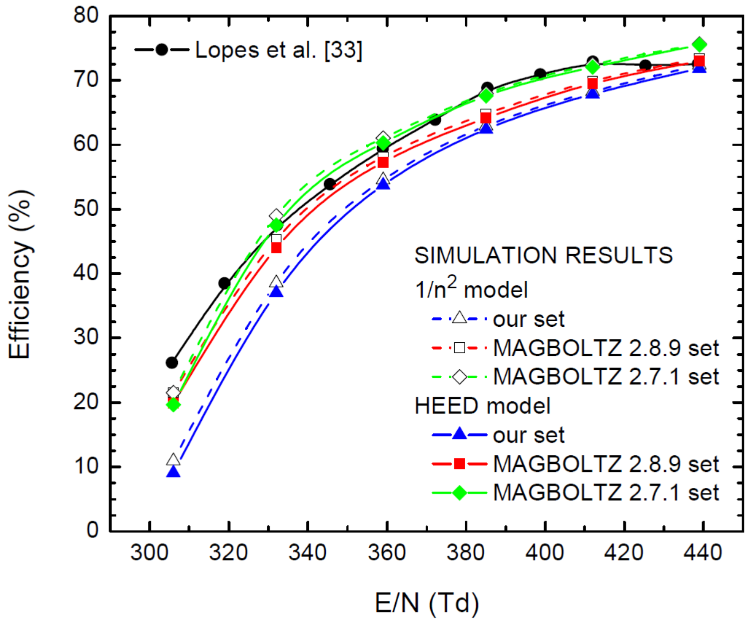
# Microscopic Monte Carlo model: Results

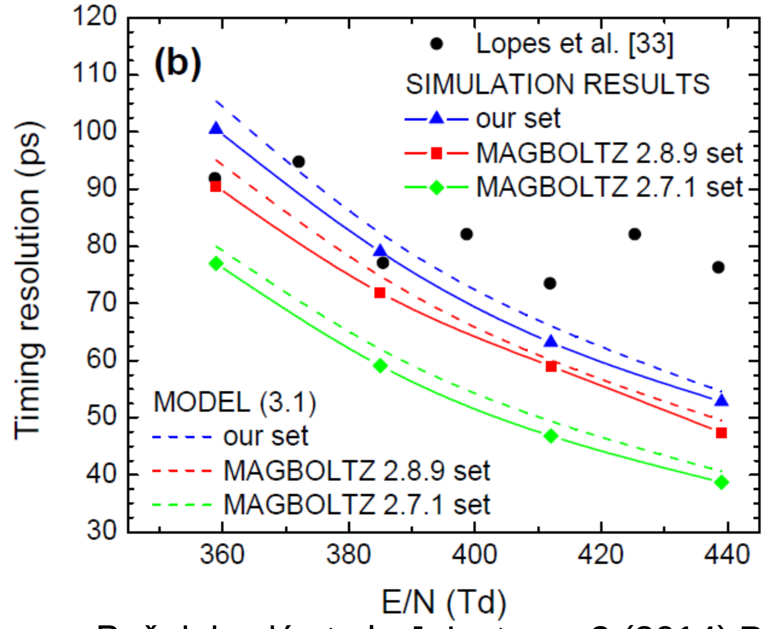
- **2 mm gas gap**
- **LOW threshold 0.4 fC** (about 70000 electrons) used to speedup the computations
- LHC gas mixtures: STD, ECO2, ECO3
- comparison with the measurements from Abbrescia et al., *Eur. Phys. J. C* **84** (2024) 300
- **large disagreement** due to: (1) threshold, (2) primary ionization?




# Previous results for a timing RPC

- **0.3 mm gas gap, threshold 2 fC** (about $10^6$ electrons)
- gas mixture of $C_2H_2F_4$ (85%), iso-$C_4H_{10}$ (5%) and $SF_6$ (10%); 3 different cross section sets for $C_2H_2F_4$
- primary ionization: 7.5 cl/mm; $1/n^2$ and HEED cluster size distributions
- comparison with measurements by Lopes et al. (2012)




Bošnjaković et al., J. Instrum. **9** (2014) P09012

# PIC/MCC model

- We have developed a 2.5D Particle-in-Cell/Monte Carlo Collision model of RPCs.
- Individual electrons and their collisions are tracked microscopically in 3D using a Monte Carlo approach.
- Electrons, positive and negative ions are mapped to number densities on a 2D grid assuming axial symmetry.
- The resulting electric field is calculated by solving the Poisson equation.

# PIC/MCC model

- Particle deposition and electric field **interpolation**: bilinear method.
- **Velocity Verlet scheme** is used to advance particles in time.
- **Time stepping** restrictions:
  CFL-like criterion

  $$\Delta t < \mathrm{CFL} \cdot \min_i \left( \frac{\Delta x_i}{v_i} \right)$$

  dielectric relaxation time

  $$\Delta t < \frac{\epsilon_0}{q_e \mu_e n_e}$$

- Uniform rescaling technique* is applied to optimize the number of particles during simulation (**super-particles**).
- Model is implemented using the AMReX software framework.

*Mirić et al., Plasma Sources Sci. Technol. **25** (2016) 065010

# AMReX framework

- open-source C++ library for massively parallel, block structured **adaptive mesh refinement (AMR)** applications
- has inbuilt **geometric multigrid solver for Poisson equation**
- provides classes and data structures for **convenient abstraction of grid and particle data**
- provides abstraction layers for MPI, OpenMP and GPU **parallelization**

# Fluid model

- 2D axis-symmetric classical fluid model of RPCs
- advection diffusion reaction equation for the time evolution of electron number density

$$\frac{\partial n_e}{\partial t} + \nabla(n_e \boldsymbol{W} - \boldsymbol{D}\nabla n_e) = n_e(\alpha - \eta)|\boldsymbol{W}|$$

- reaction equations for the ion number densities

$$\frac{\partial n_p}{\partial t} = n_e \alpha |\boldsymbol{W}| \qquad \frac{\partial n_n}{\partial t} = n_e \eta |\boldsymbol{W}|$$

- local field approximation is assumed
- electric field

$$\mathbf{E} = -\nabla\phi$$

- Poisson equation

$$\Delta\phi = -\frac{q_e(n_p - n_n - n_e)}{\varepsilon_0}$$

- spatial discretization: finite volume method and a TVD scheme with Koren flux limiter
- time integration: Heun’s method

Simonović et al., Plasma Sources Sci. Technol. **33** (2024) 085012

## Adaptive mesh refinement

- a hierarchy of refined mesh levels is used for computational efficiency by employing a finer mesh required at the streamer front while a coarser mesh can be used in other parts of the domain

### Refinement criteria

- ionization frequency

$$\bar{\alpha}(c_1|\mathbf{E}|)\Delta x < c_0\,, \qquad \bar{\alpha} = \alpha - \eta$$

- potential curvature

$$\frac{\Delta x^2|\rho|}{\epsilon_0} < c_2$$

### De-refinement criteria

$$\bar{\alpha}(c_1|\mathbf{E}|)\Delta x < 0.1, \qquad \Delta x < 30\mu\mathrm{m}$$

Where

$$c_1 = 1.2, \qquad c_0 = 0.8, \qquad c_2 = 1\mathrm{V}$$

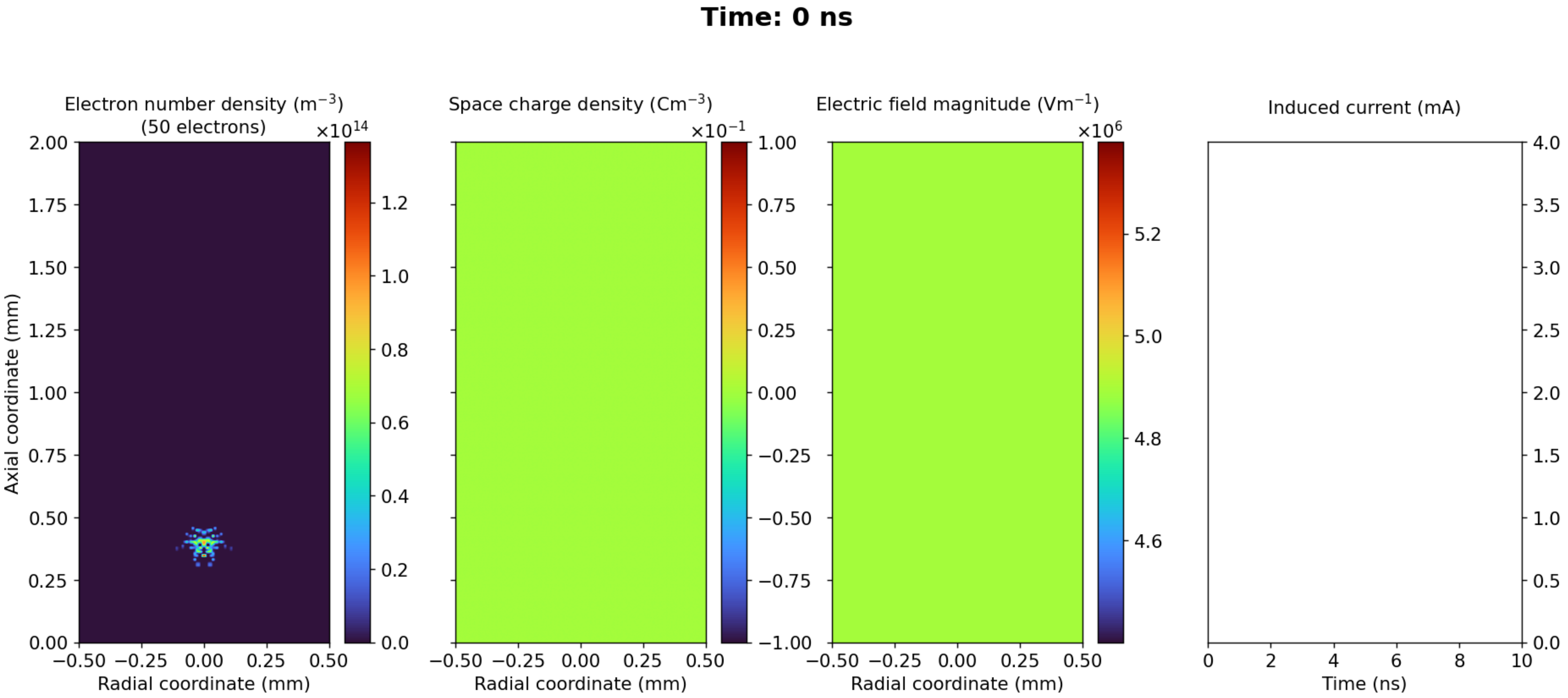
## Boundary conditions

- number density of electrons — zero Neumann conditions at boundaries perpendicular to the radial coordinate and zero Dirichlet conditions at boundaries perpendicular to the axial coordinate i.e. absorbing electrodes
- electric field — zero Neumann conditions at all boundaries
- electric potential — zero Neumann conditions at boundaries perpendicular to the radial coordinate and Dirichlet conditions at boundaries perpendicular to the axial coordinate

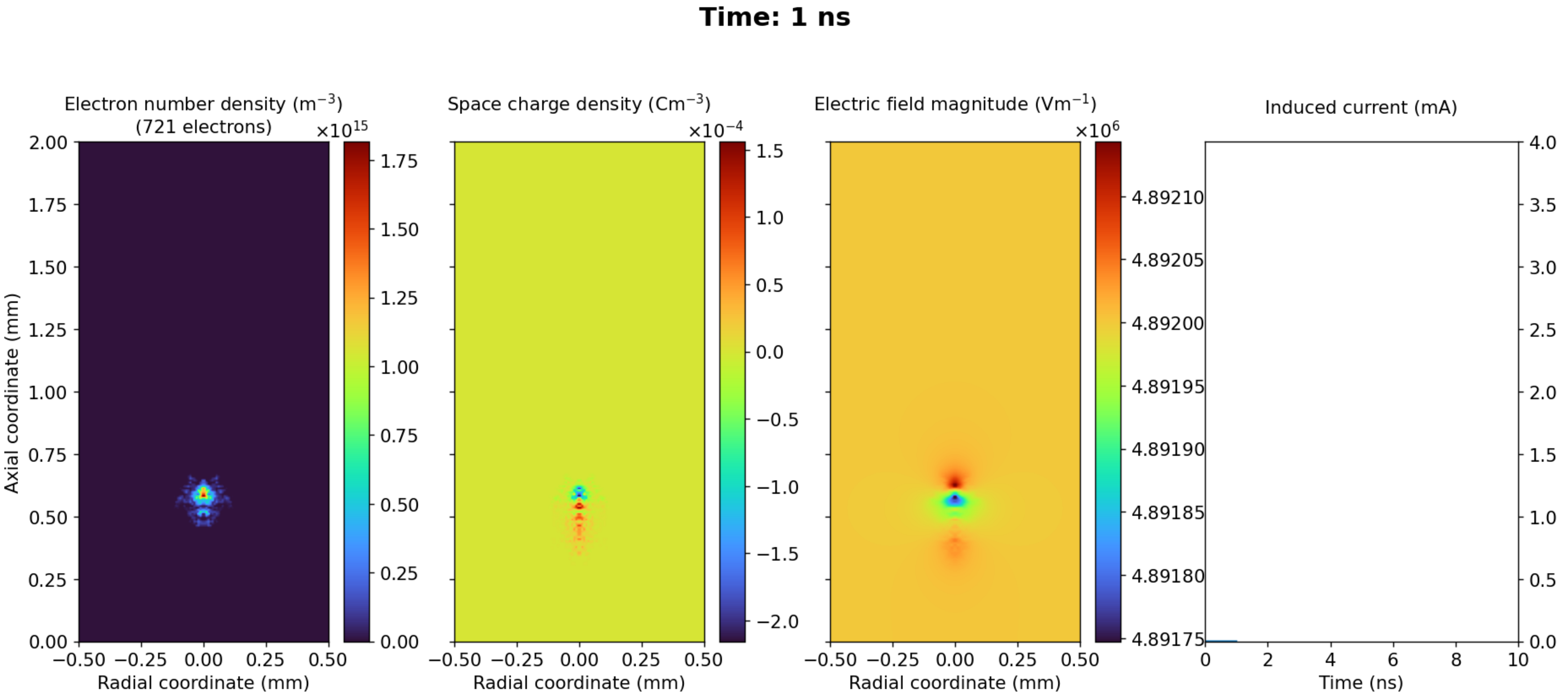
Simonović et al., Plasma Sources Sci. Technol. **33** (2024) 085012

# PIC/MCC MODEL
# ECO3 GAS MIXTURE
# E/N = 200 Td

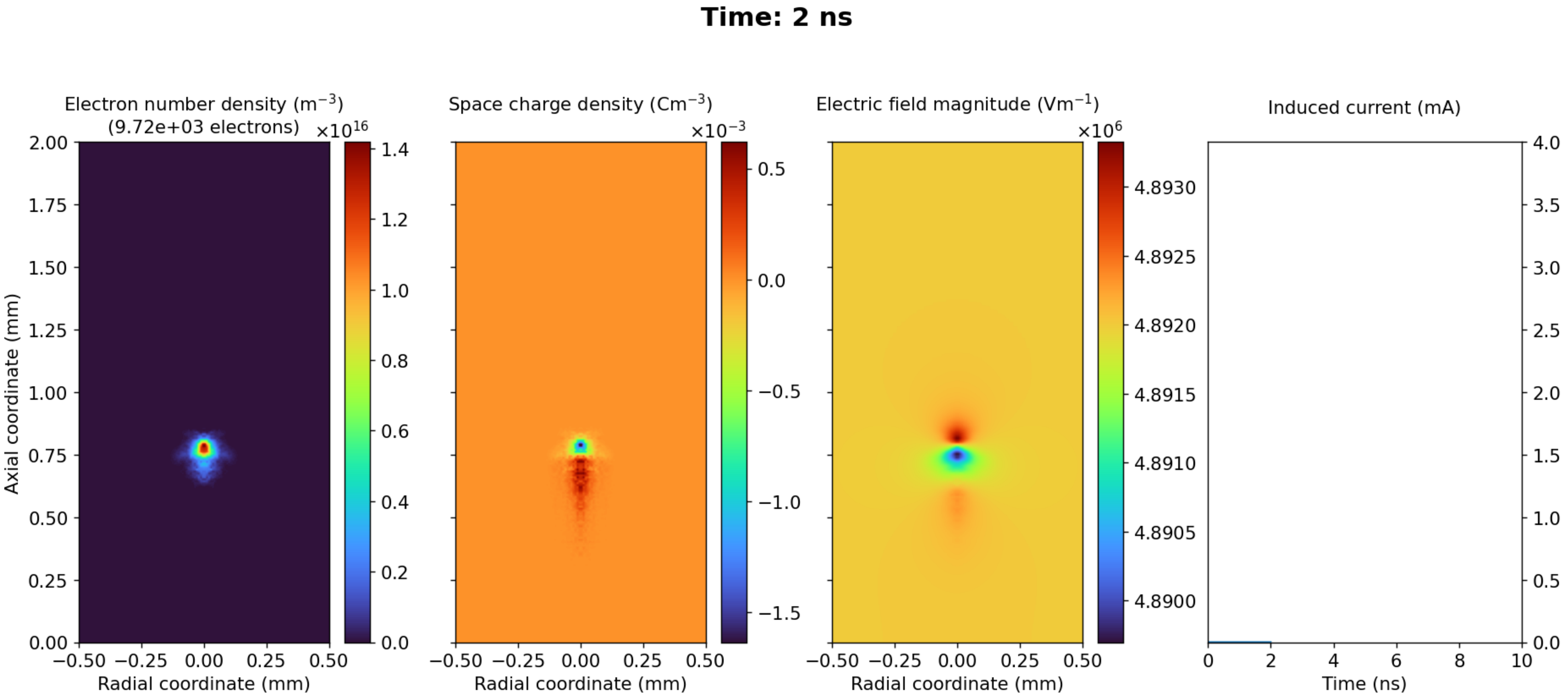
# PIC/MCC model
# ECO3 gas mixture
# E/N = 200 Td



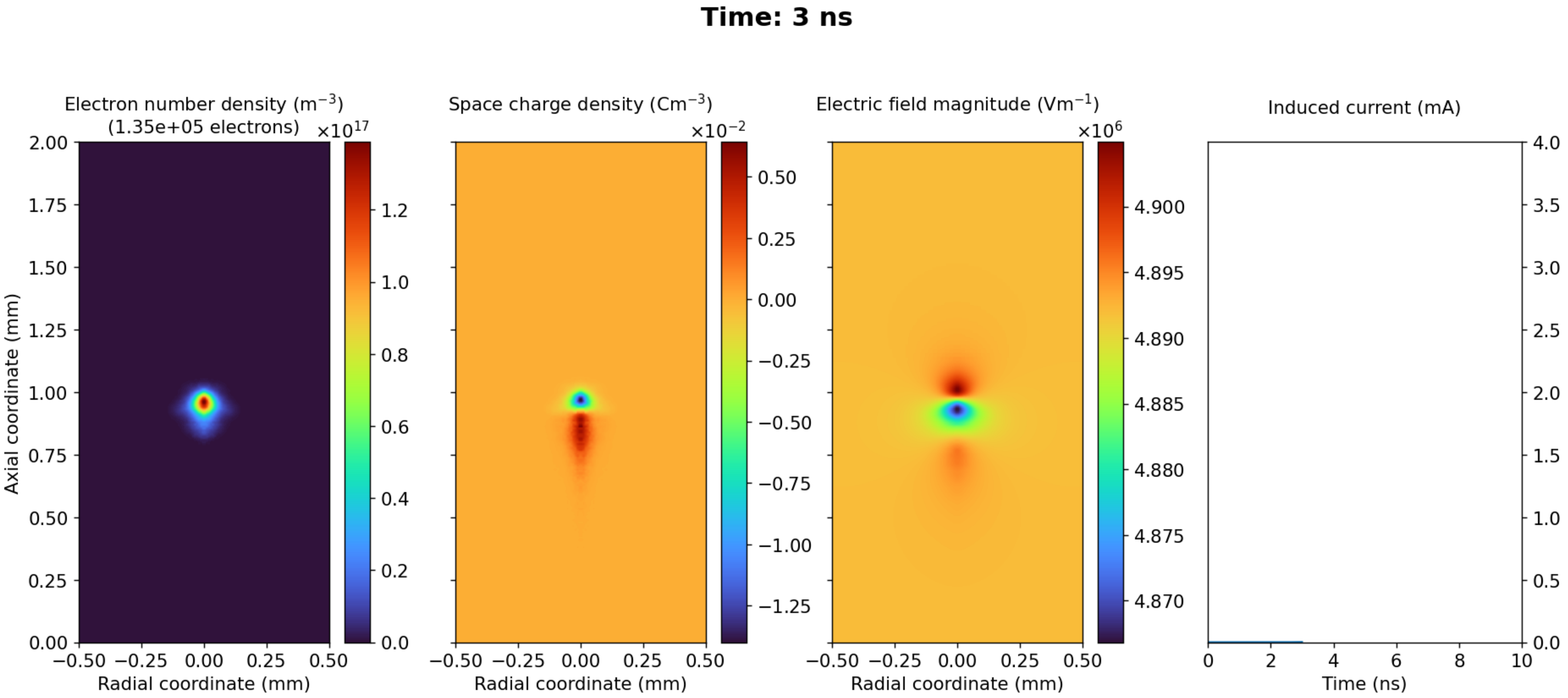
# PIC/MCC model
# ECO3 gas mixture
# E/N = 200 Td



# PIC/MCC model
# ECO3 gas mixture
# E/N = 200 Td

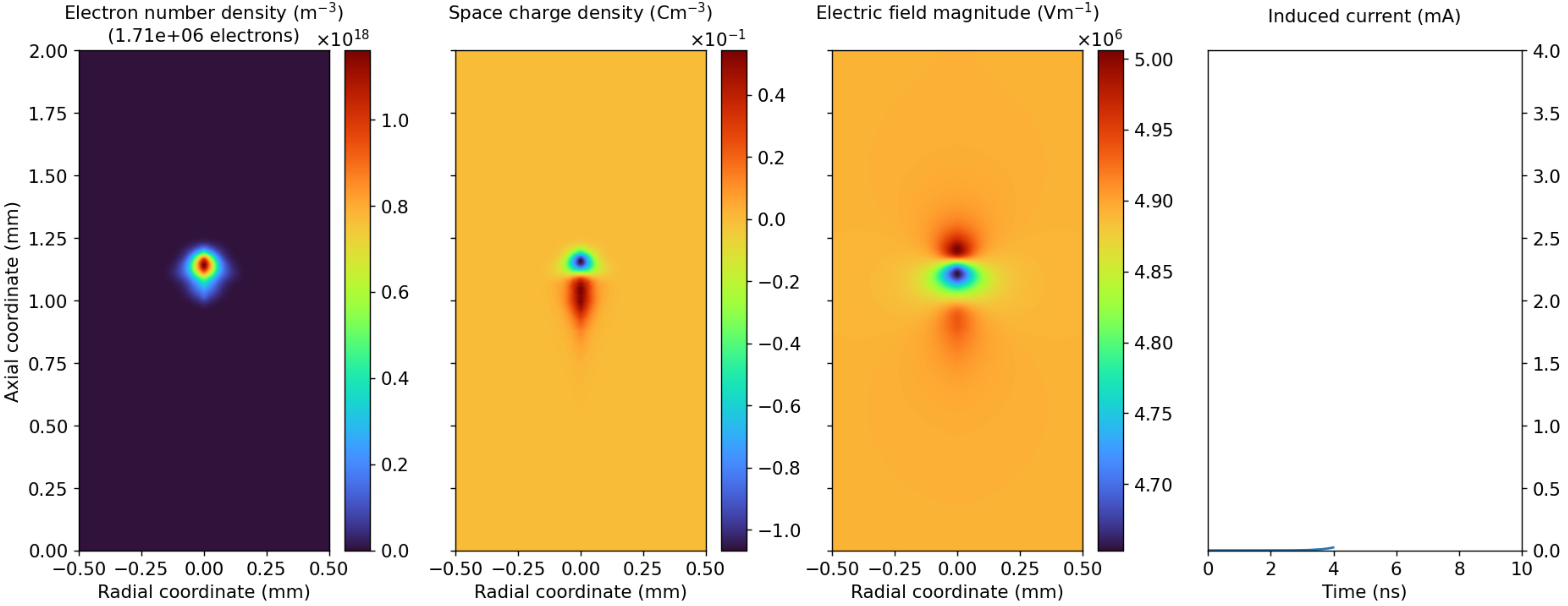


# PIC/MCC model
# ECO3 gas mixture
# E/N = 200 Td

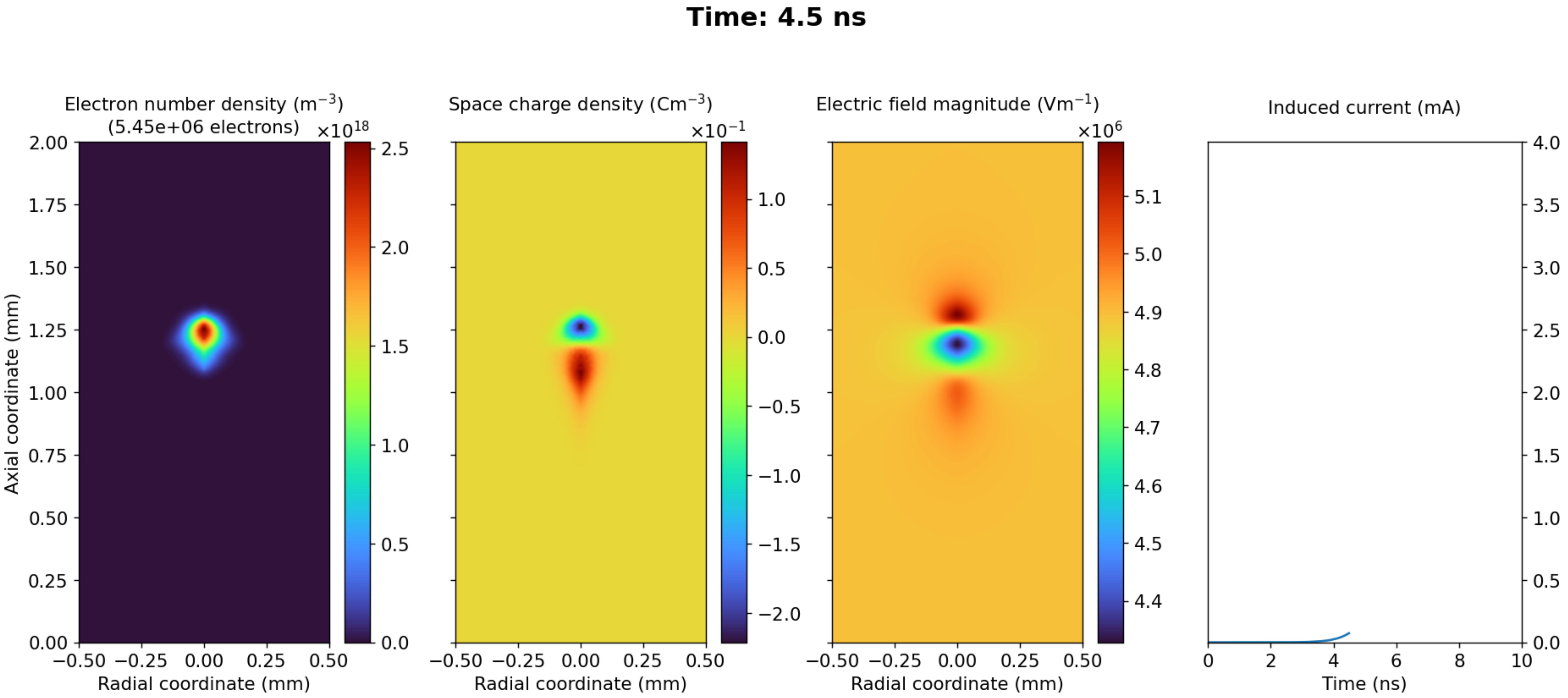


# PIC/MCC model
# ECO3 gas mixture
# E/N = 200 Td

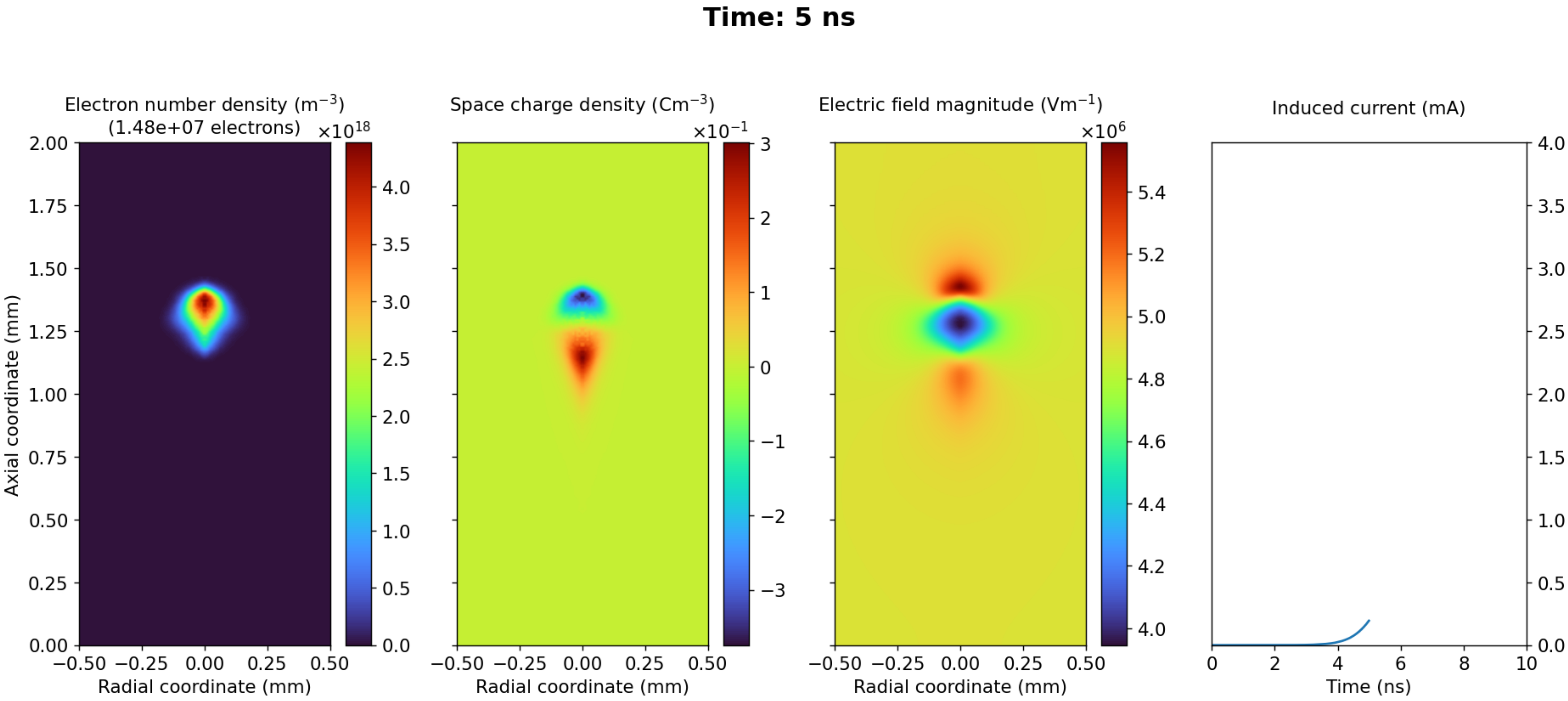
**Time: 4 ns**



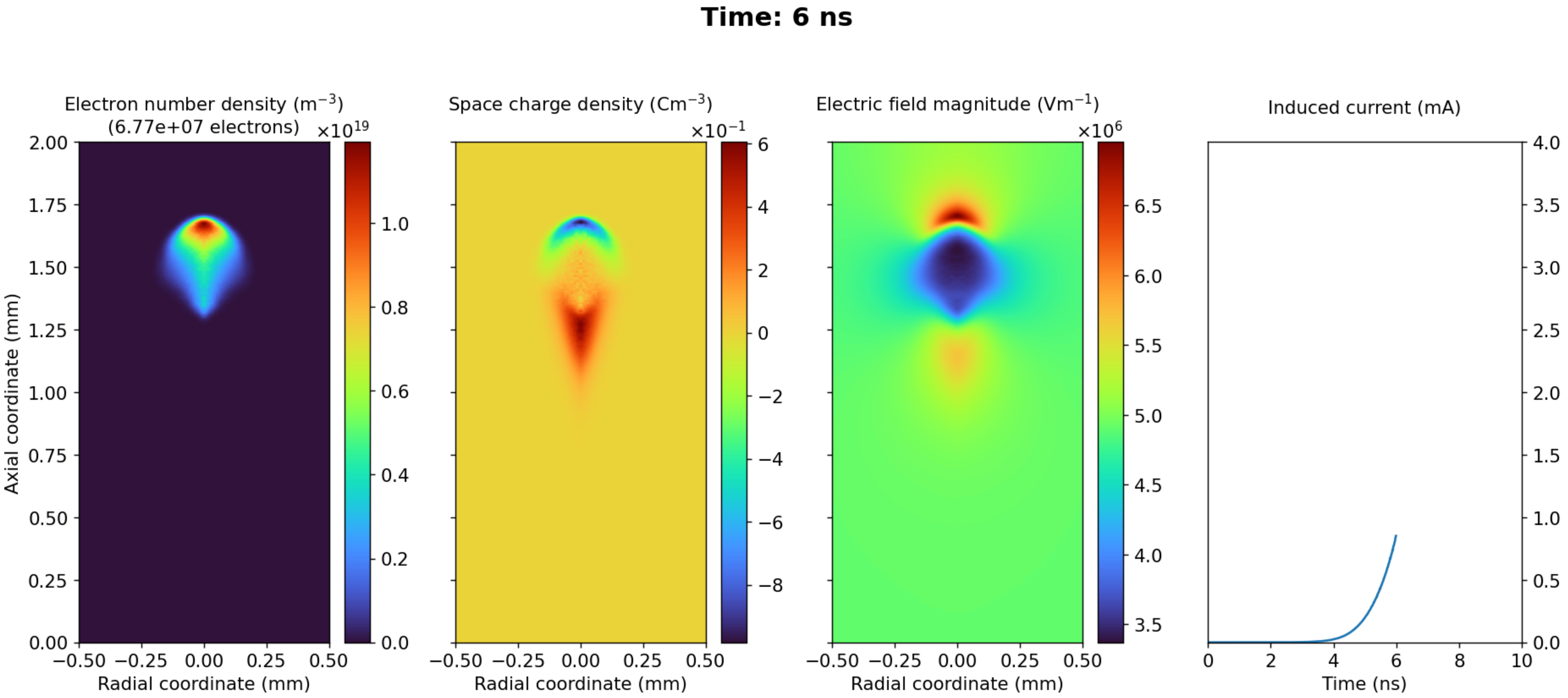
# PIC/MCC model
# ECO3 gas mixture
# E/N = 200 Td



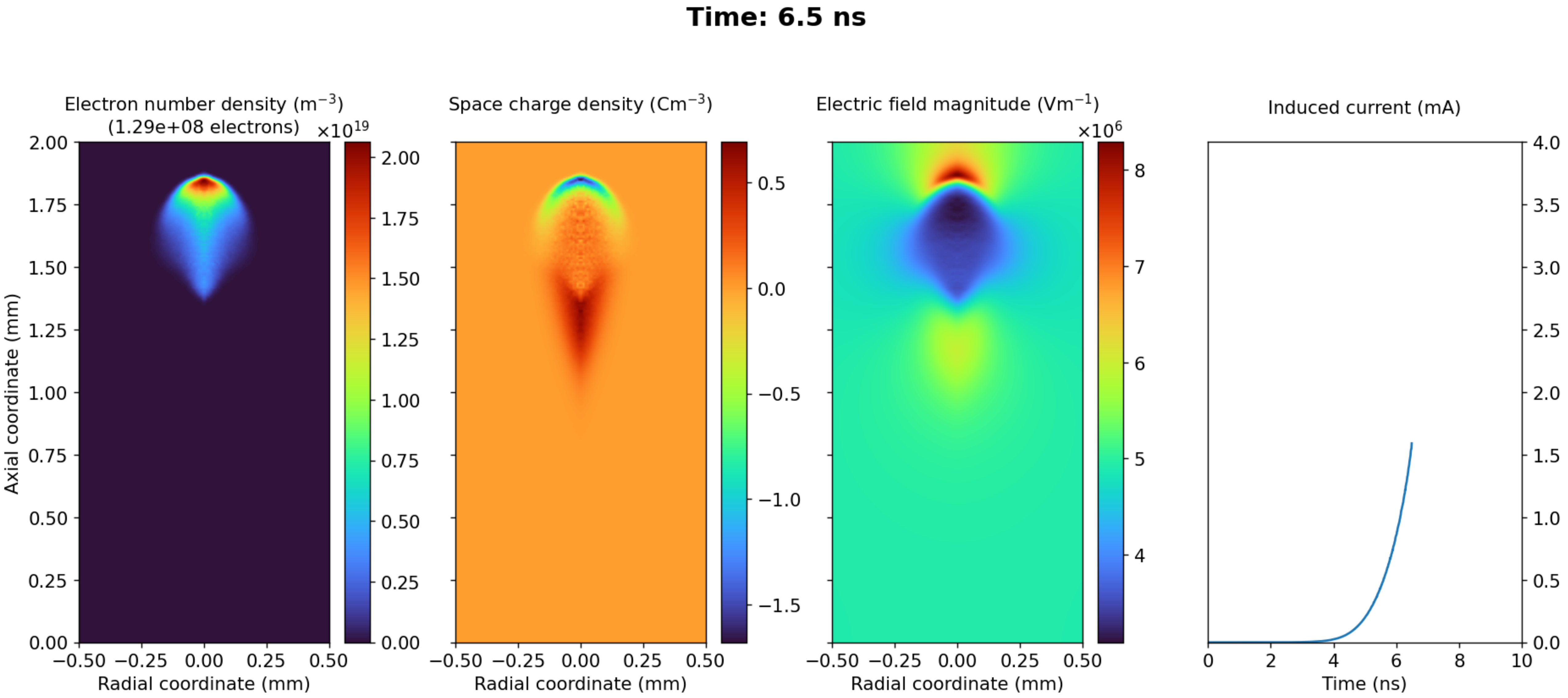
**PIC/MCC model**
**ECO3 gas mixture**
**E/N = 200 Td**



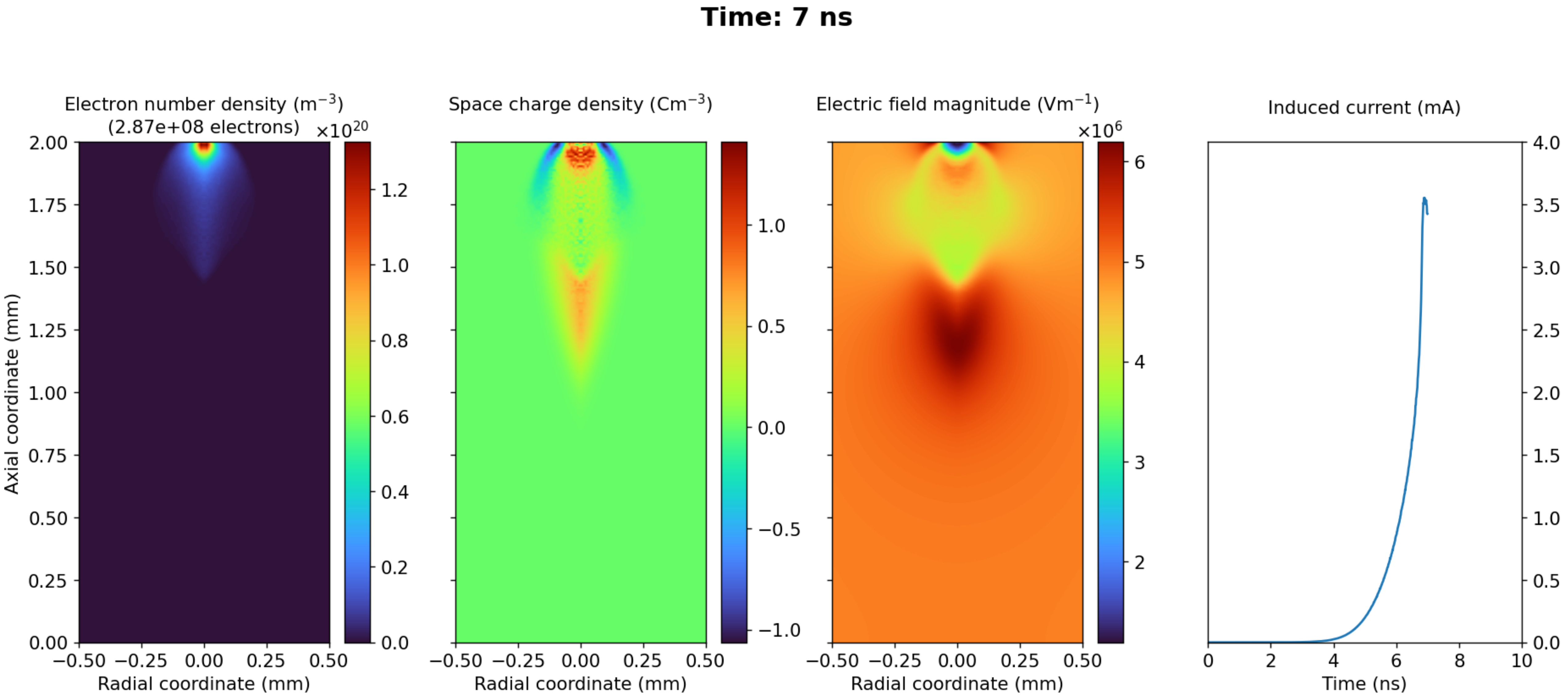
# PIC/MCC model
# ECO3 gas mixture
# E/N = 200 Td



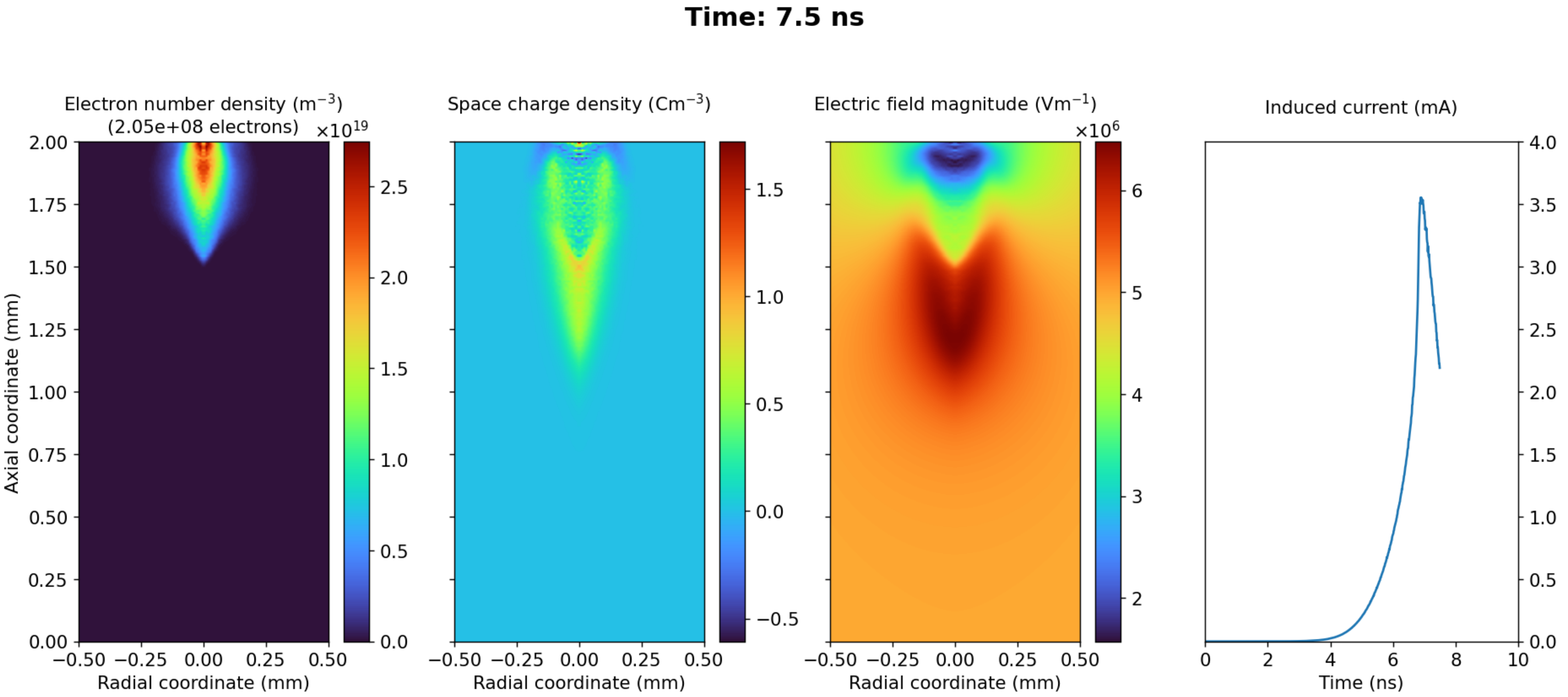
# PIC/MCC model
# ECO3 gas mixture
# E/N = 200 Td



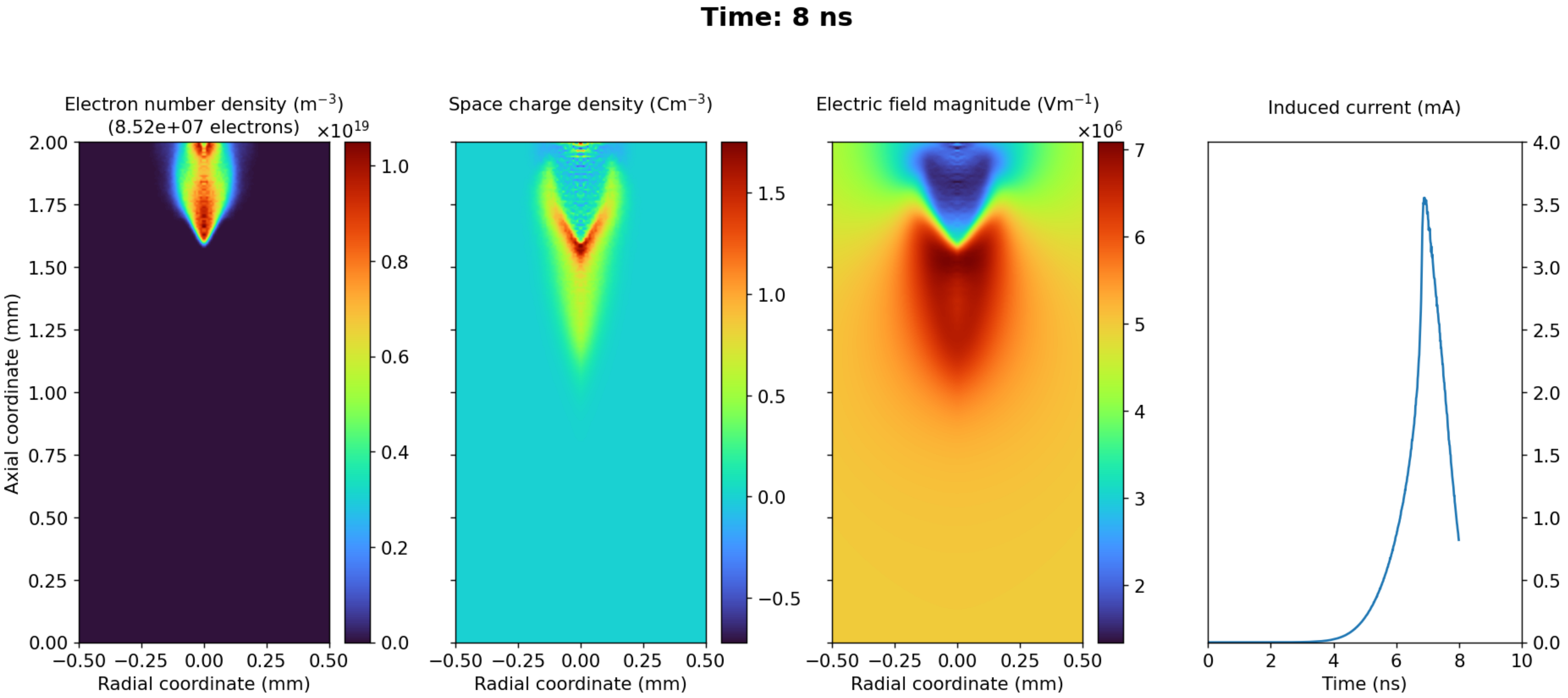
# PIC/MCC model
# ECO3 gas mixture
# E/N = 200 Td



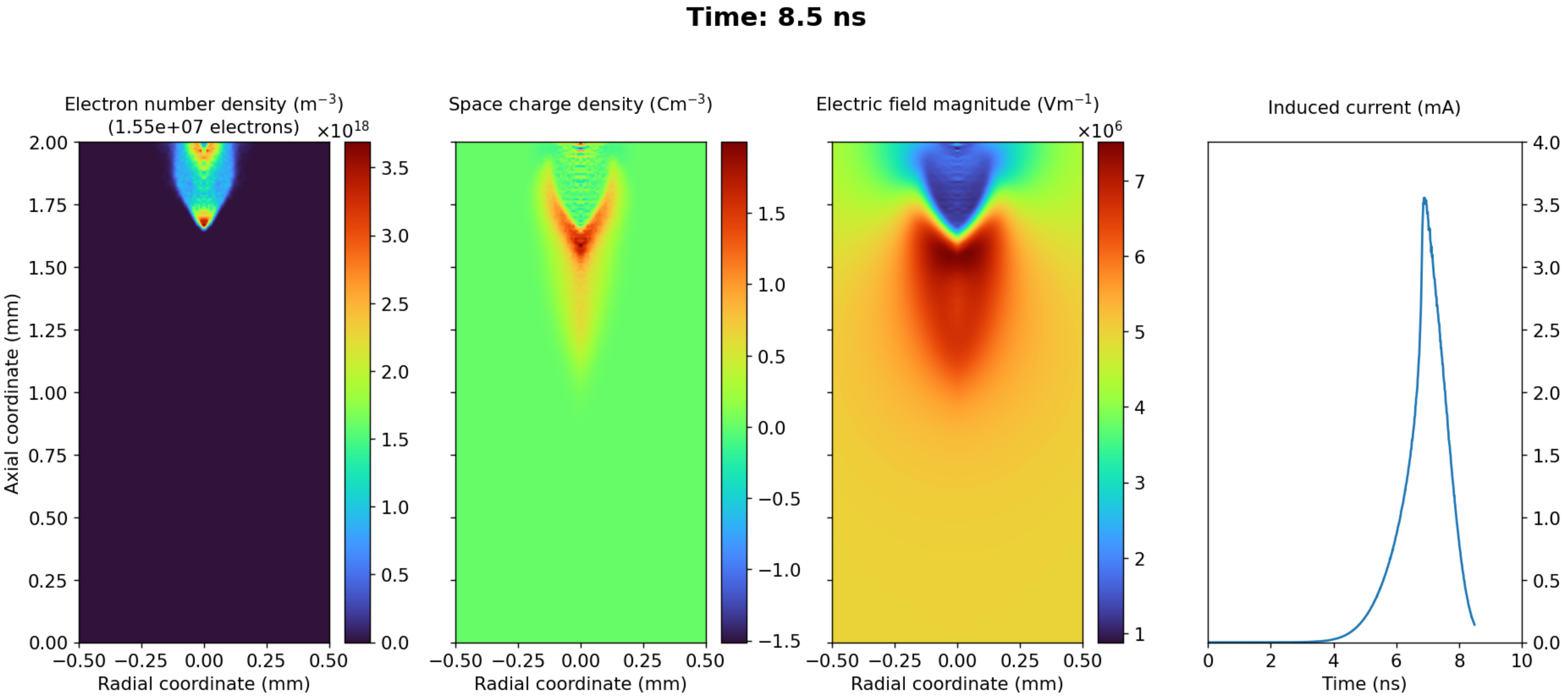
# PIC/MCC model
# ECO3 gas mixture
# E/N = 200 Td



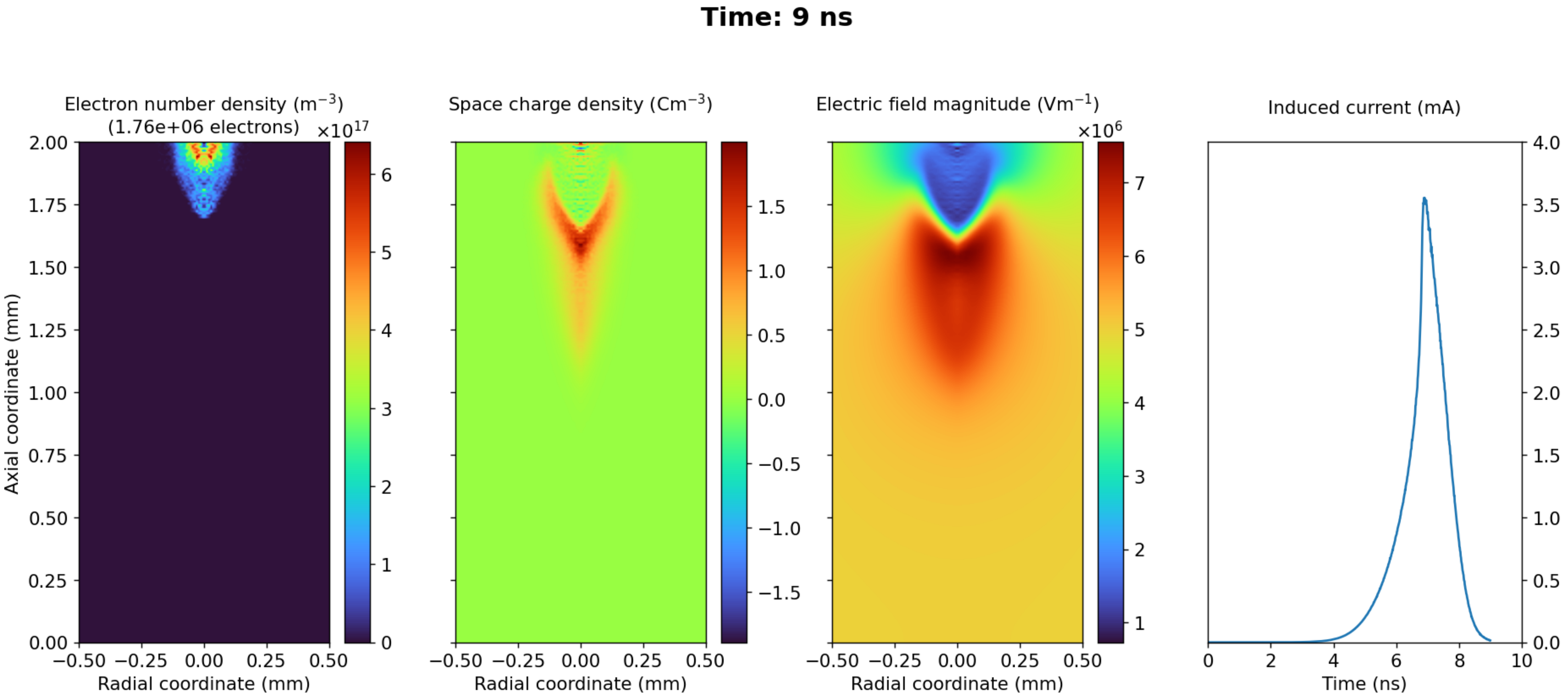
**PIC/MCC model**
**ECO3 gas mixture**
**E/N = 200 Td**



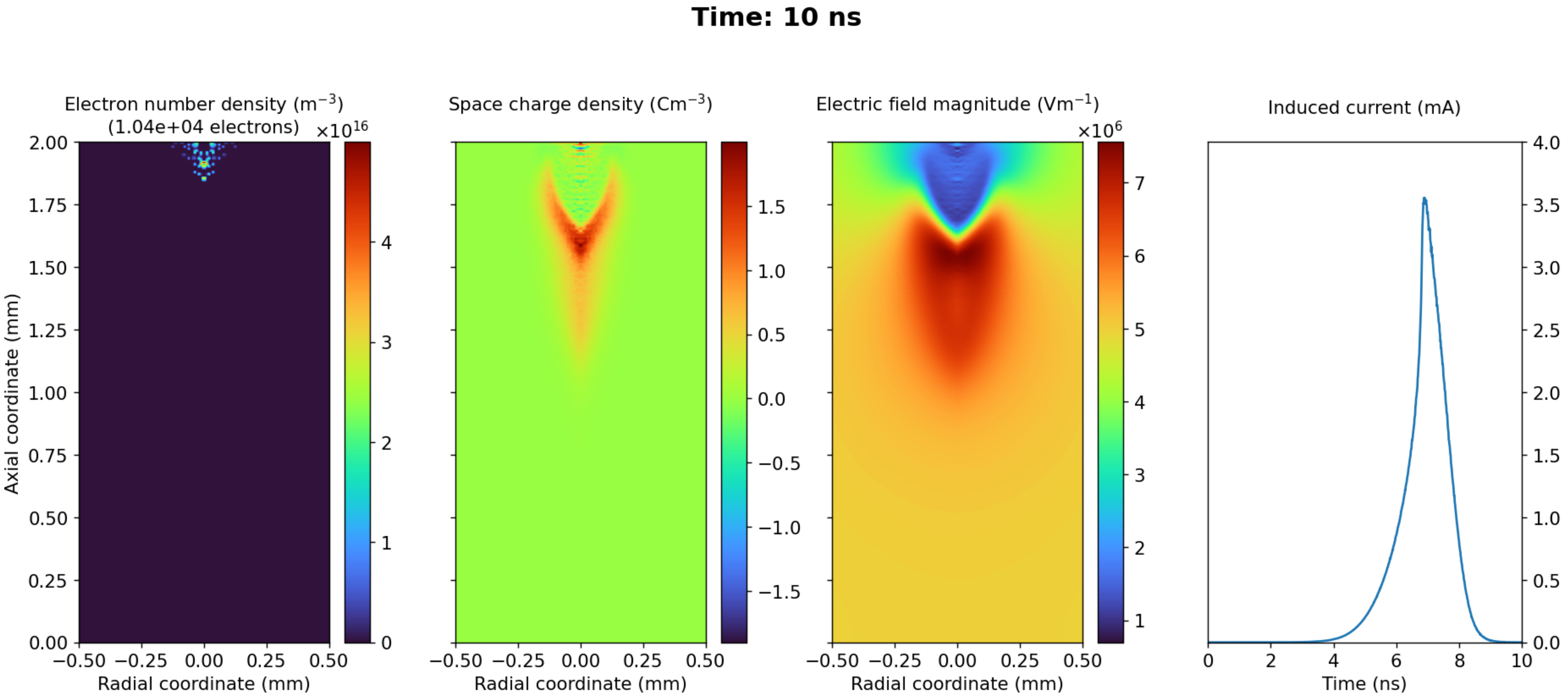
# PIC/MCC model
# ECO3 gas mixture
# E/N = 200 Td



# PIC/MCC model
# ECO3 gas mixture
# E/N = 200 Td

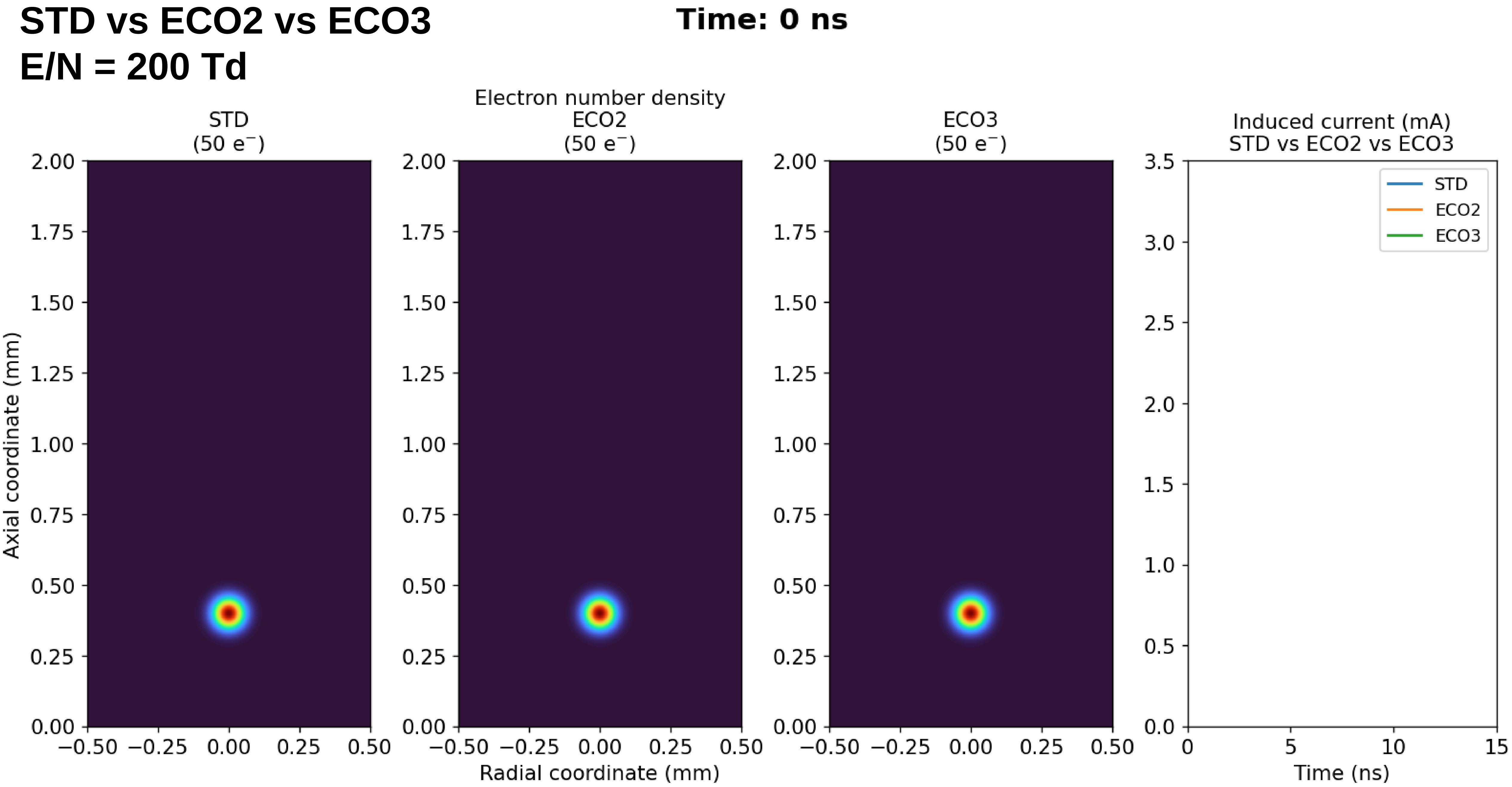


# PIC/MCC model
# ECO3 gas mixture
# E/N = 200 Td



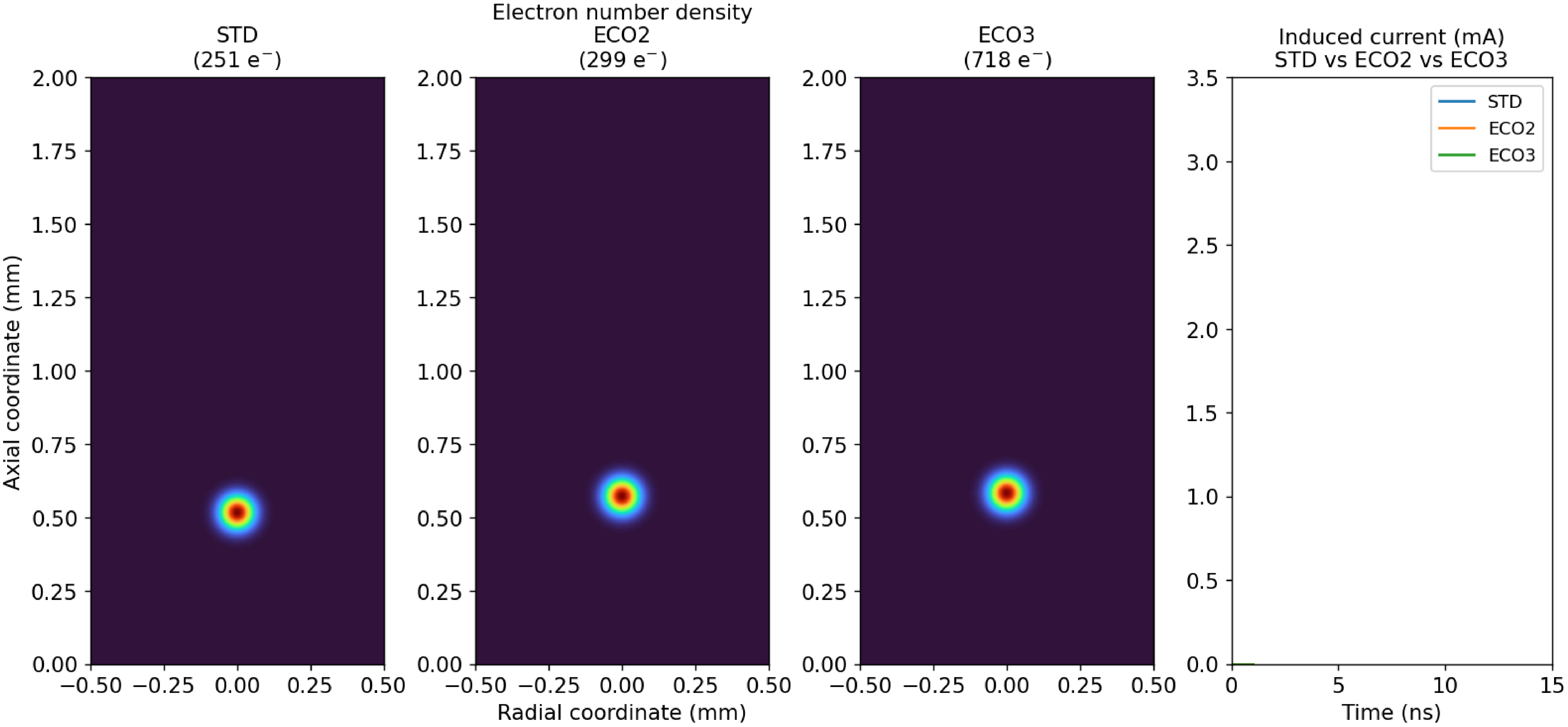
# FLUID MODEL (BULK)
# STD VS ECO2 VS ECO3
# E/N = 200 Td

**Fluid model (bulk)**
**STD vs ECO2 vs ECO3**
**E/N = 200 Td**



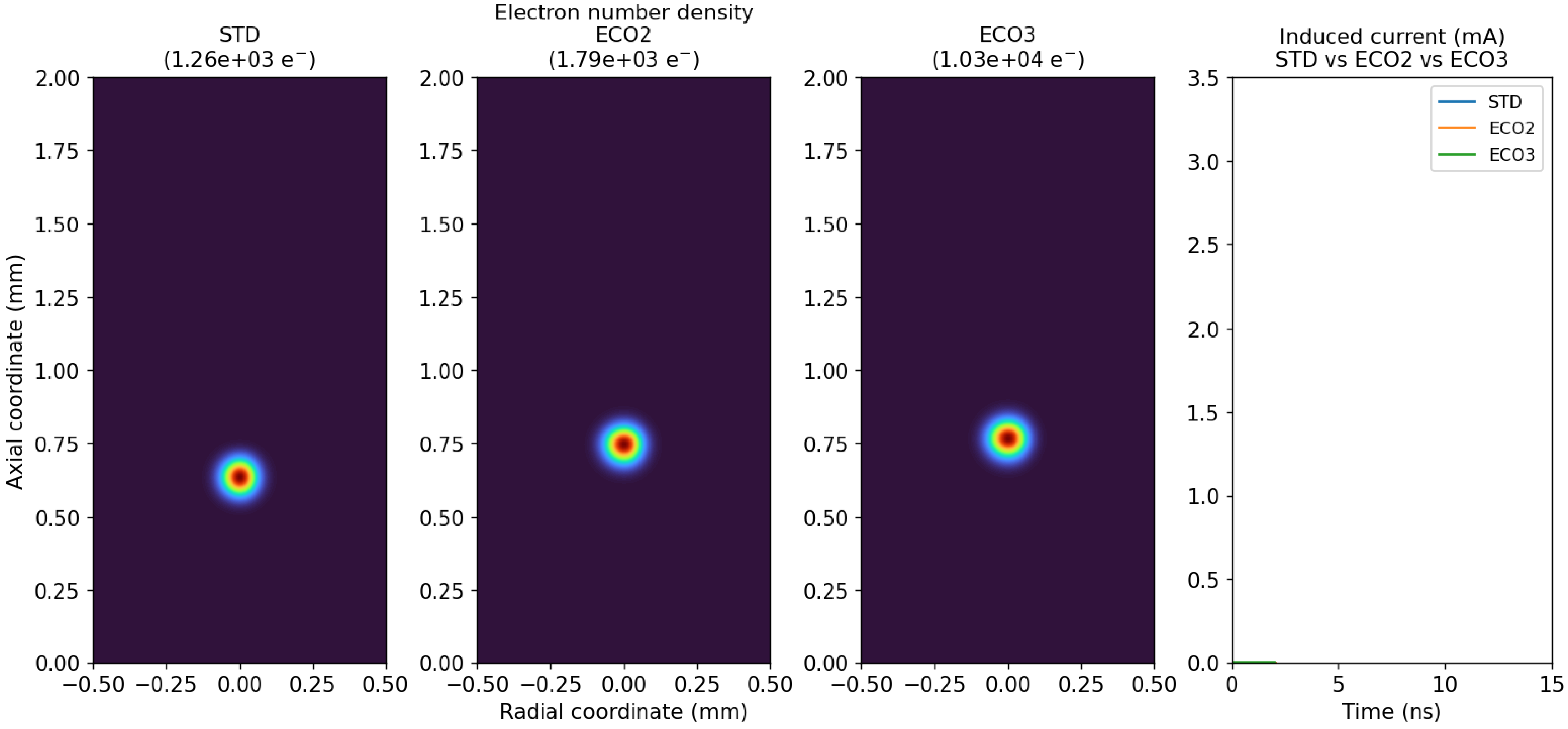
# Fluid model (bulk)
# STD vs ECO2 vs ECO3
# E/N = 200 Td

**Time: 1 ns**



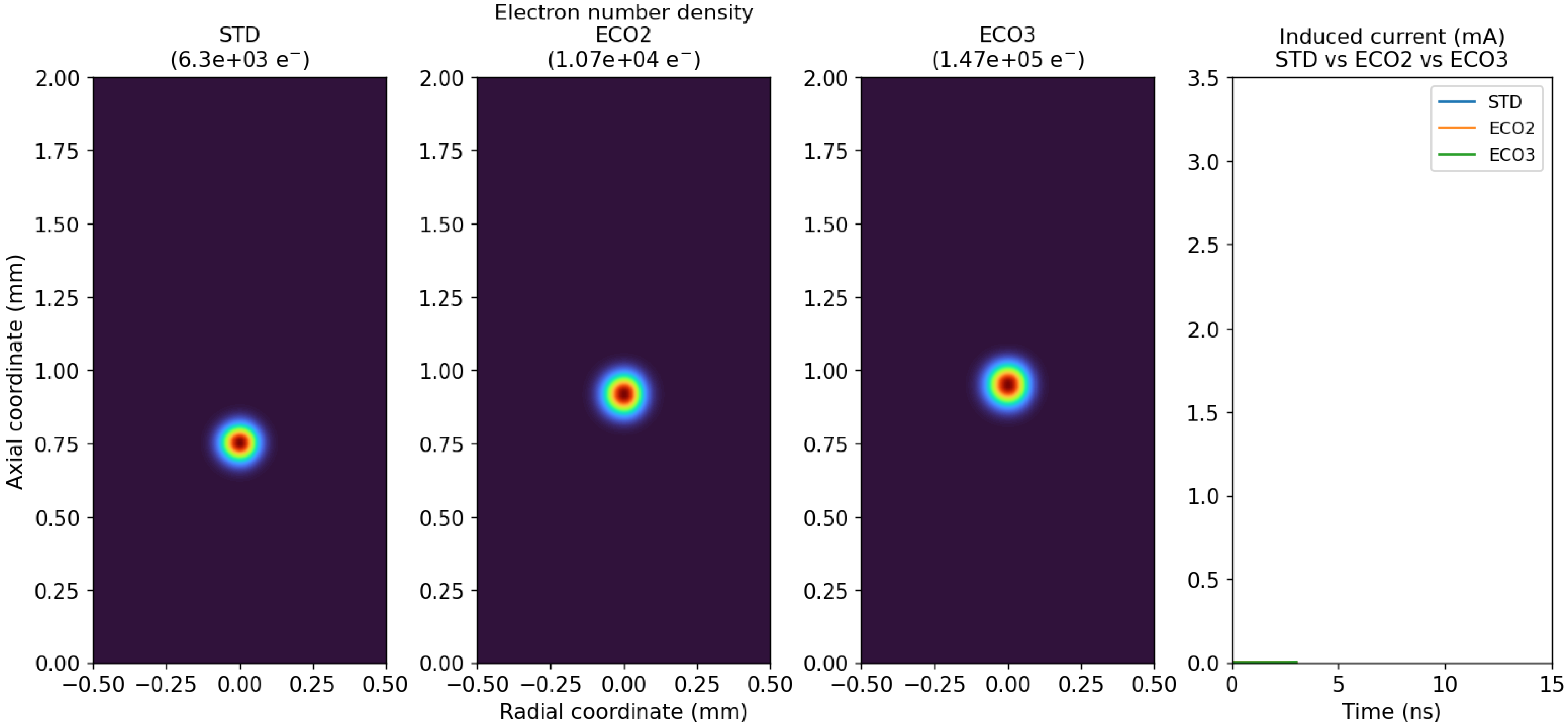
# Fluid model (bulk)
# STD vs ECO2 vs ECO3
# E/N = 200 Td

**Time: 2 ns**



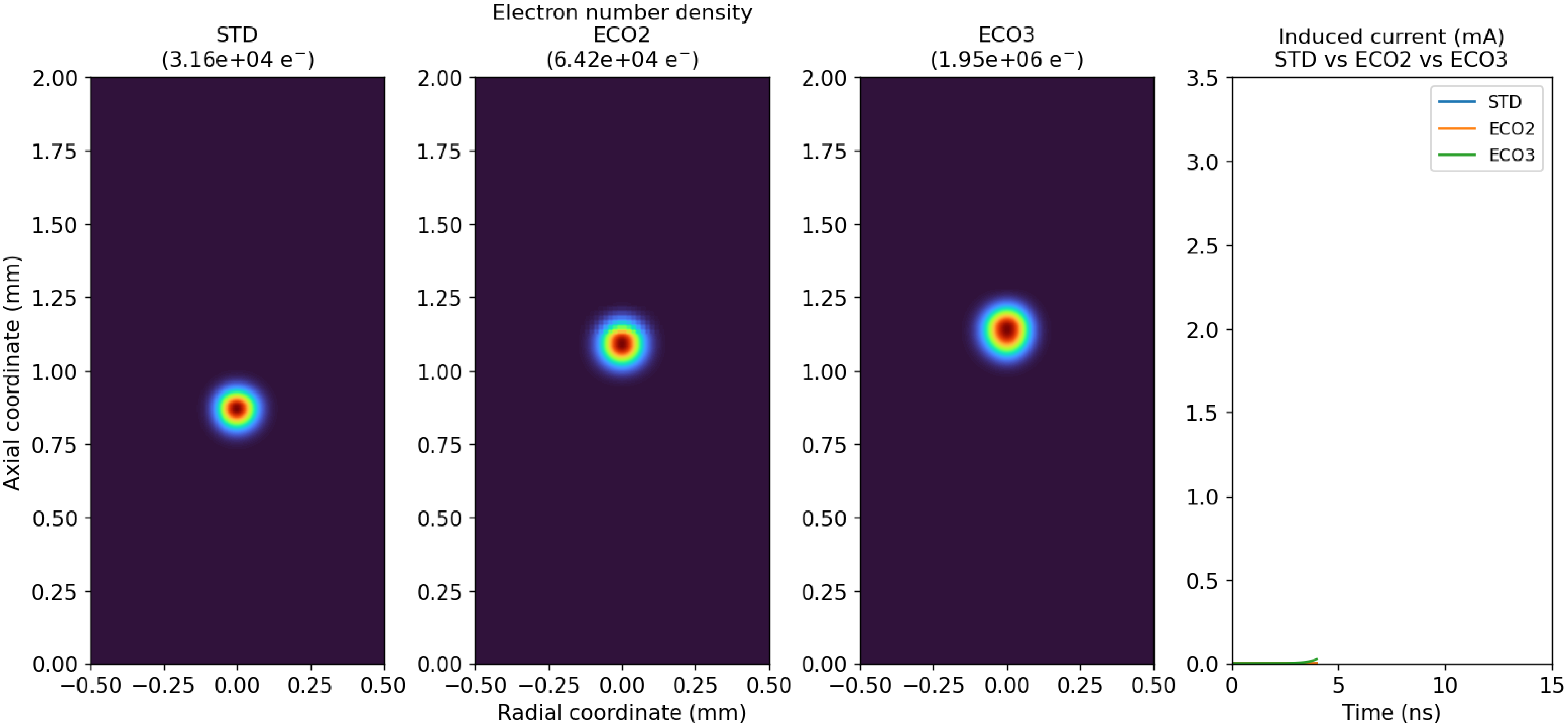
**Fluid model (bulk)**
**STD vs ECO2 vs ECO3**
**E/N = 200 Td**

**Time: 3 ns**



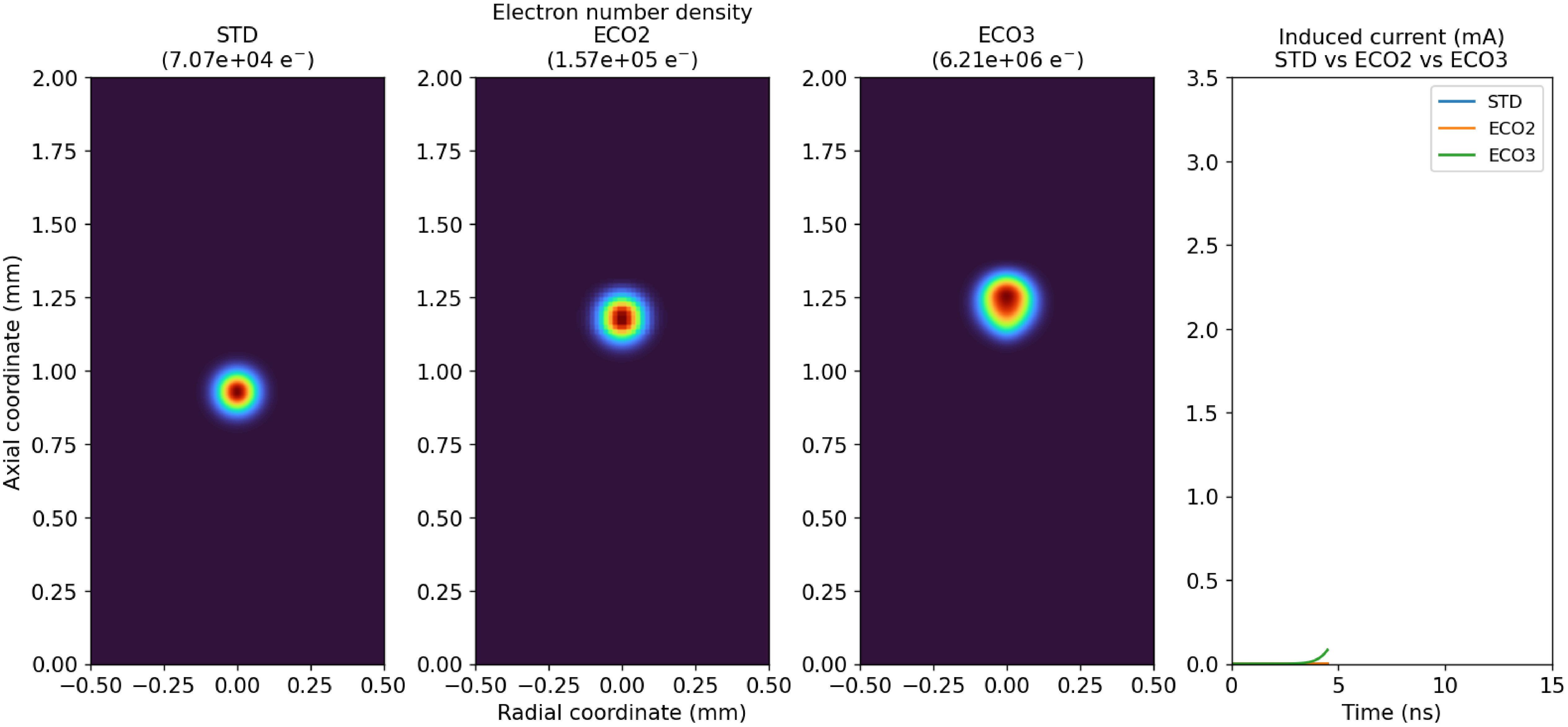
# Fluid model (bulk)
# STD vs ECO2 vs ECO3
# E/N = 200 Td

**Time: 4 ns**



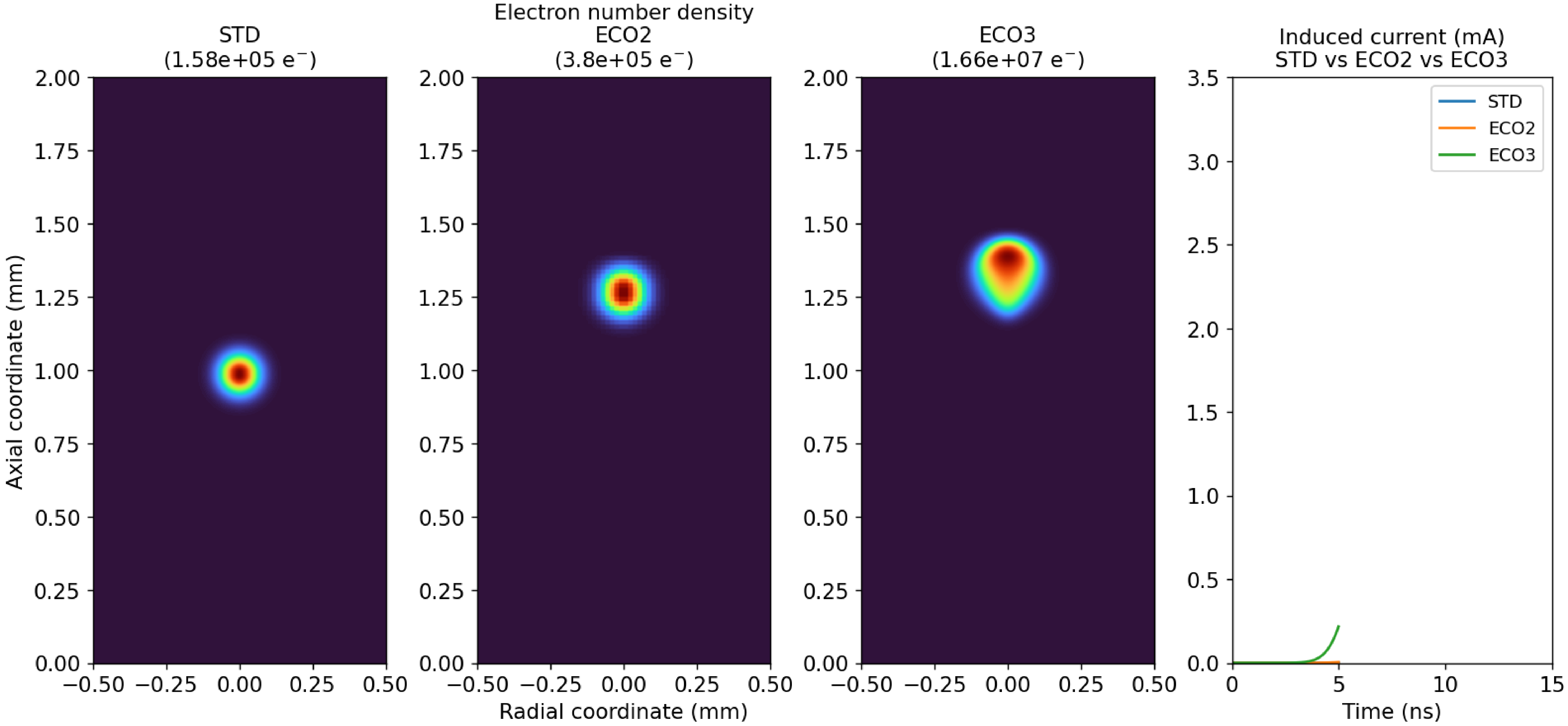
# Fluid model (bulk)
# STD vs ECO2 vs ECO3
# E/N = 200 Td

**Time: 4.5 ns**



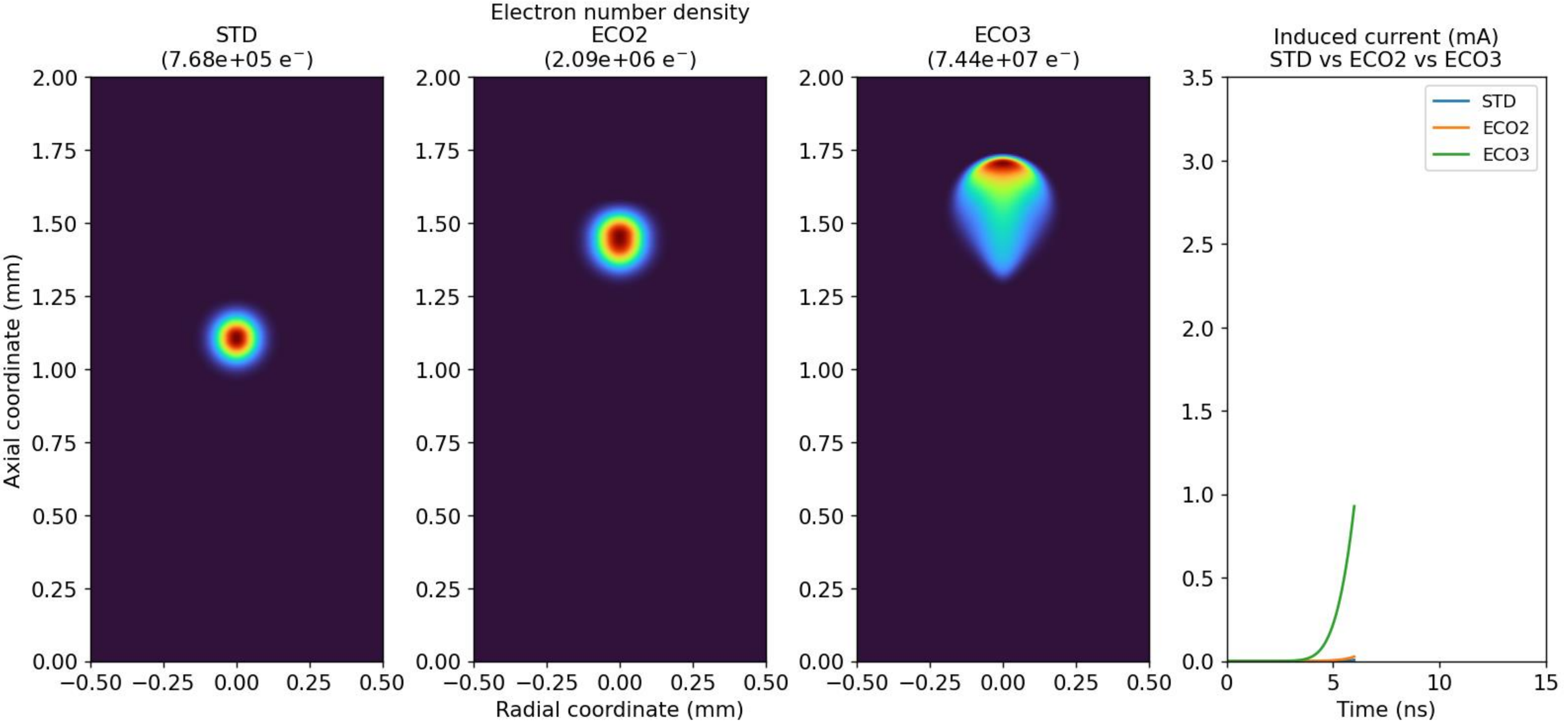
# Fluid model (bulk)
# STD vs ECO2 vs ECO3
# E/N = 200 Td

**Time: 5 ns**



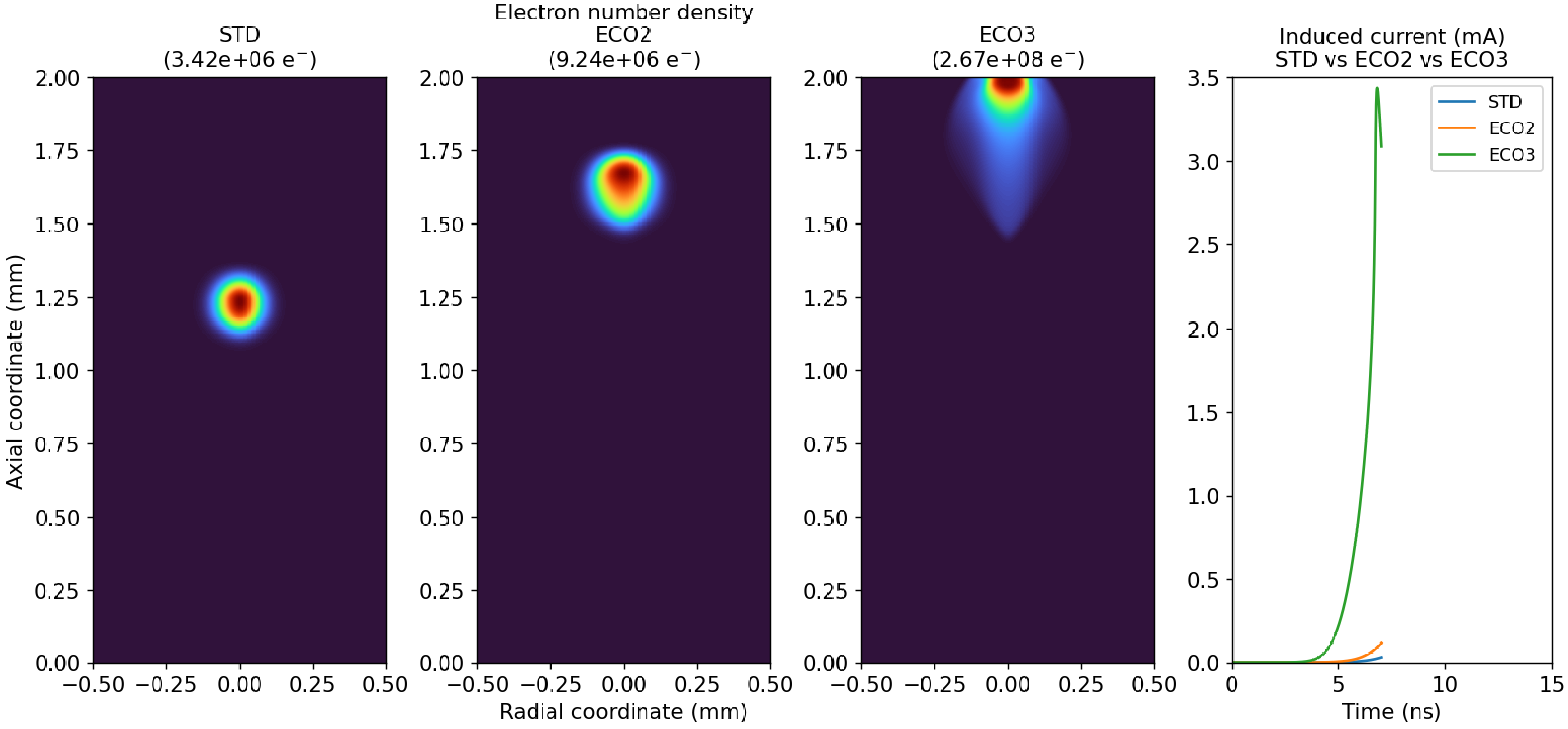
# Fluid model (bulk)
# STD vs ECO2 vs ECO3
# E/N = 200 Td

**Time: 6 ns**



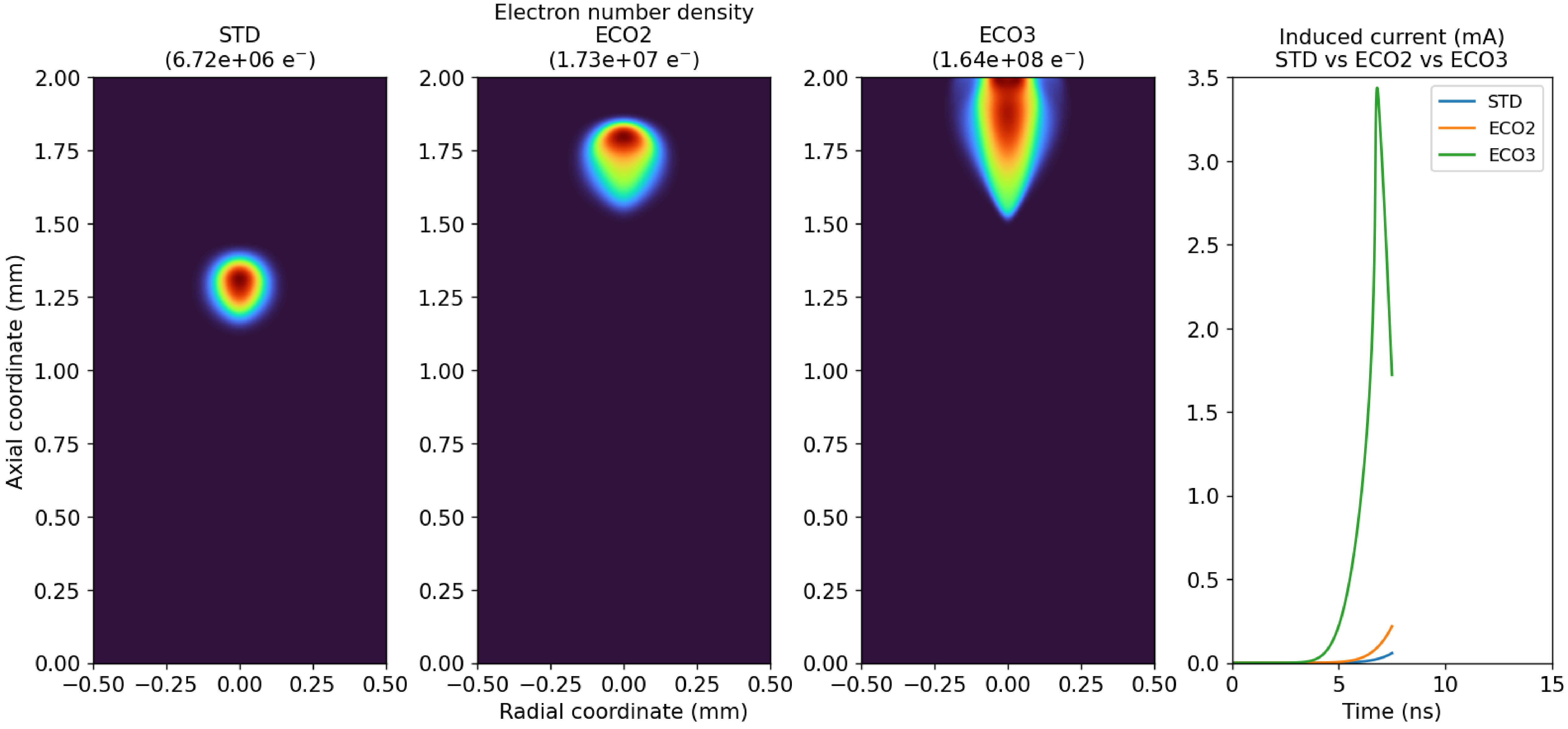
# Fluid model (bulk)
# STD vs ECO2 vs ECO3
# E/N = 200 Td

**Time: 7 ns**



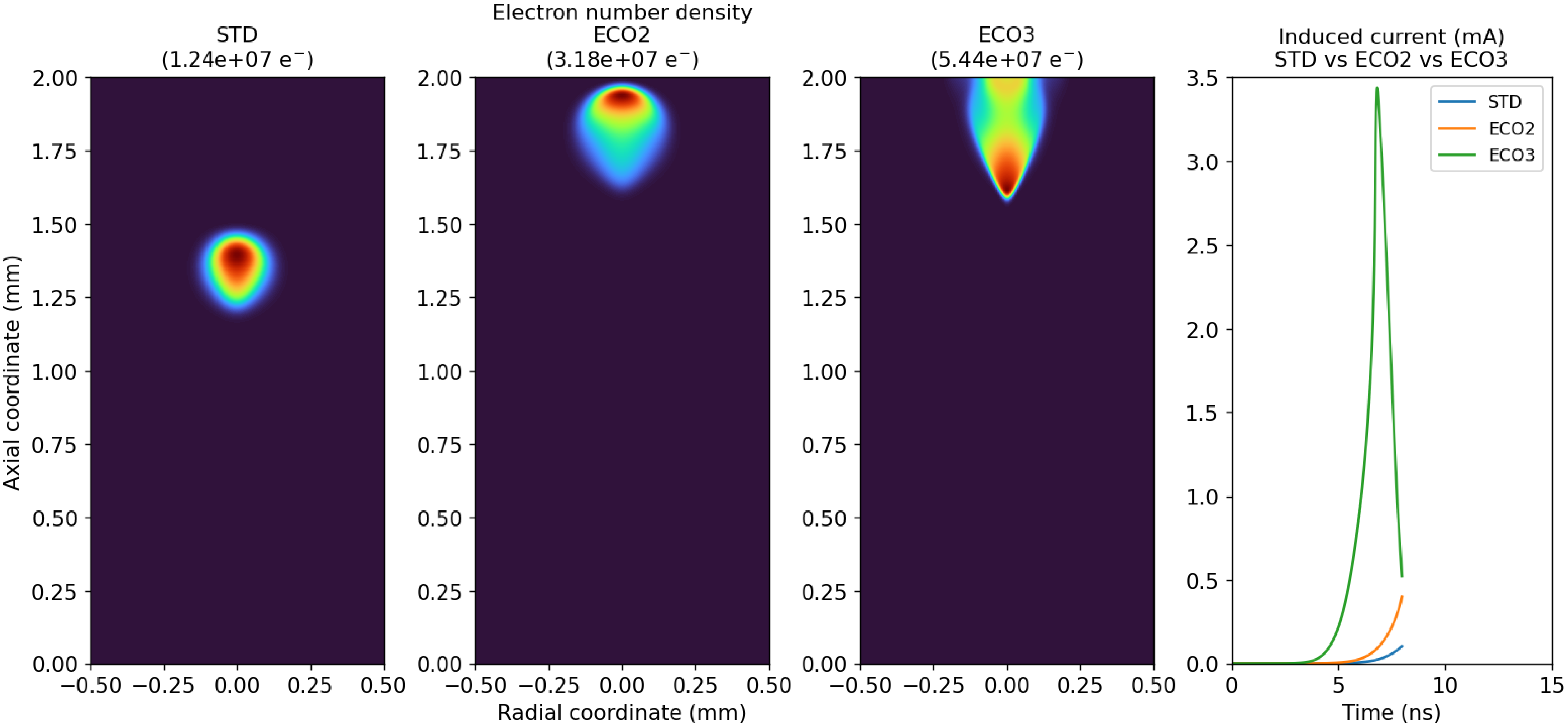
# Fluid model (bulk)
# STD vs ECO2 vs ECO3
# E/N = 200 Td

Time: 7.5 ns



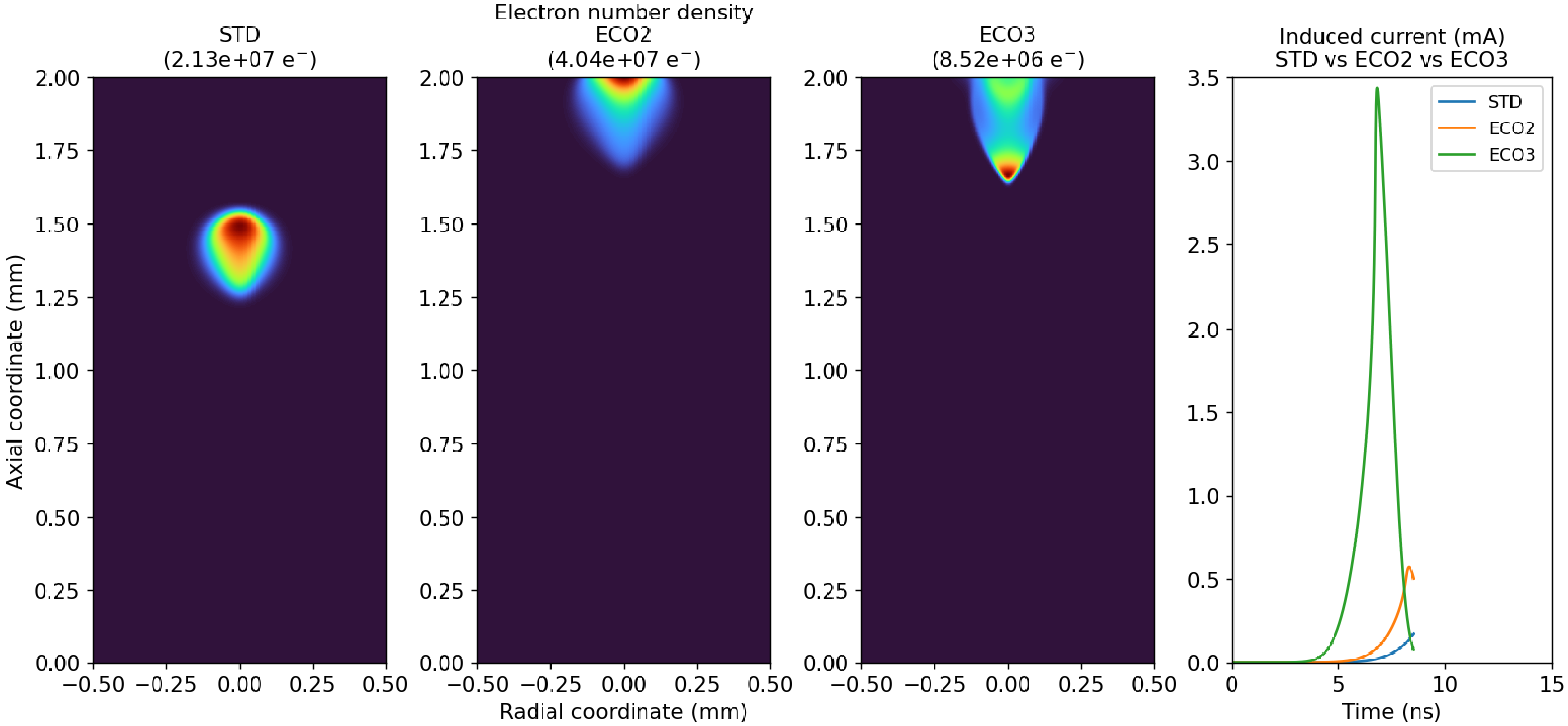
# Fluid model (bulk)
# STD vs ECO2 vs ECO3
# E/N = 200 Td

**Time: 8 ns**



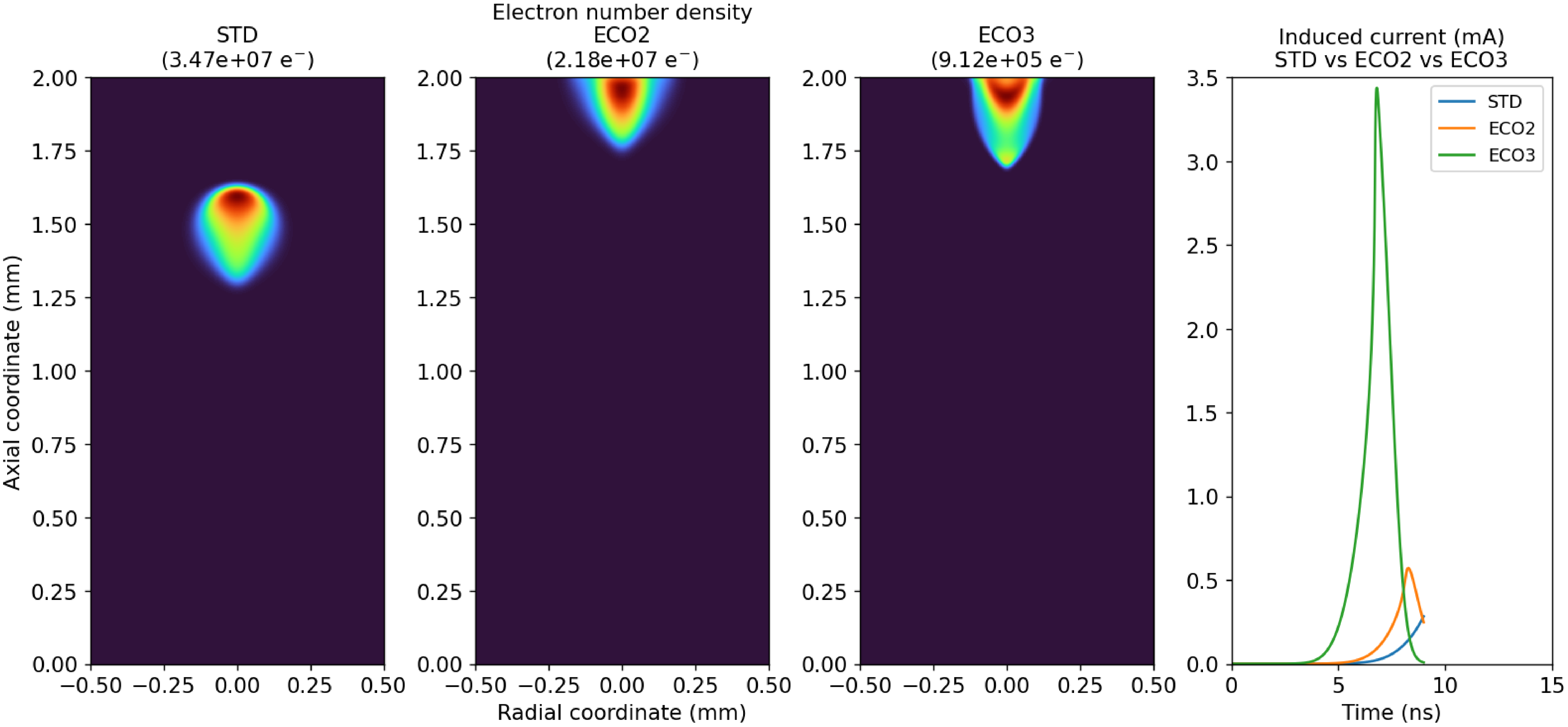
# Fluid model (bulk)
# STD vs ECO2 vs ECO3
# E/N = 200 Td

**Time: 8.5 ns**



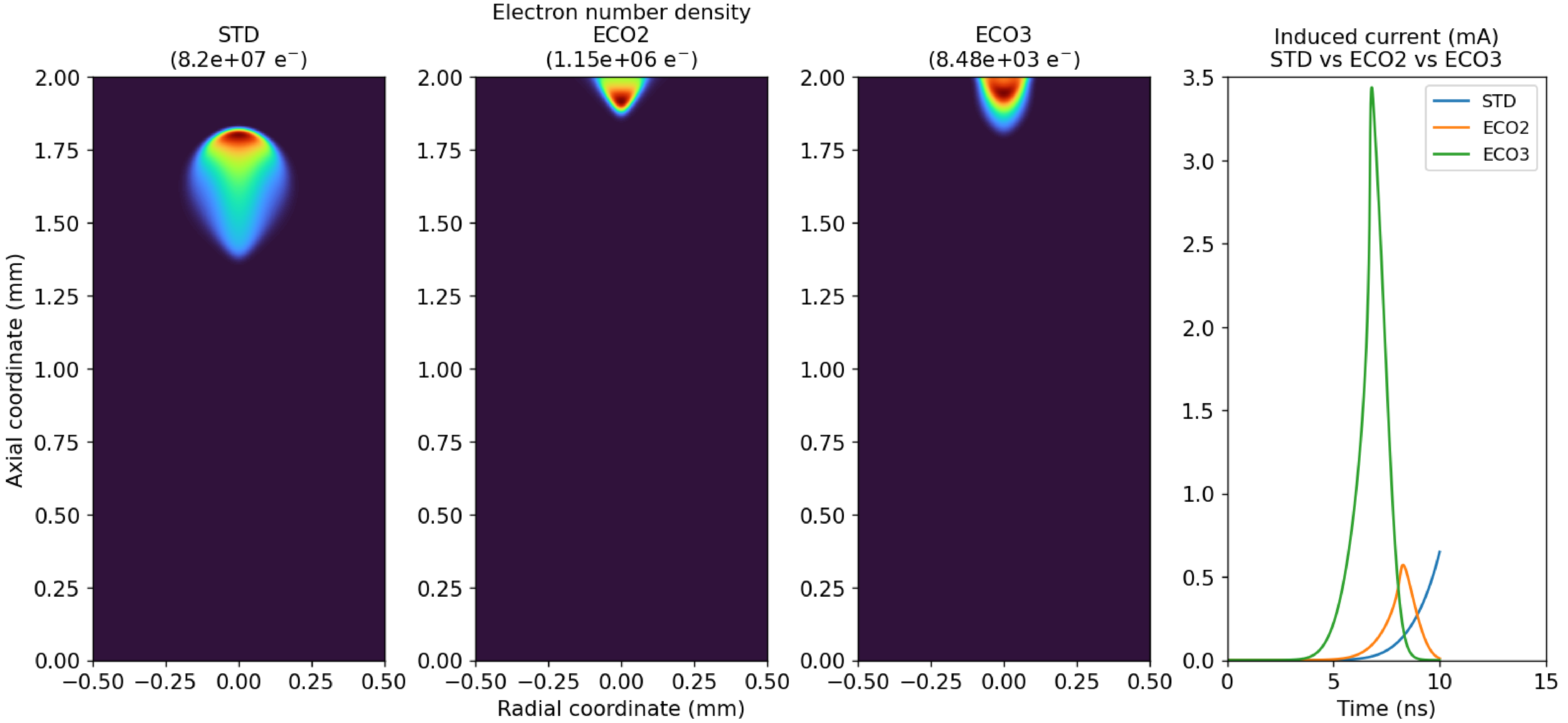
**Fluid model (bulk)**
**STD vs ECO2 vs ECO3**
**E/N = 200 Td**

**Time: 9 ns**



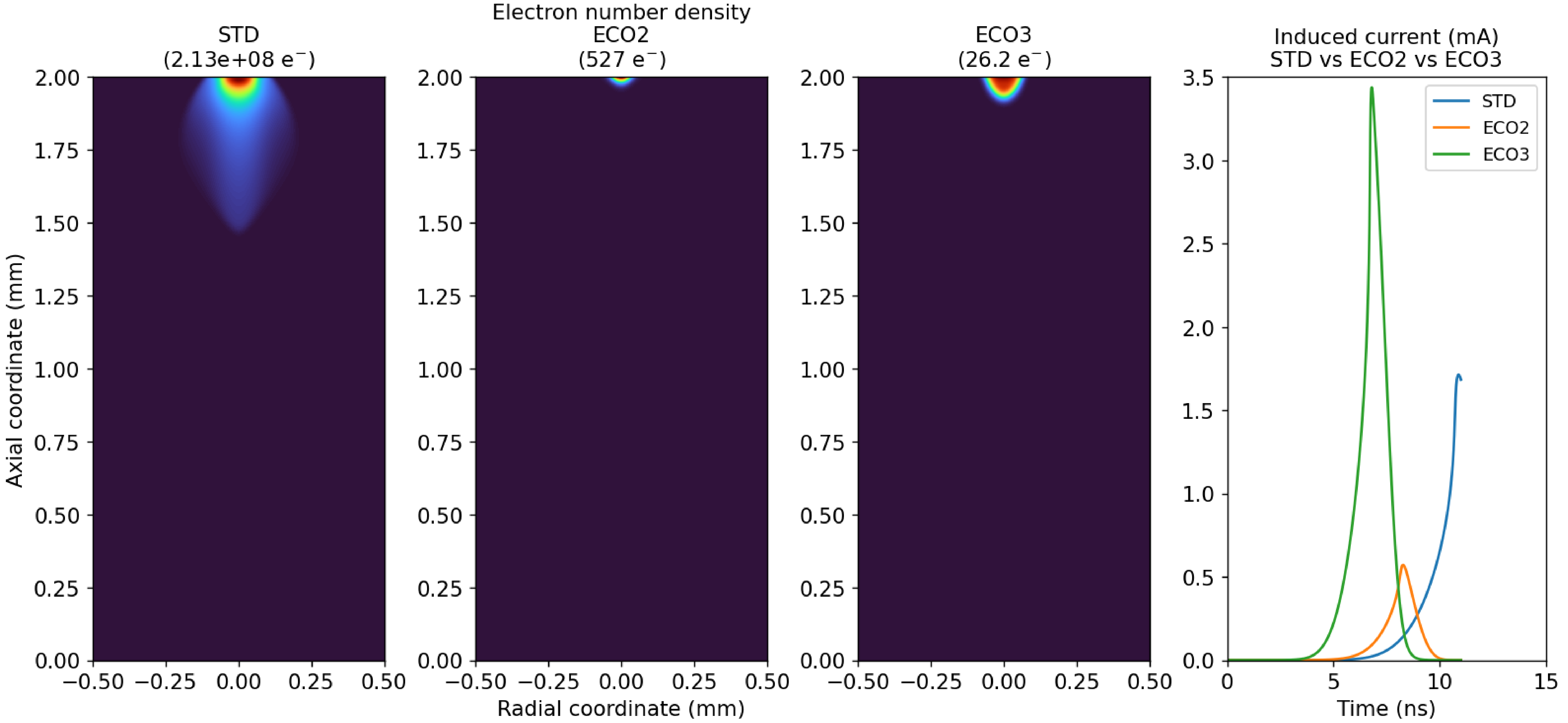
# Fluid model (bulk)
# STD vs ECO2 vs ECO3
# E/N = 200 Td

**Time: 10 ns**



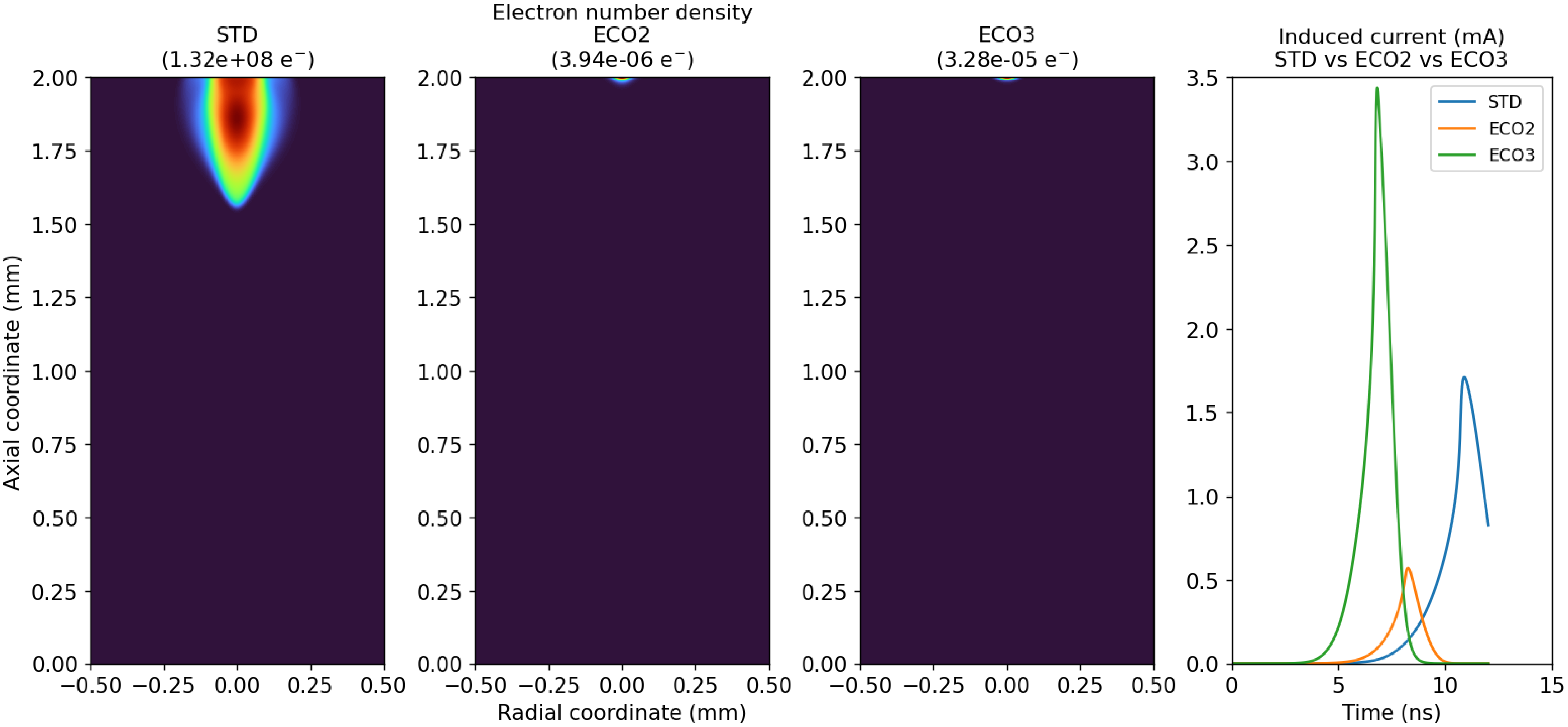
# Fluid model (bulk)
# STD vs ECO2 vs ECO3
# E/N = 200 Td

**Time: 11 ns**



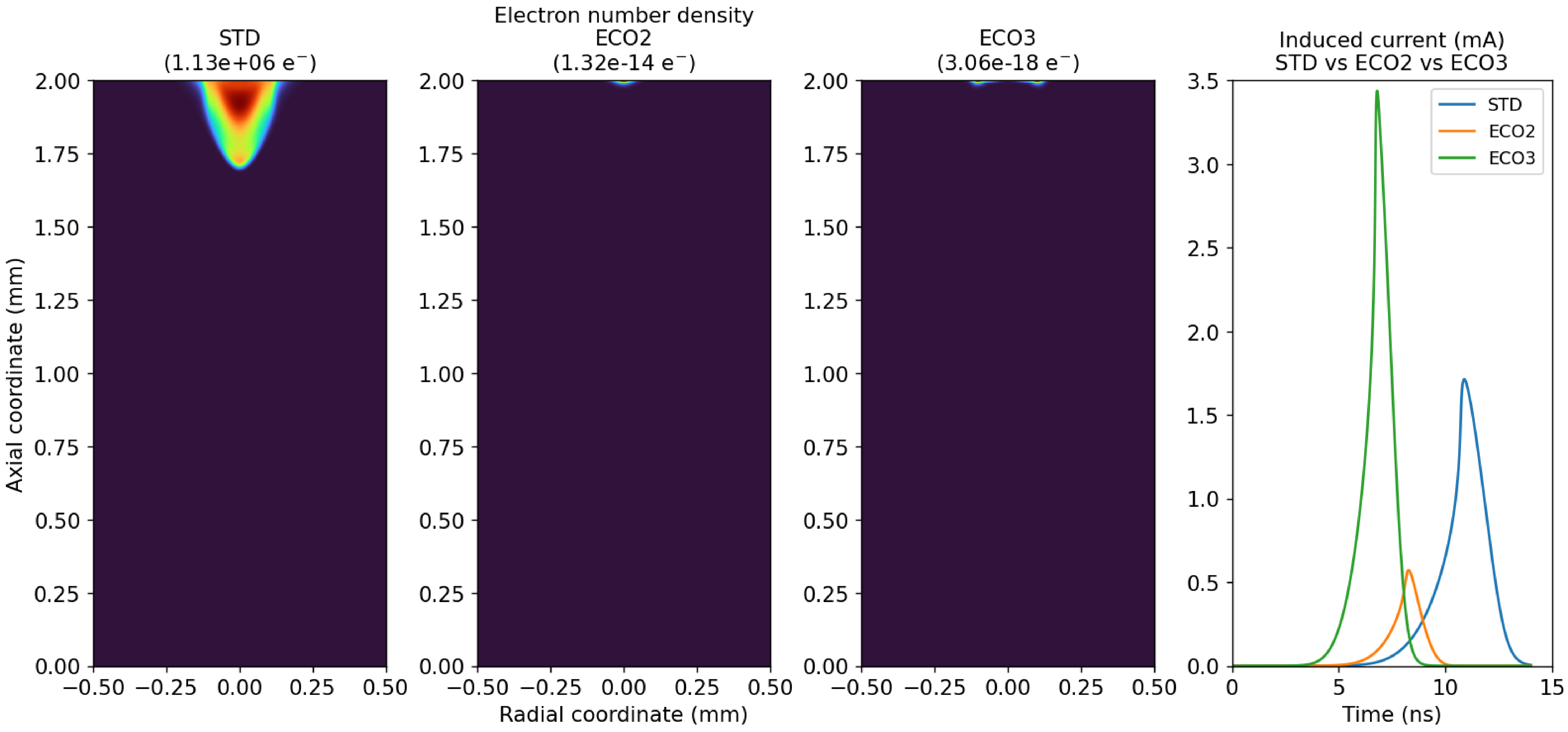
# Fluid model (bulk)
# STD vs ECO2 vs ECO3
# E/N = 200 Td

**Time: 12 ns**



**Fluid model (bulk)**
**STD vs ECO2 vs ECO3**
**E/N = 200 Td**

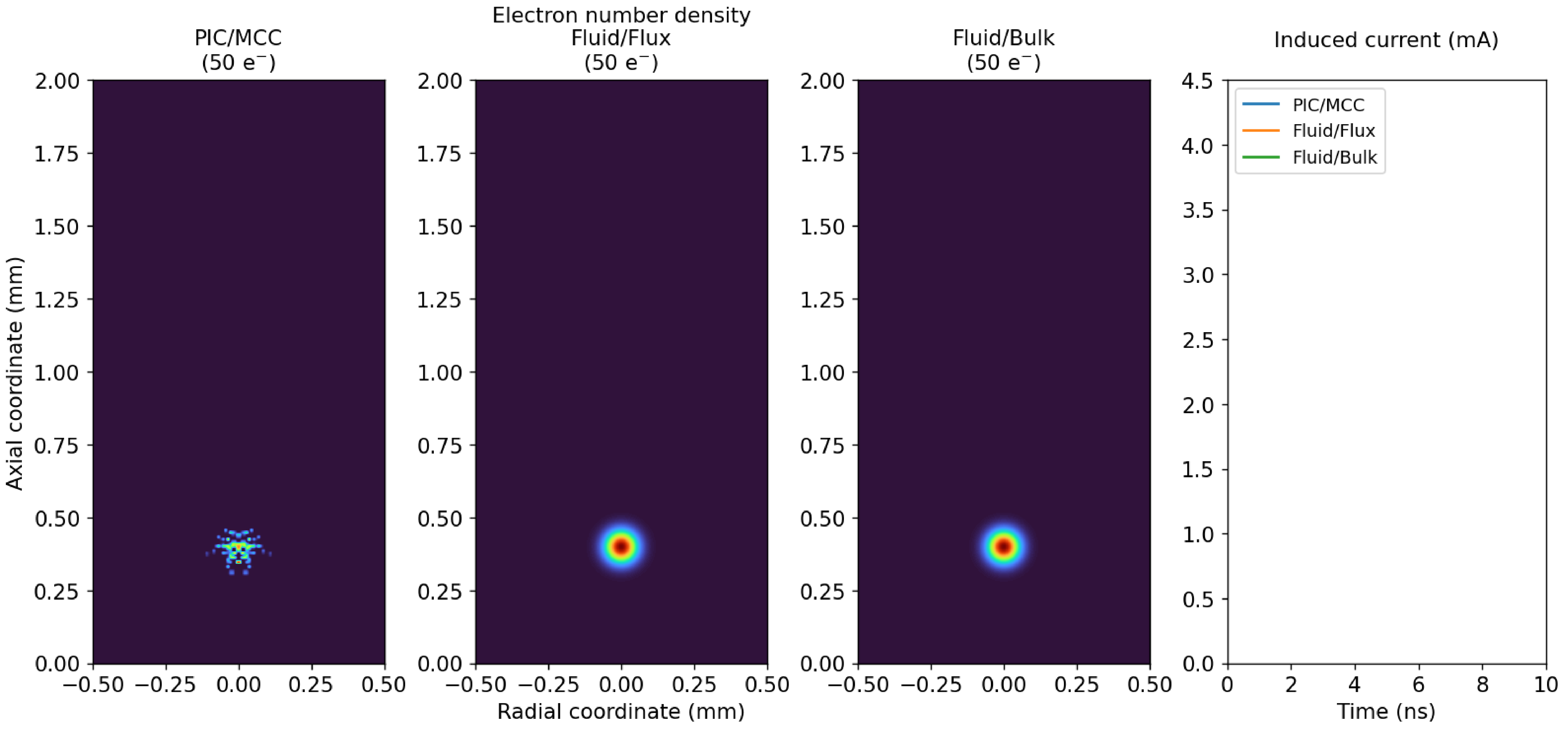
**Time: 14 ns**



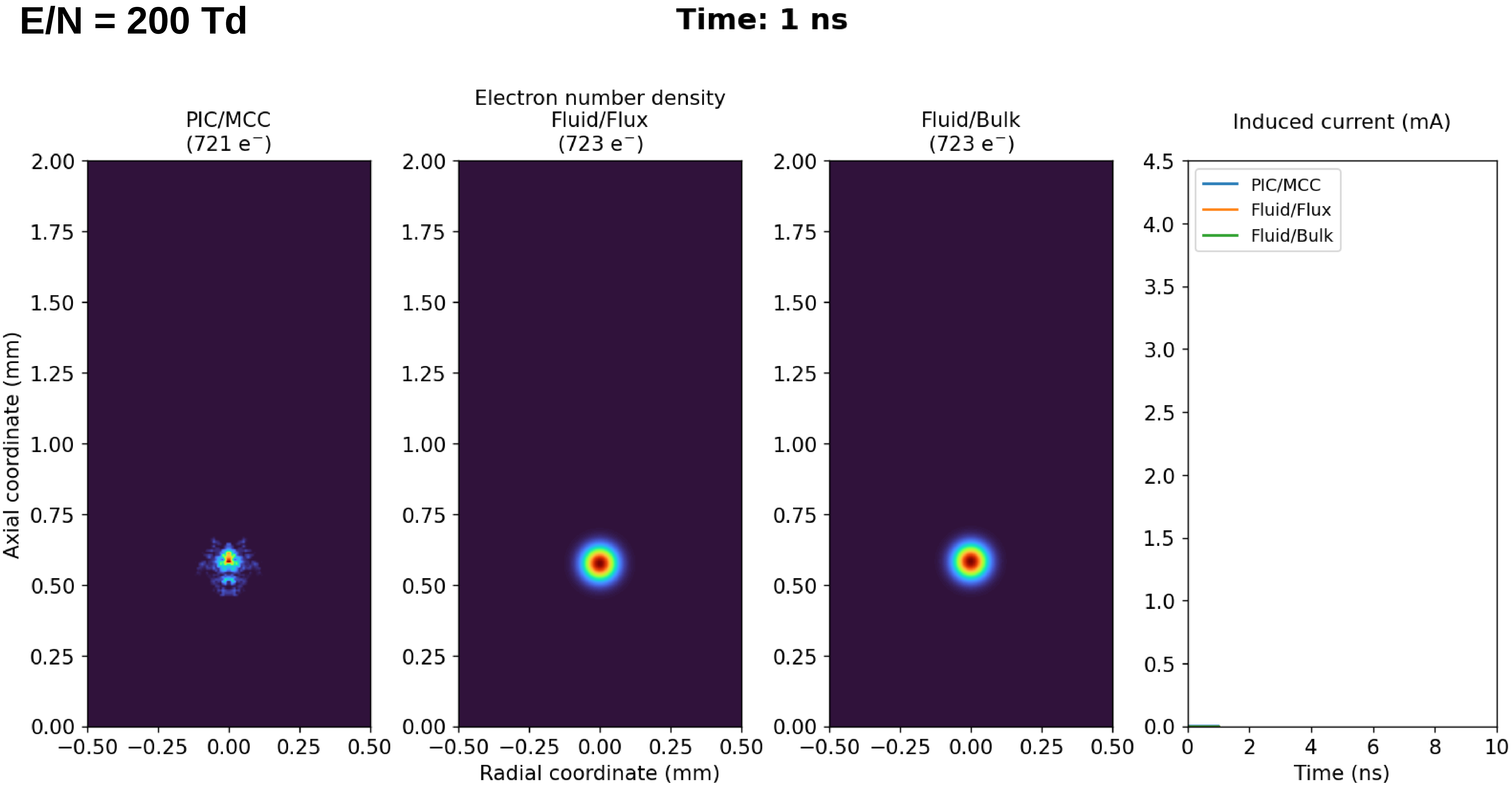
# PIC/MCC VS FLUID MODEL
# E/N = 200 Td

# PIC/MCC vs Fluid model
# E/N = 200 Td

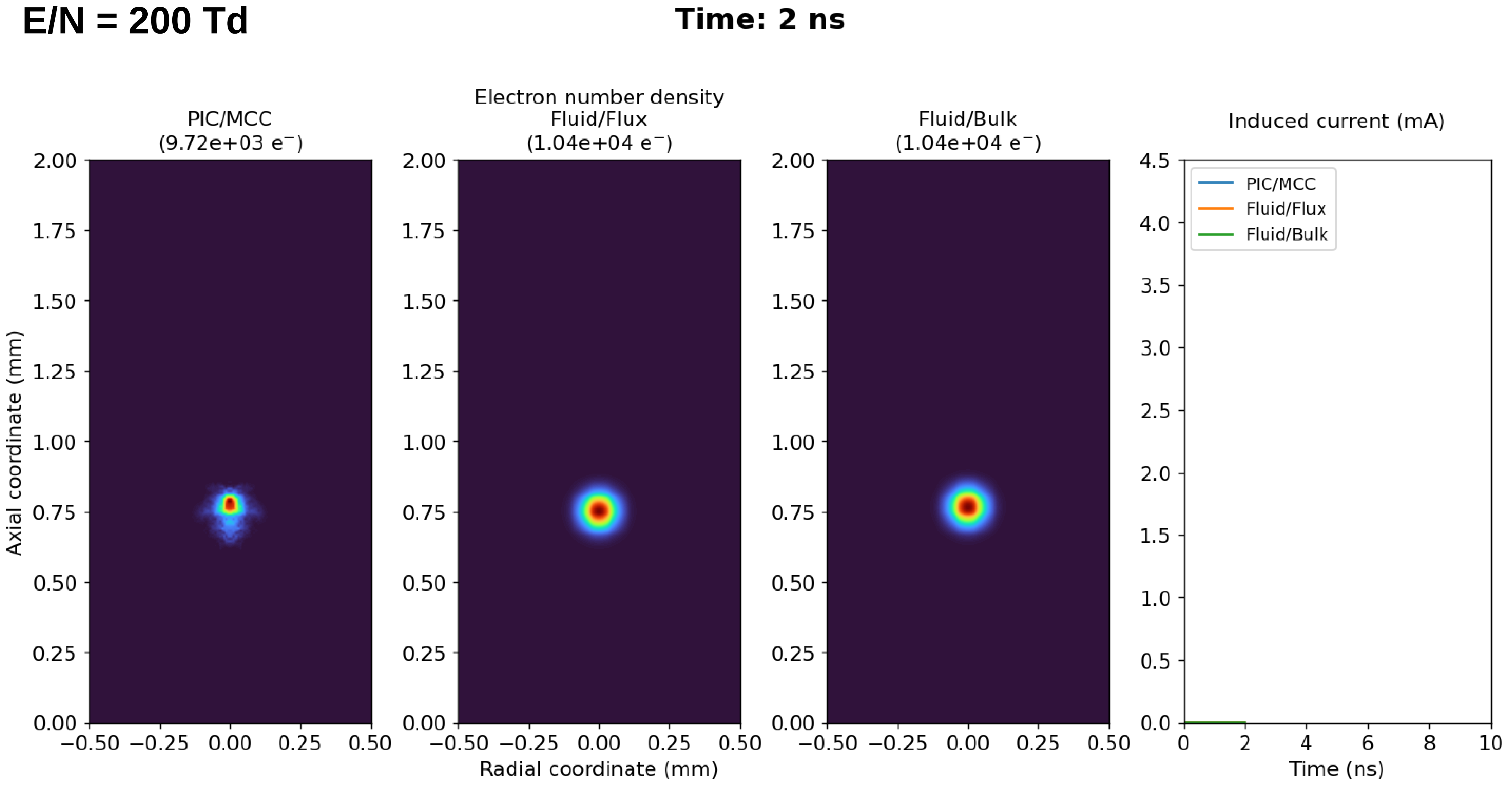
**Time: 0 ns**



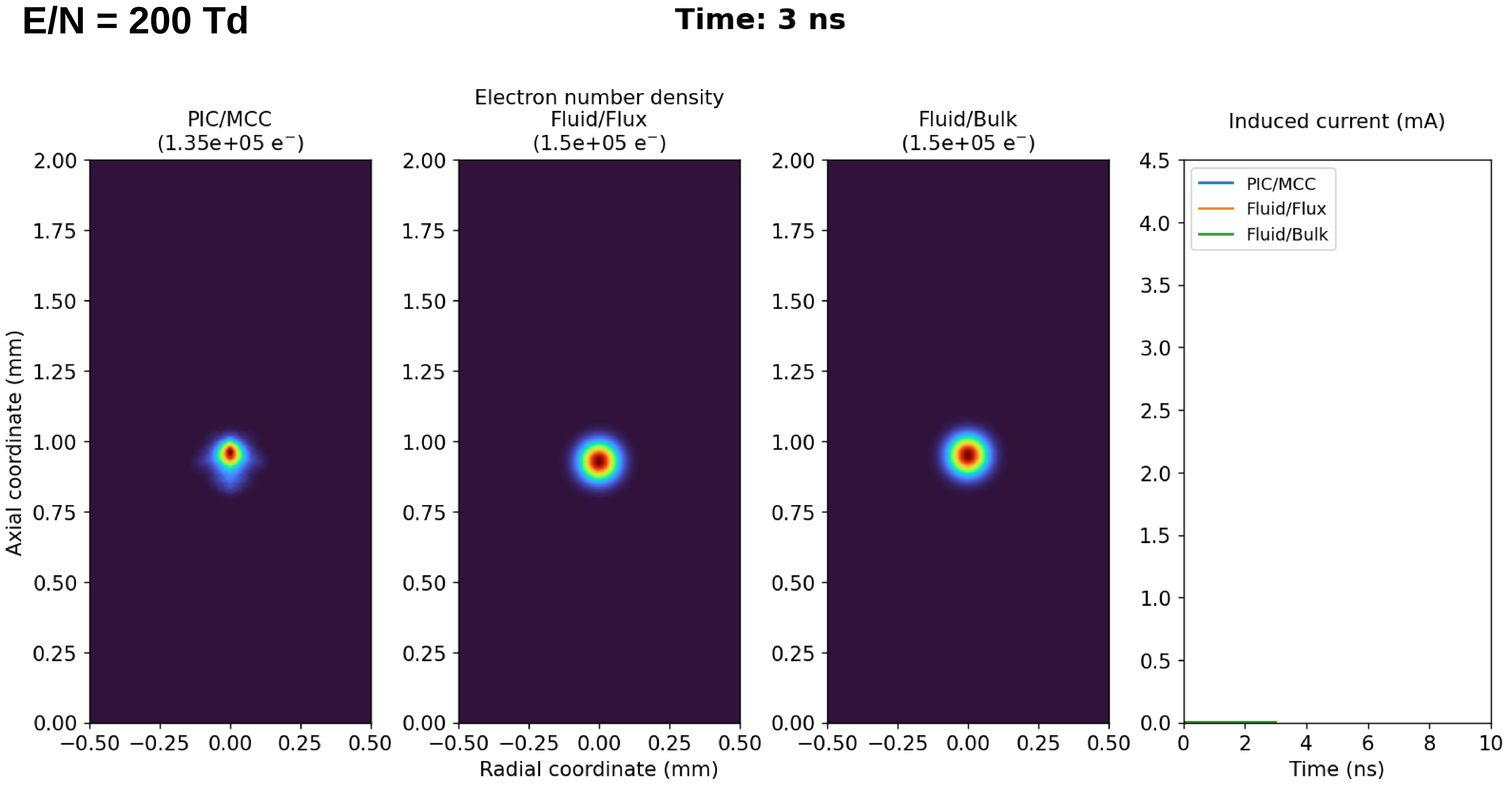
# PIC/MCC vs Fluid model
# E/N = 200 Td



# PIC/MCC vs Fluid model
# E/N = 200 Td

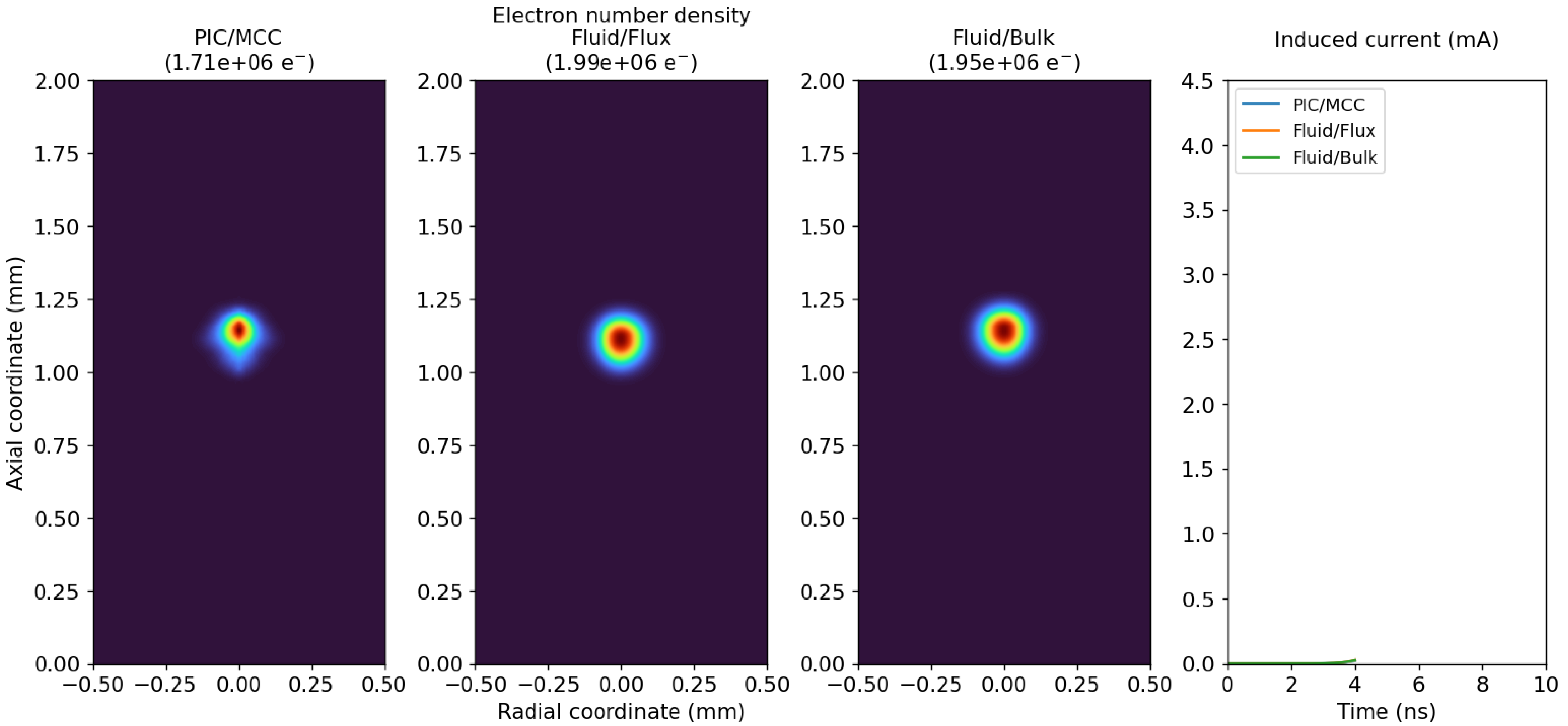


# PIC/MCC vs Fluid model
# E/N = 200 Td



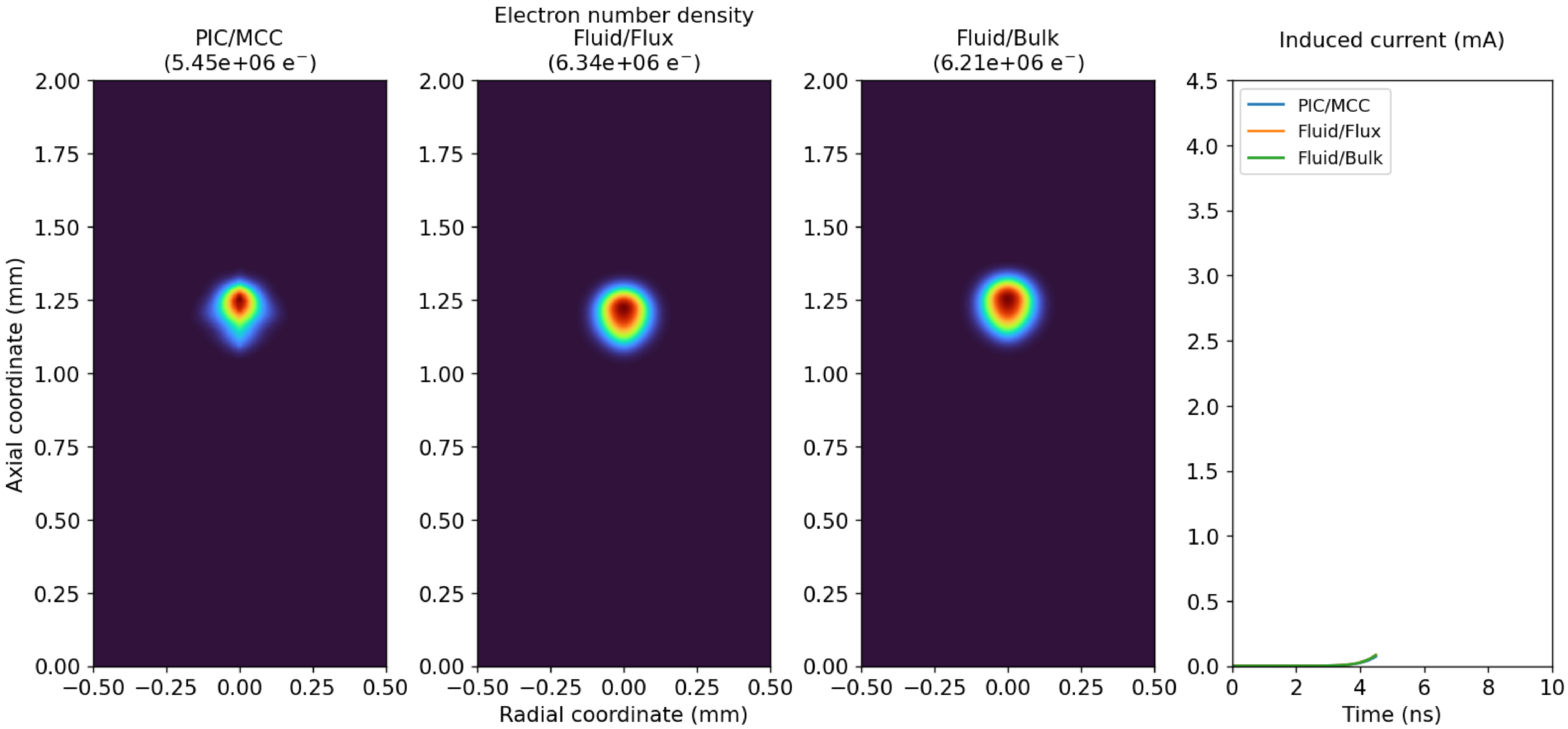
# PIC/MCC vs Fluid model
# E/N = 200 Td

**Time: 4 ns**

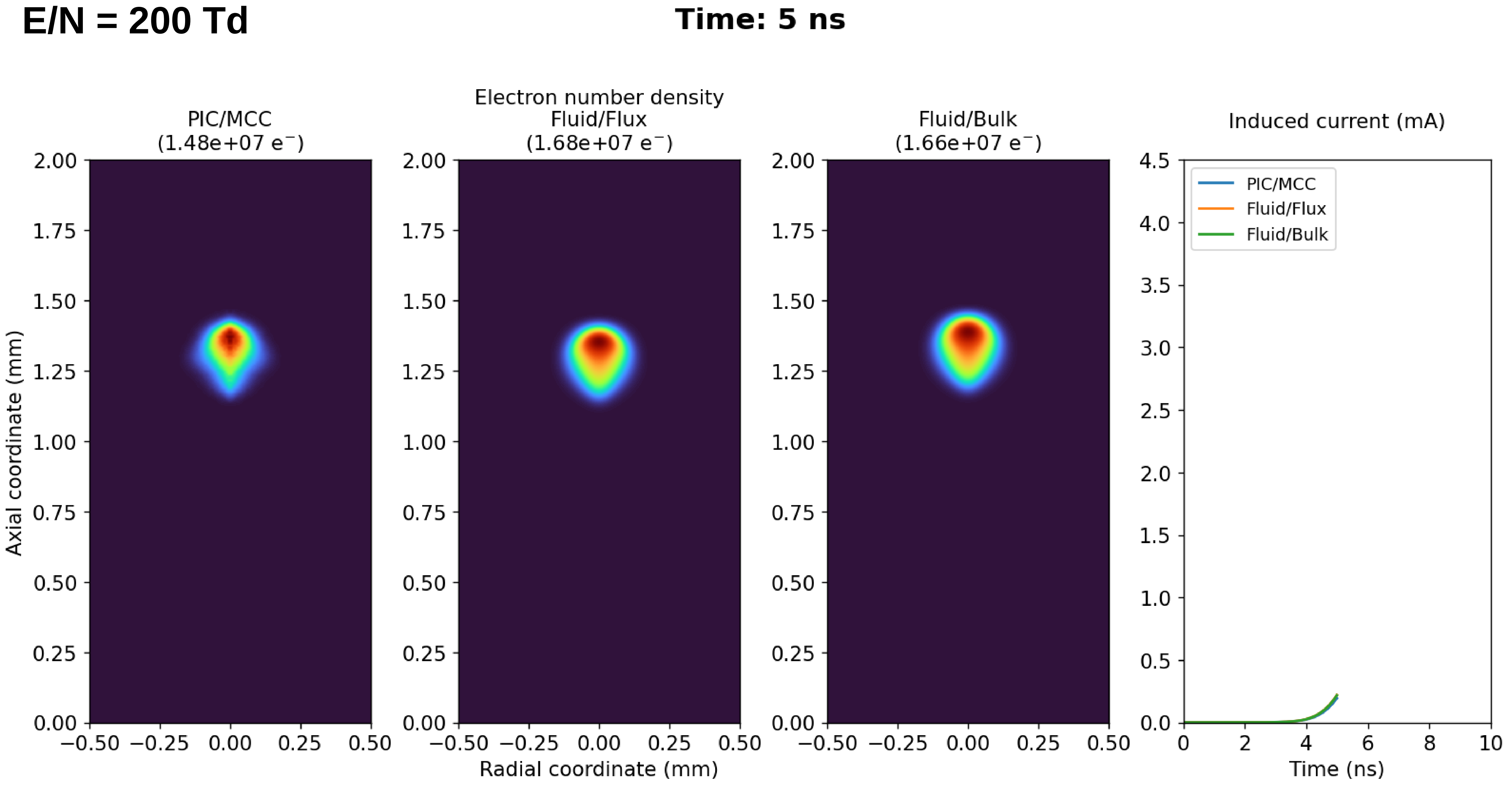


# PIC/MCC vs Fluid model
# E/N = 200 Td

**Time: 4.5 ns**

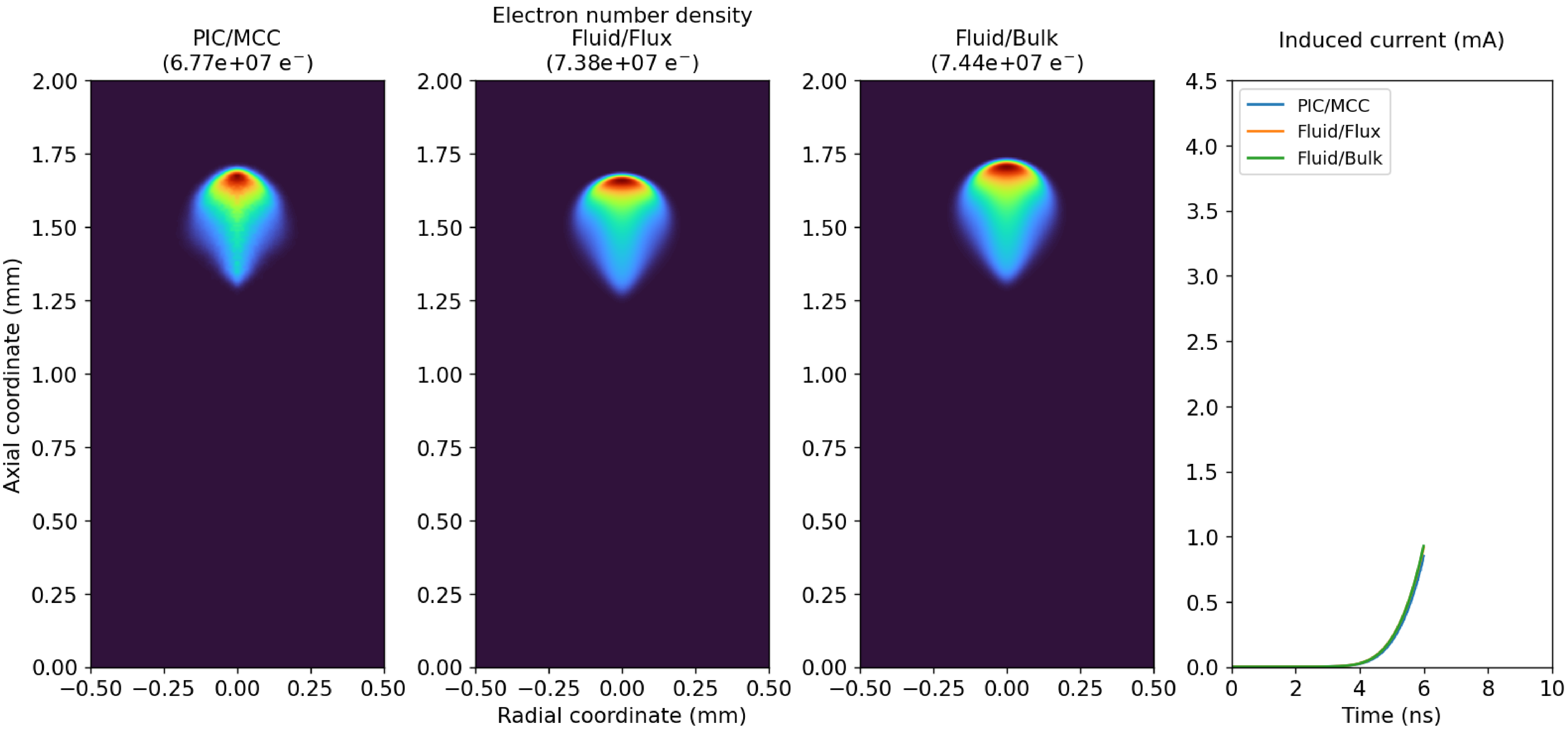


# PIC/MCC vs Fluid model
# E/N = 200 Td



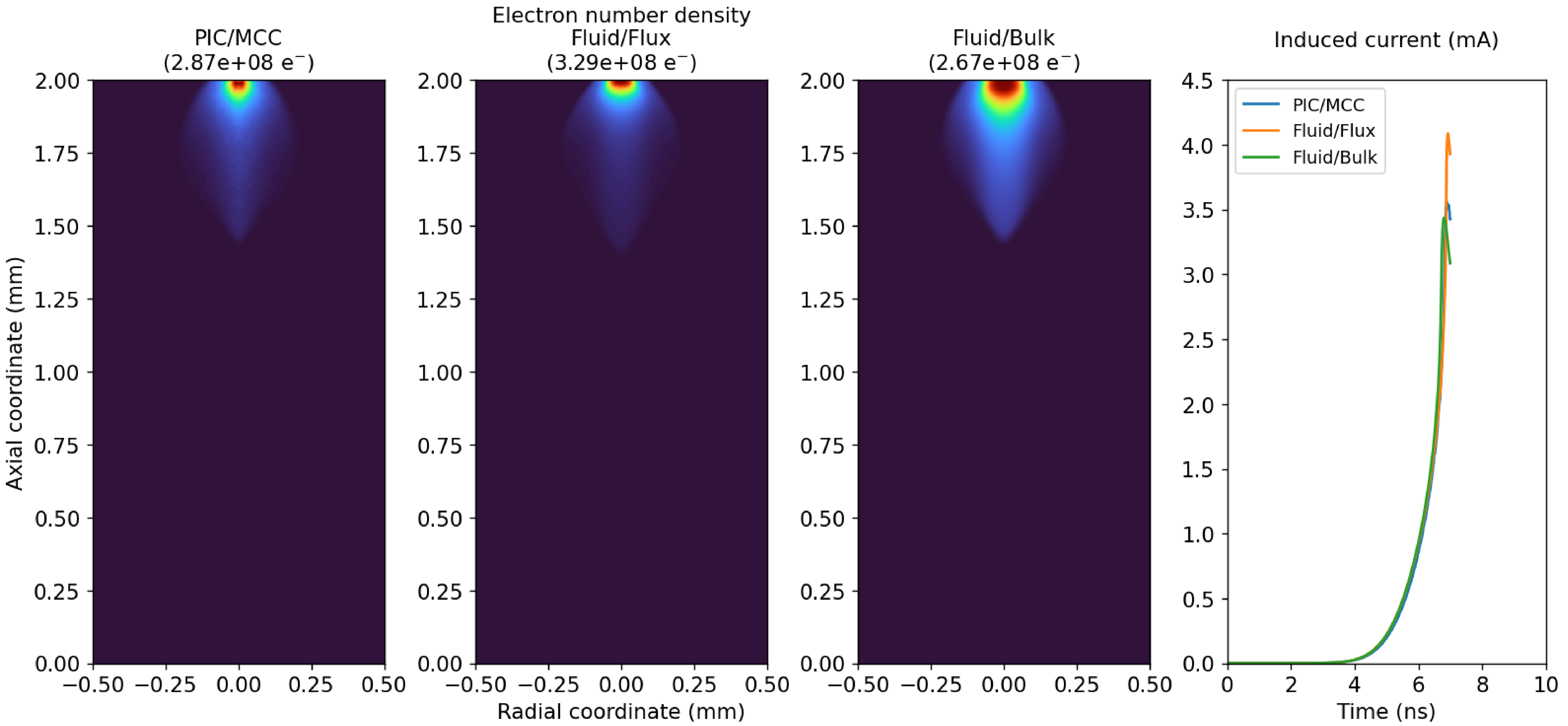
# PIC/MCC vs Fluid model
# E/N = 200 Td

**Time: 6 ns**

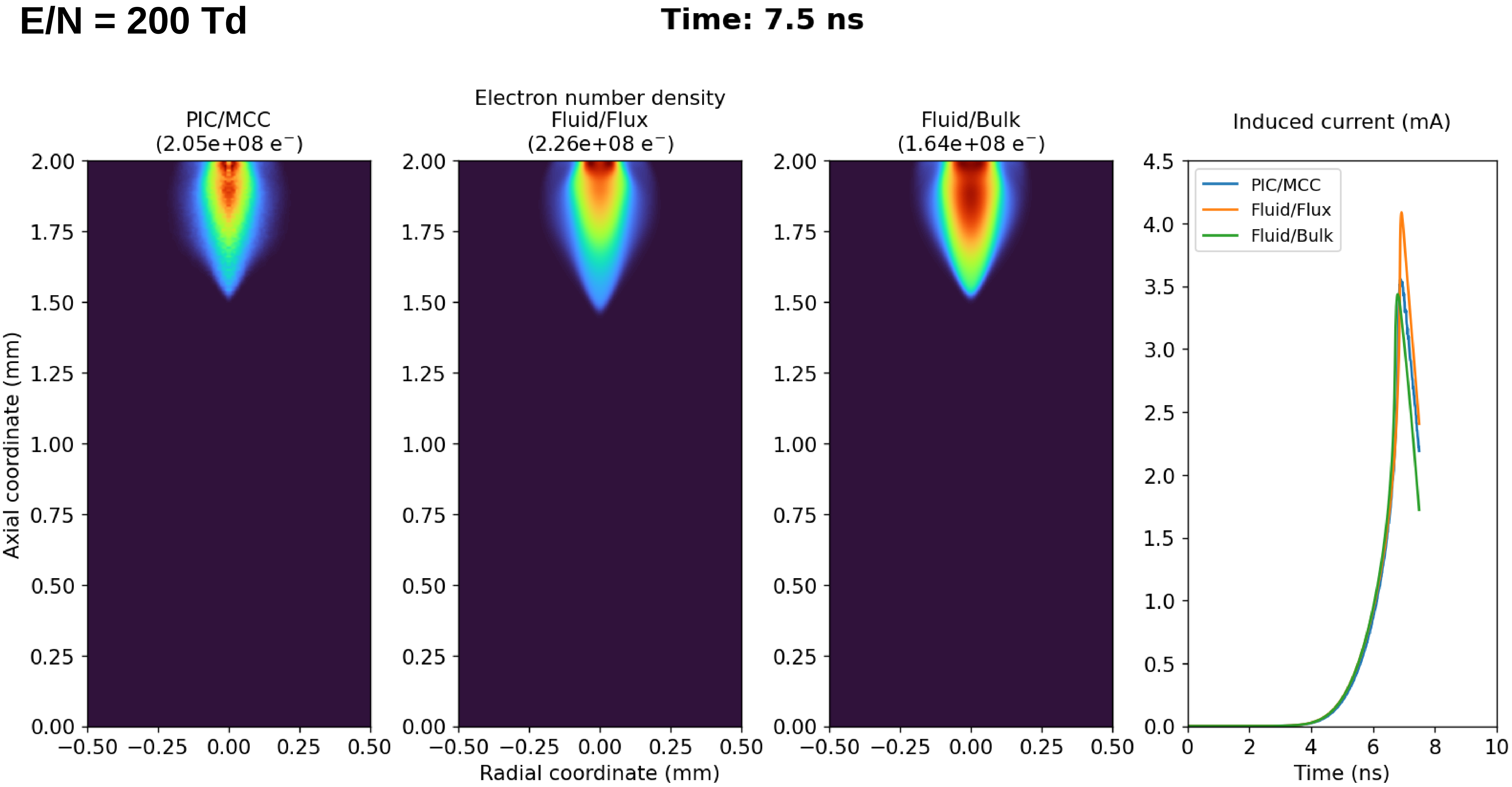


# PIC/MCC vs Fluid model
# E/N = 200 Td

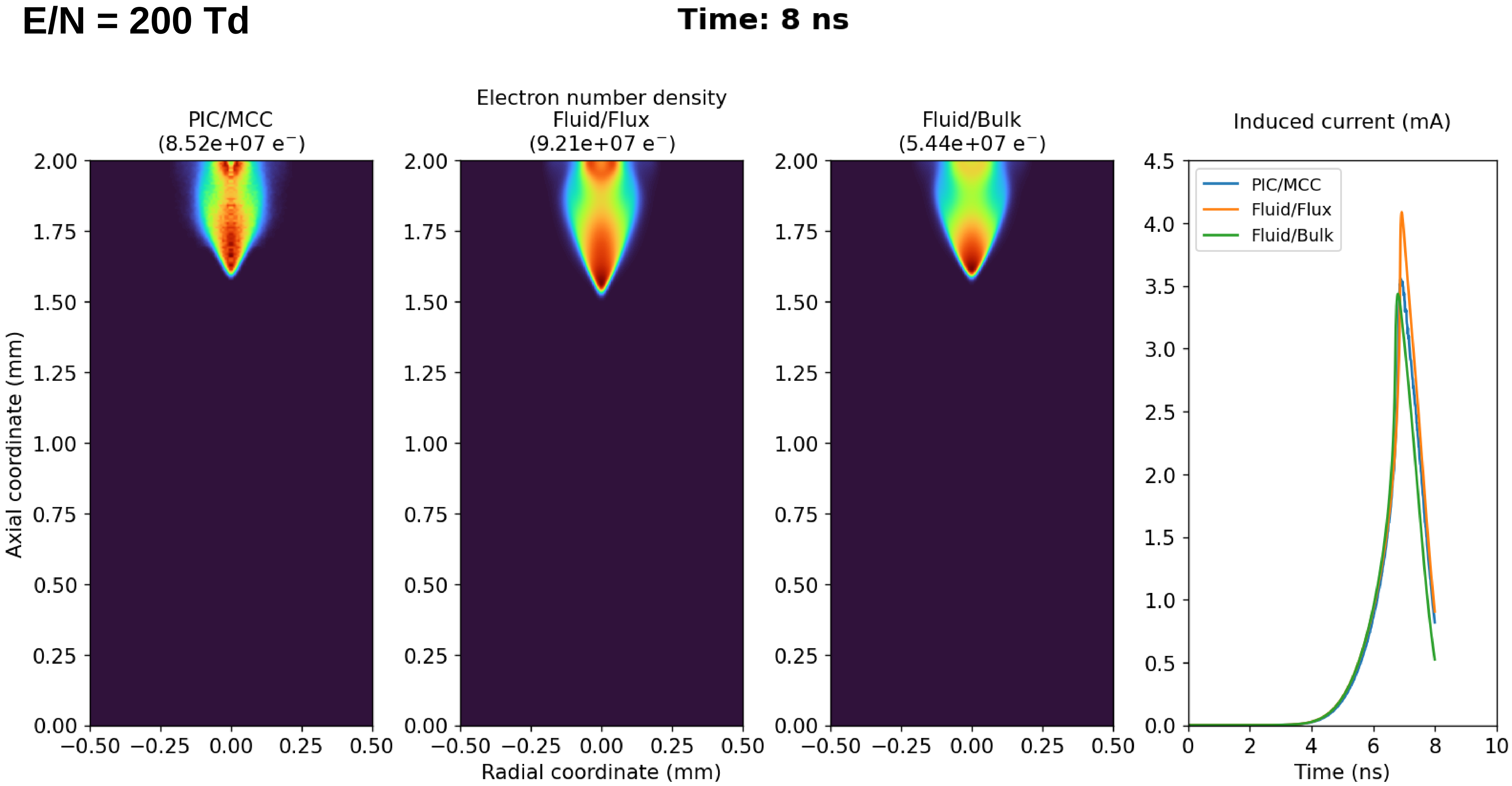
**Time: 7 ns**



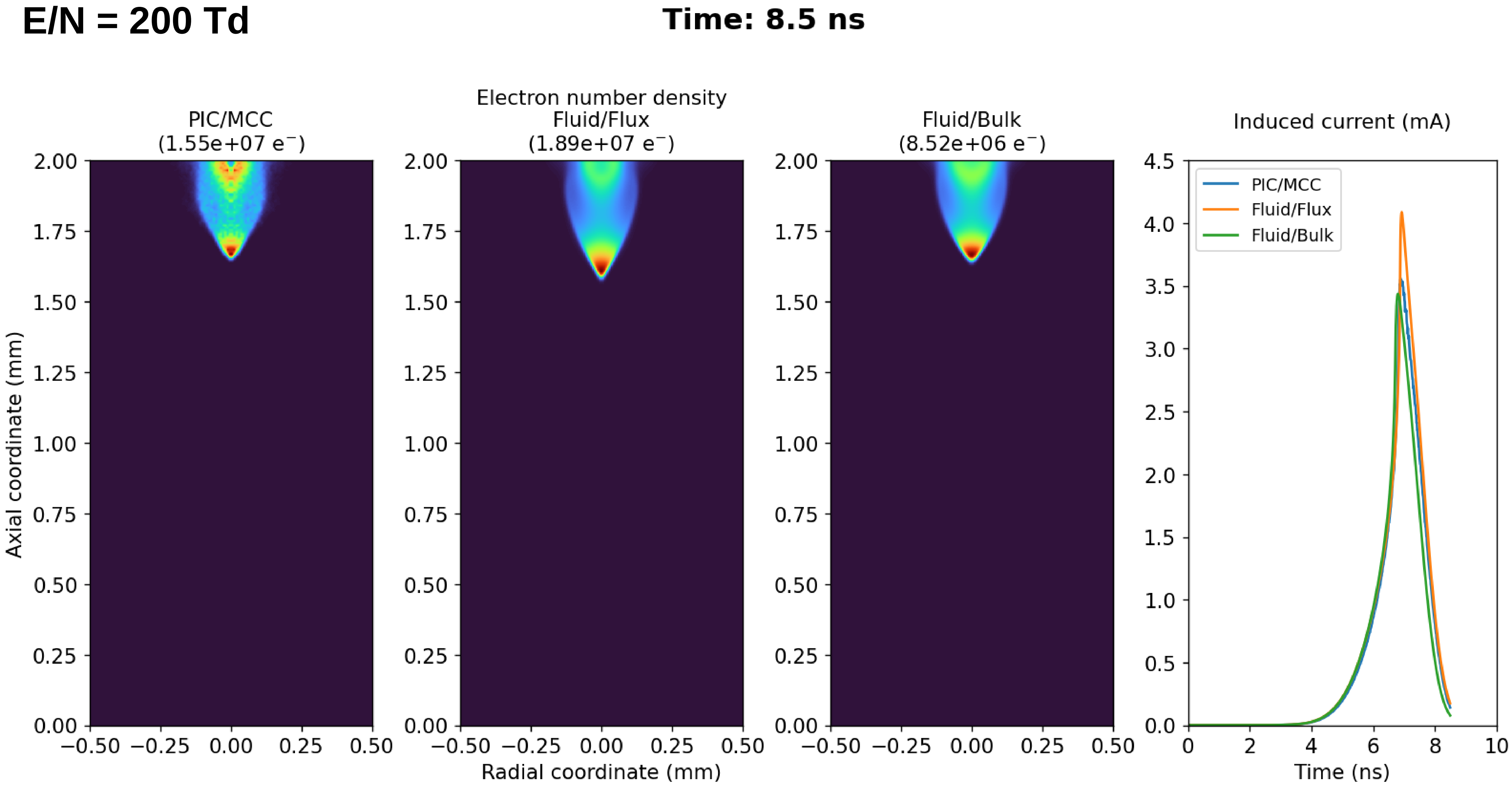
# PIC/MCC vs Fluid model
# E/N = 200 Td



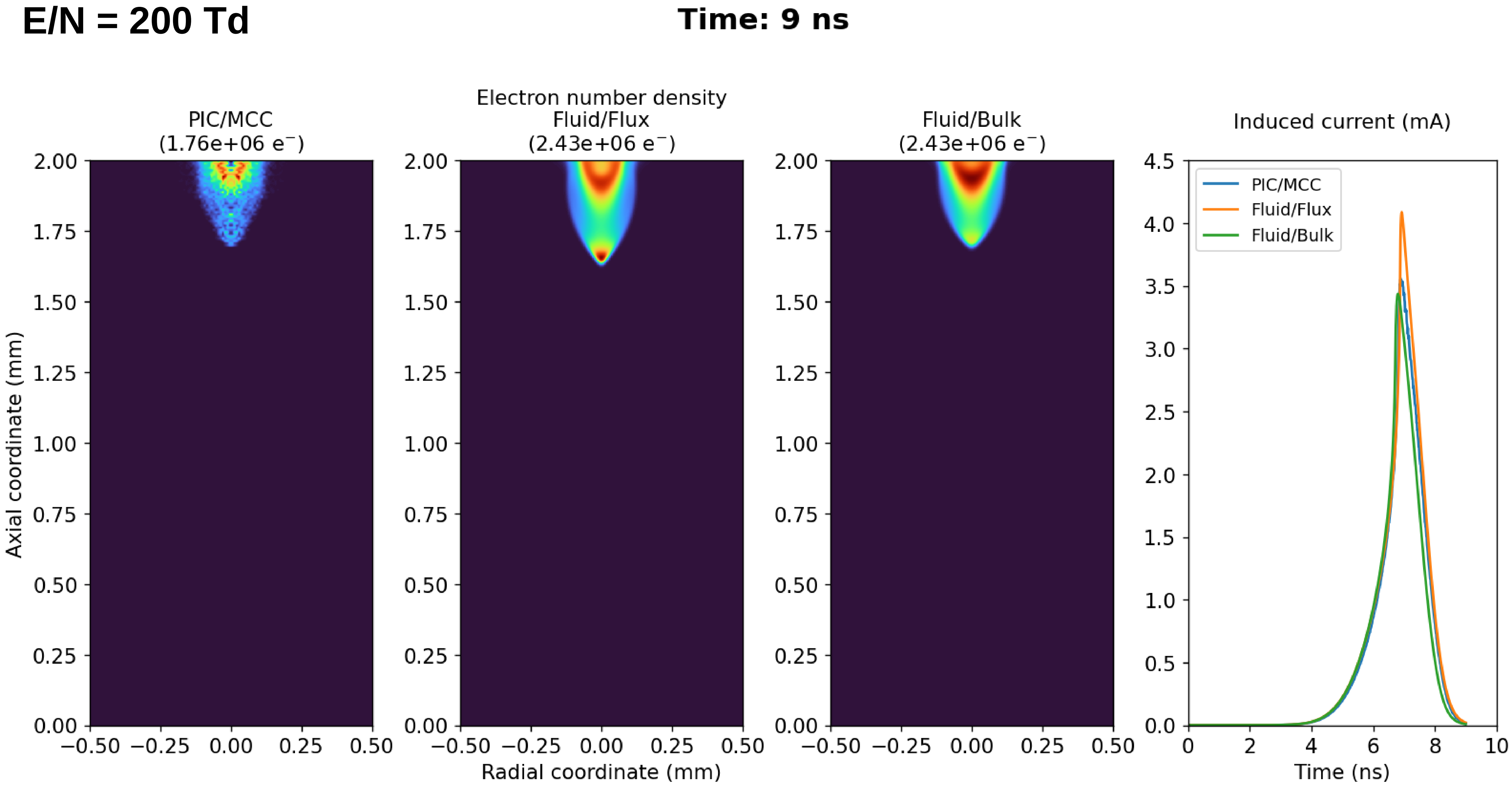
# PIC/MCC vs Fluid model
# E/N = 200 Td



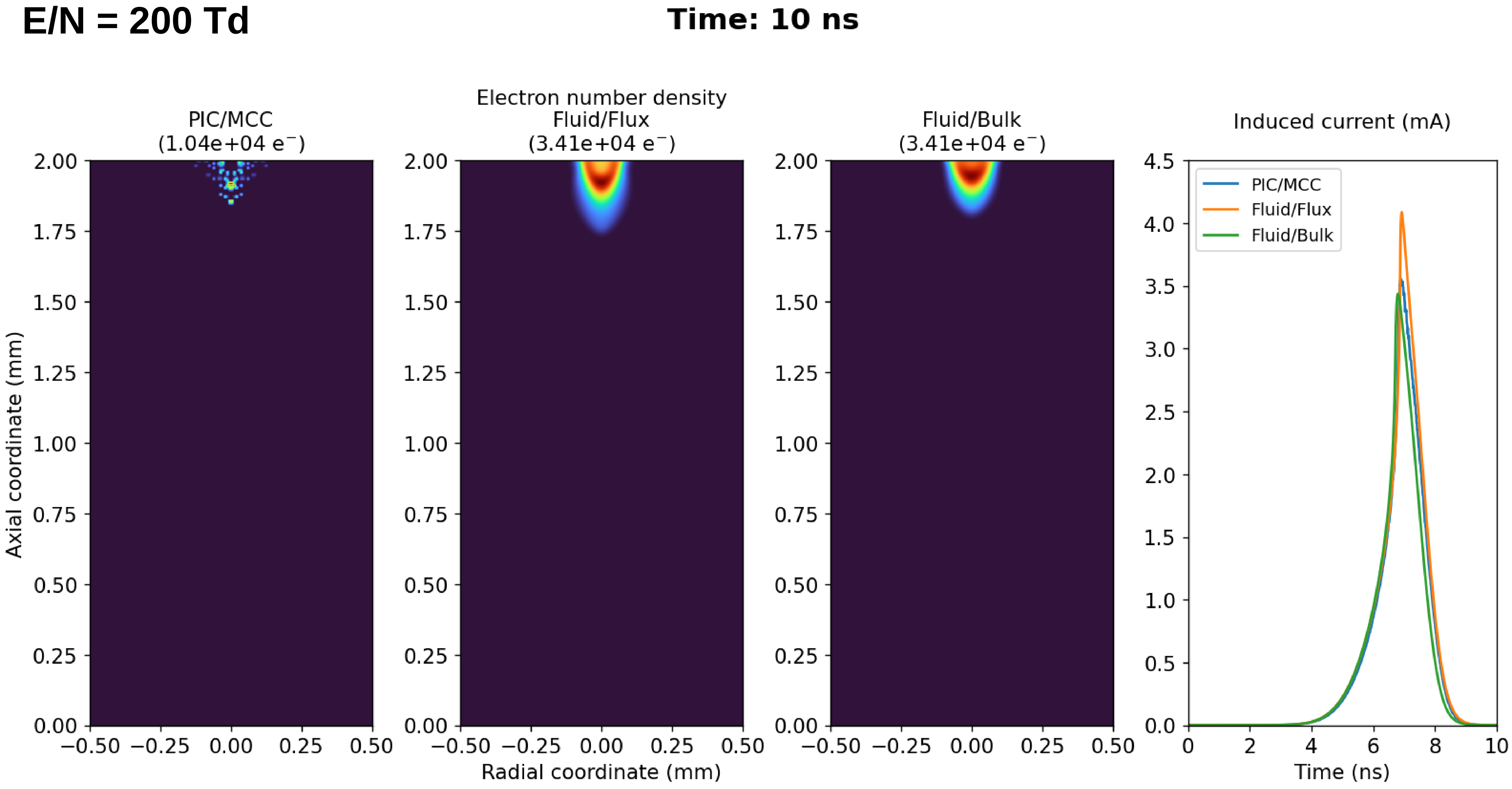
# PIC/MCC vs Fluid model
# E/N = 200 Td



# PIC/MCC vs Fluid model
# E/N = 200 Td

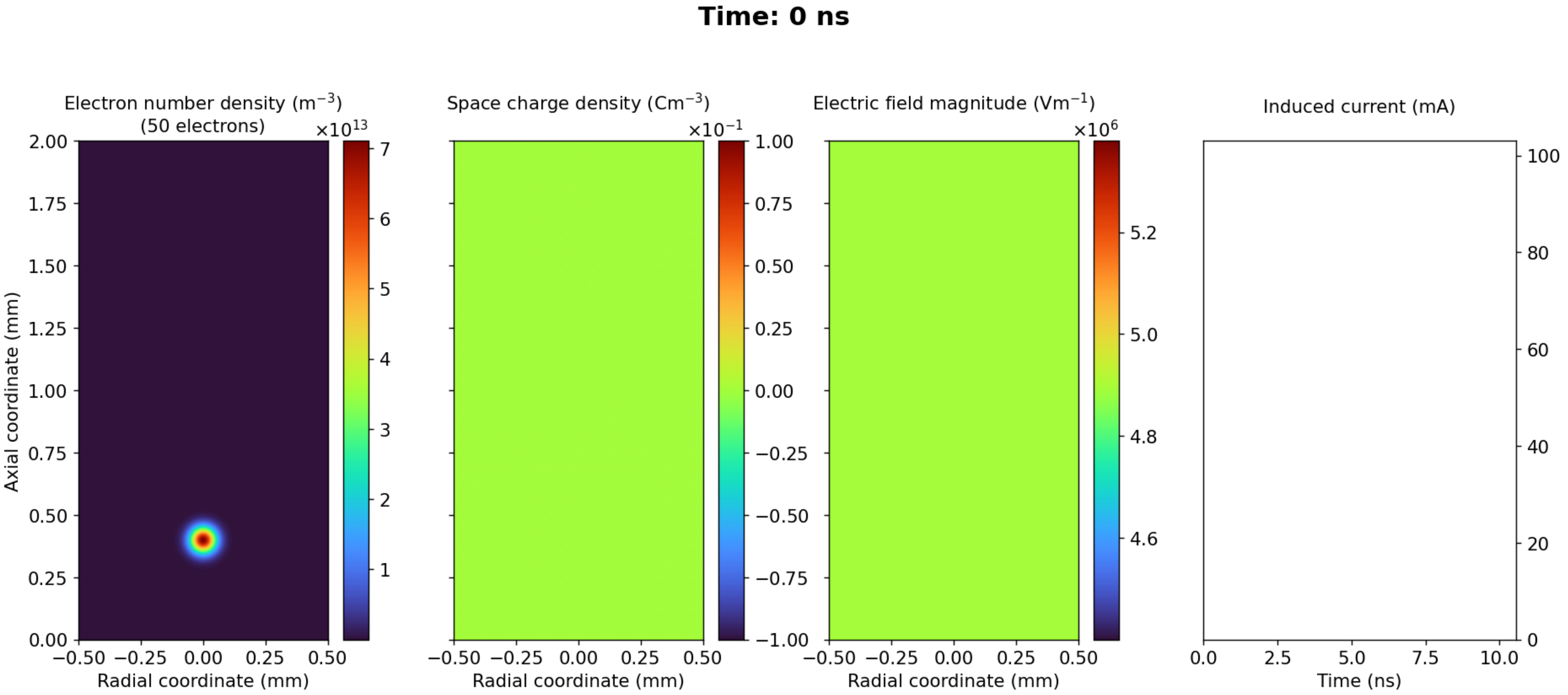


# PIC/MCC vs Fluid model
# E/N = 200 Td



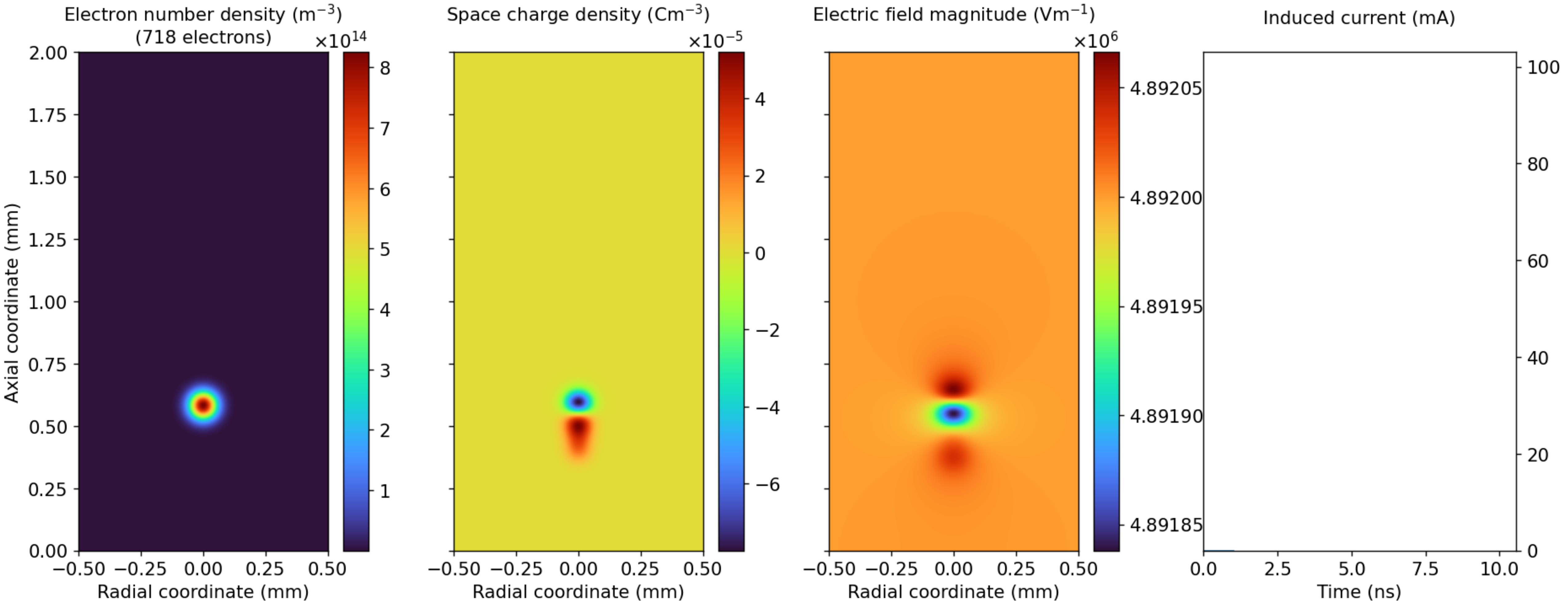
**FLUID MODEL (BULK)**
**$E/N = 200$ Td**
**$n_{BG} = 10^4\ m^{-3}$**

# Fluid model (bulk)
# E/N = 200 Td
# $n_{BG} = 10^4$ m$^{-3}$

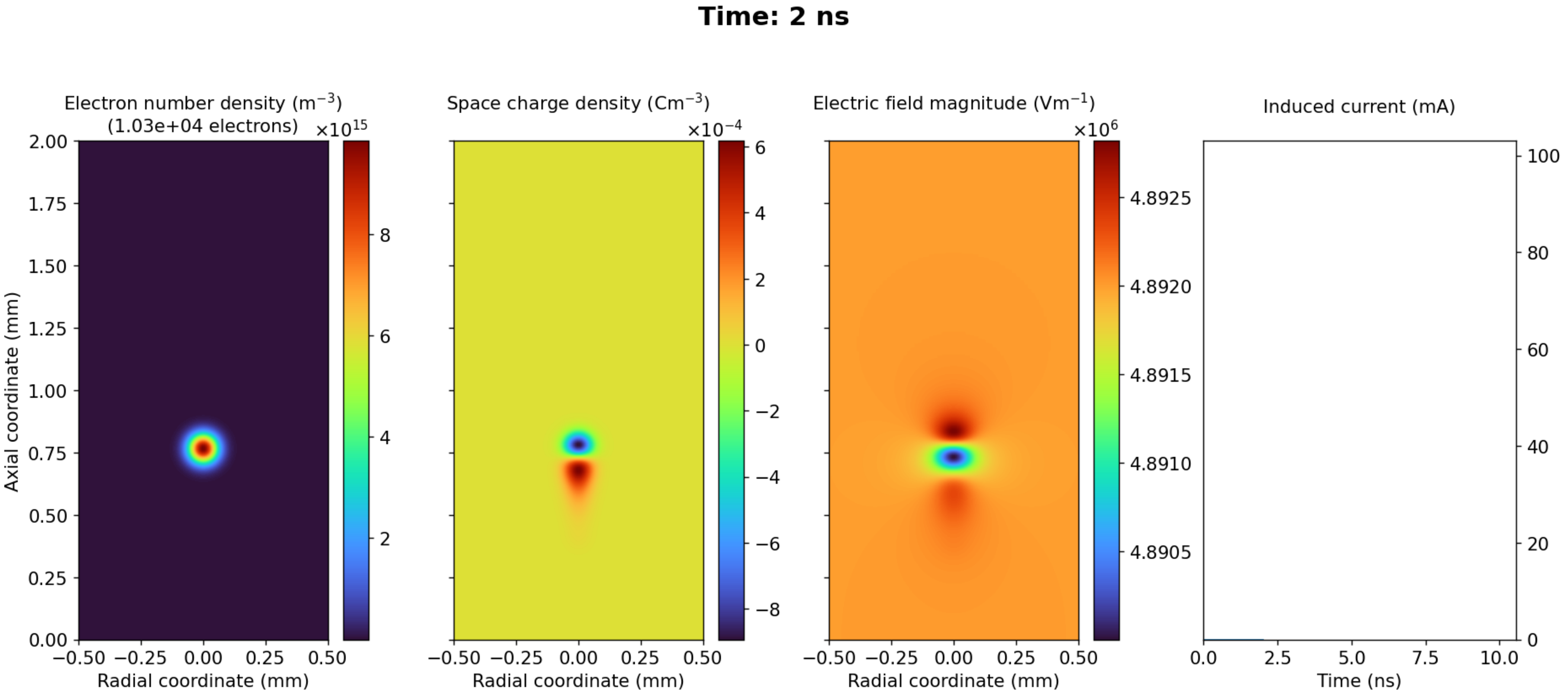


# Fluid model (bulk)
# E/N = 200 Td
# $n_{BG} = 10^4\ m^{-3}$

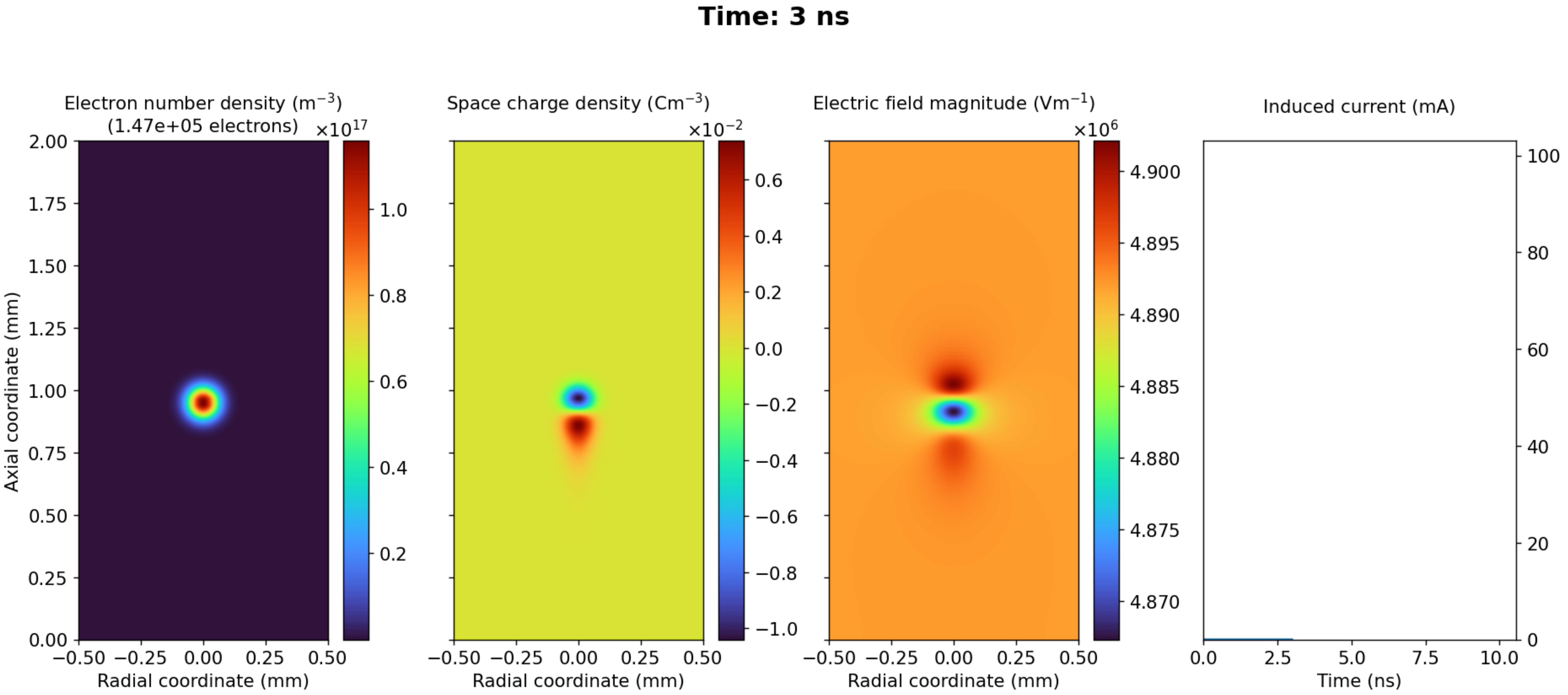
**Time: 1 ns**



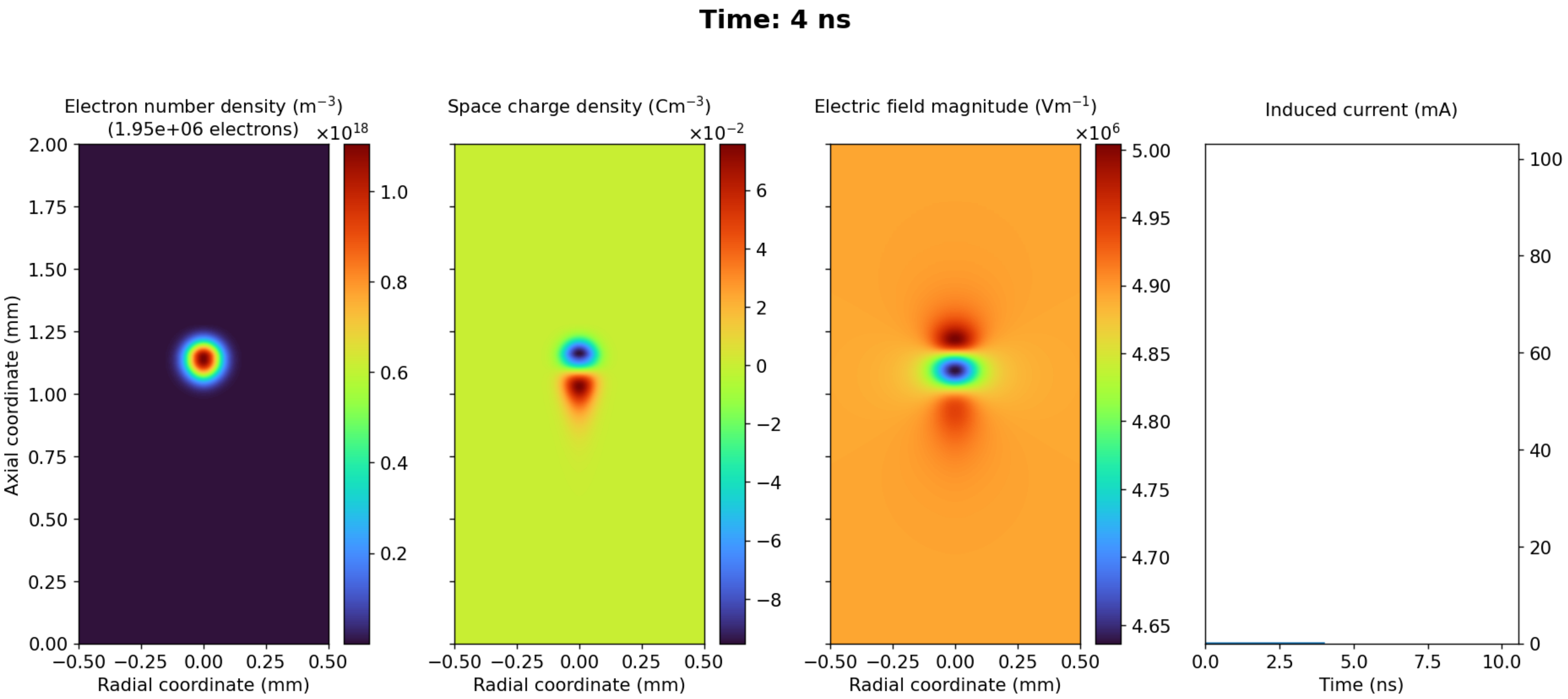
# Fluid model (bulk)
# E/N = 200 Td
# $n_{BG} = 10^4\ m^{-3}$



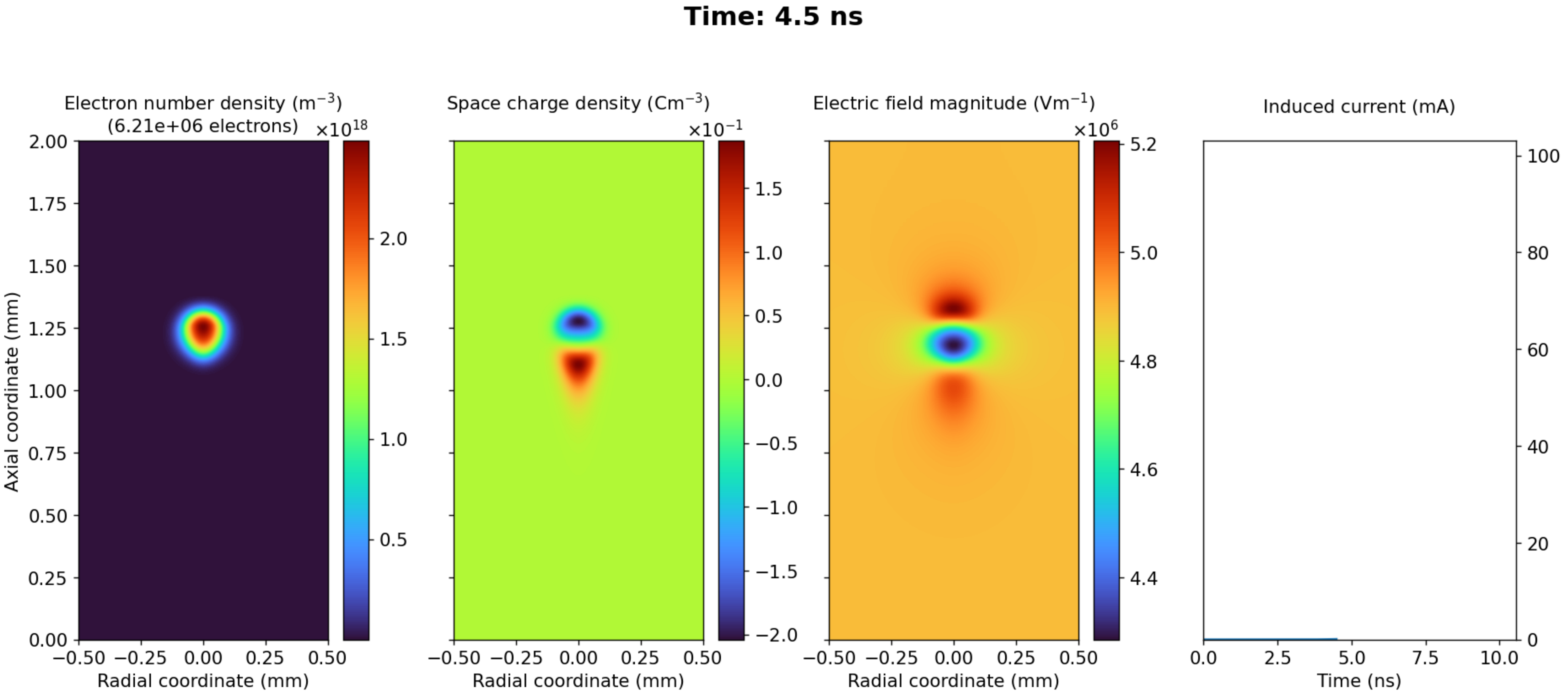
# Fluid model (bulk)
# E/N = 200 Td
# $n_{BG} = 10^4\ m^{-3}$



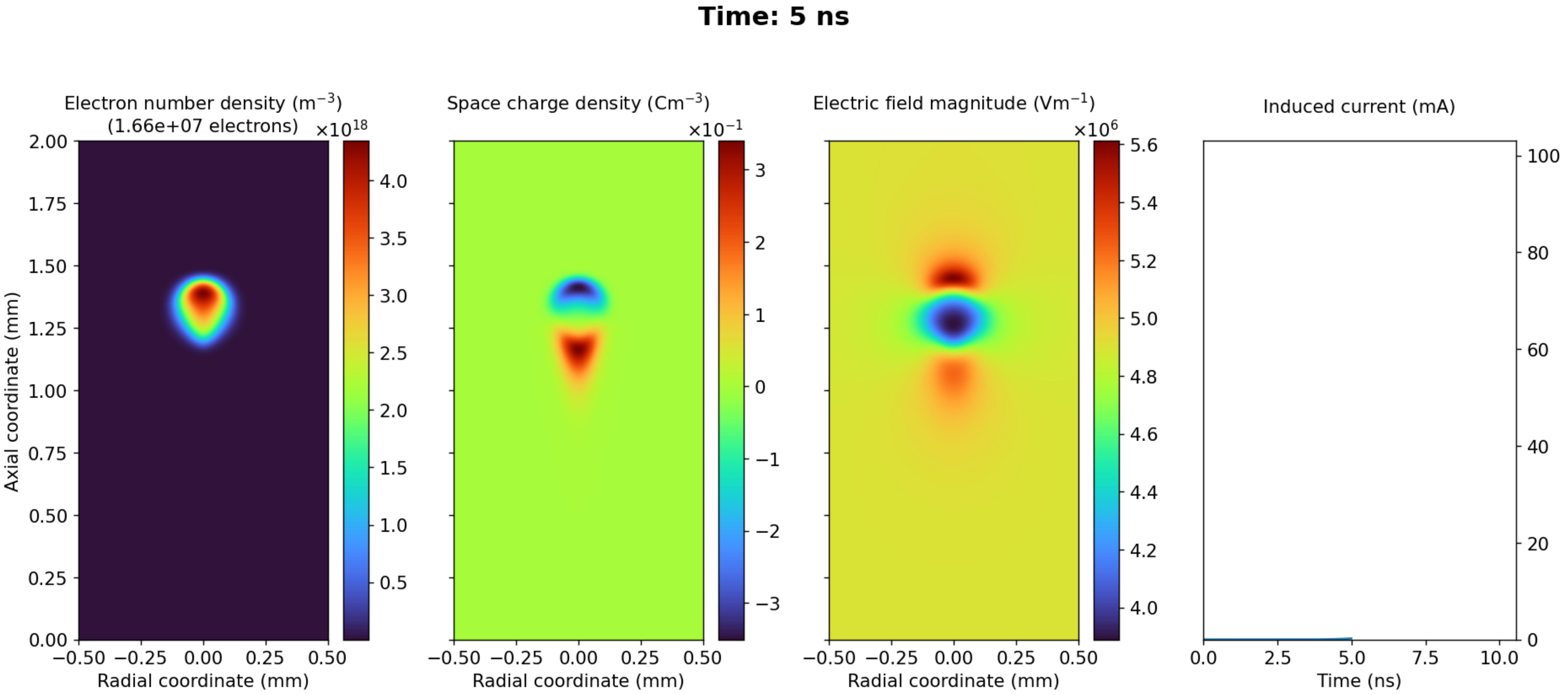
# Fluid model (bulk)
# E/N = 200 Td
# $n_{BG} = 10^4\ m^{-3}$



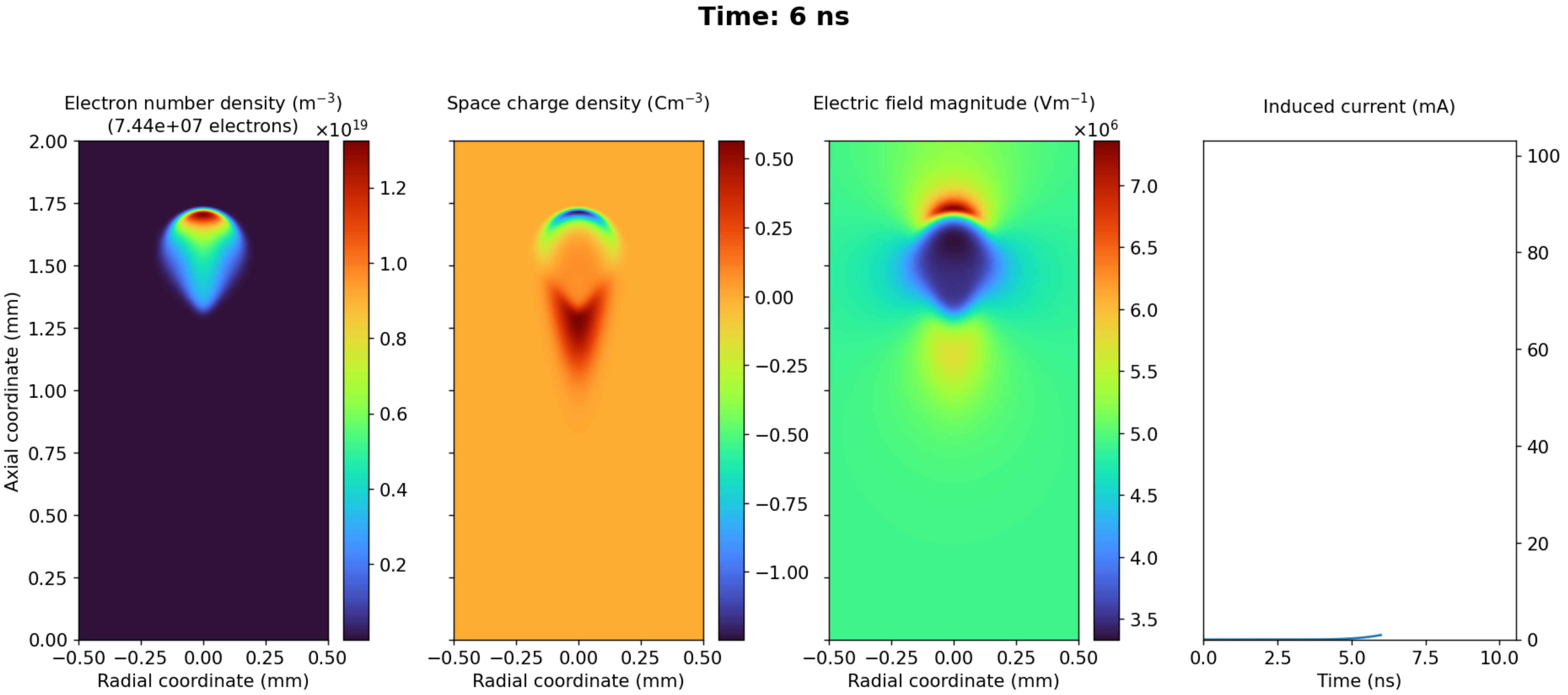
# Fluid model (bulk)
# E/N = 200 Td
# $n_{BG} = 10^4\ m^{-3}$



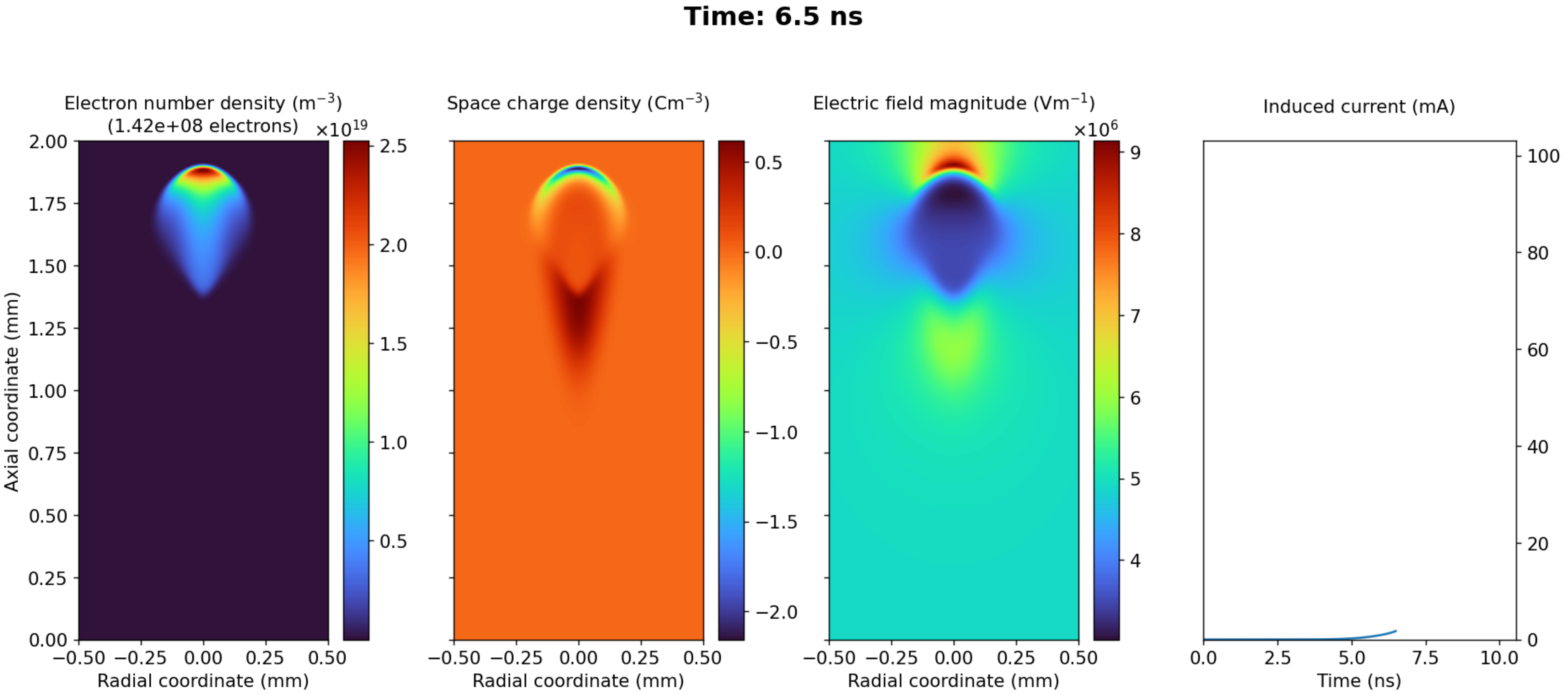
# Fluid model (bulk)
# E/N = 200 Td
# $n_{BG} = 10^4\ m^{-3}$



# Fluid model (bulk)
# E/N = 200 Td
# $n_{BG} = 10^4\ m^{-3}$

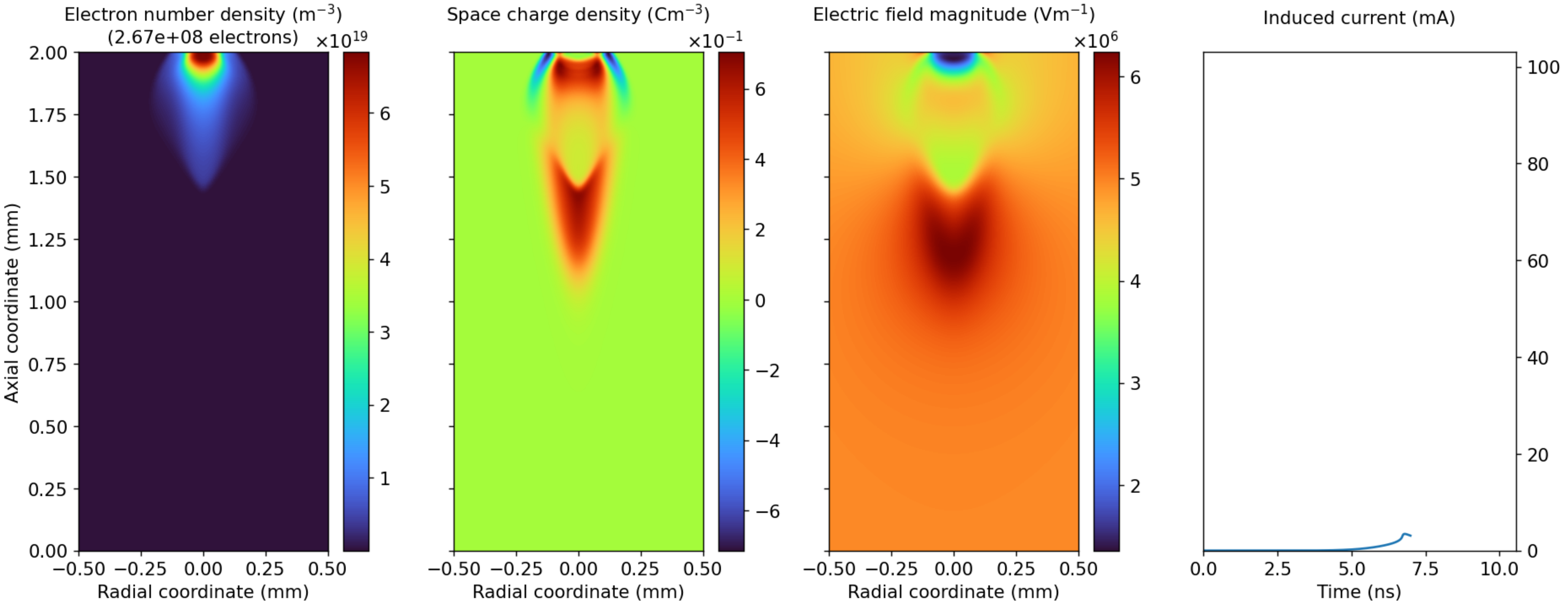


**Fluid model (bulk)**
**E/N = 200 Td**
**$n_{BG} = 10^4\ m^{-3}$**

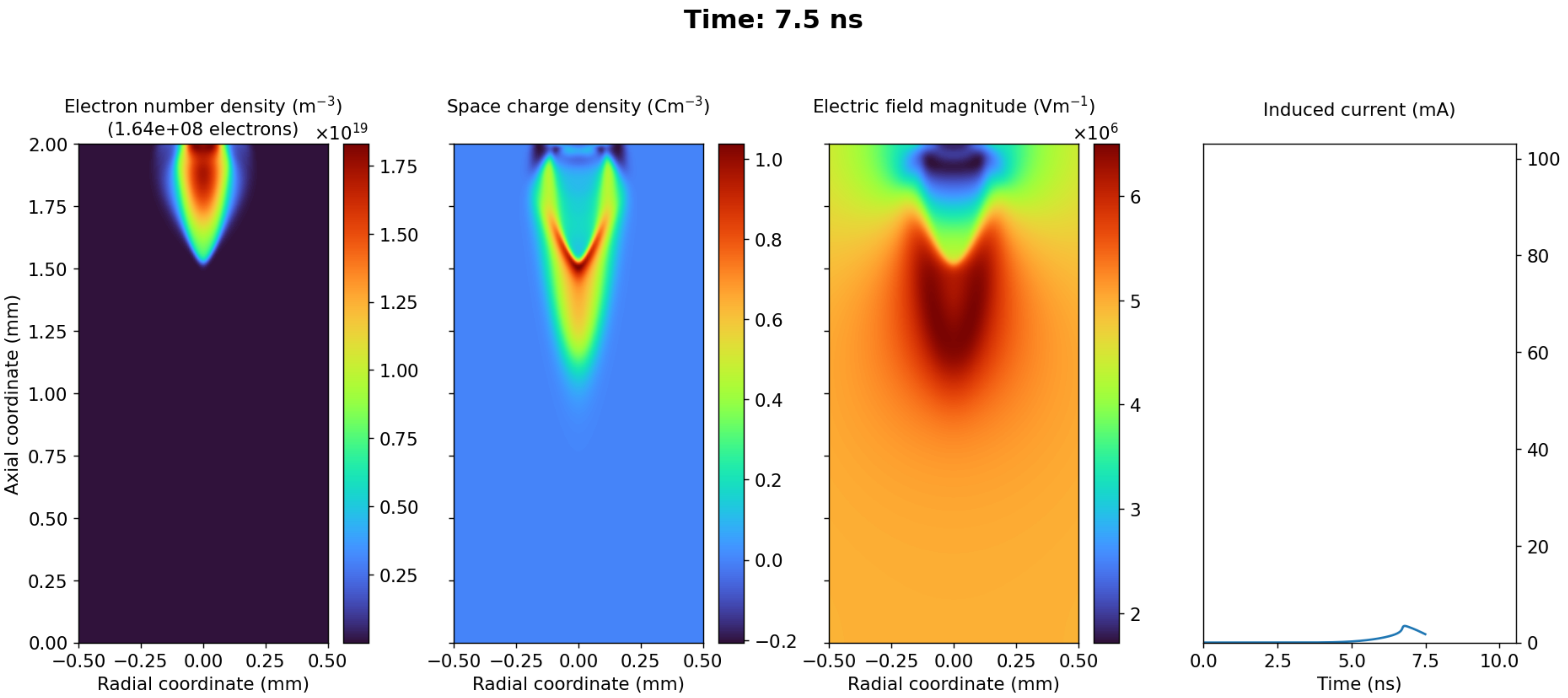


# Fluid model (bulk)
# E/N = 200 Td
# $n_{BG} = 10^4$ m$^{-3}$

**Time: 7 ns**

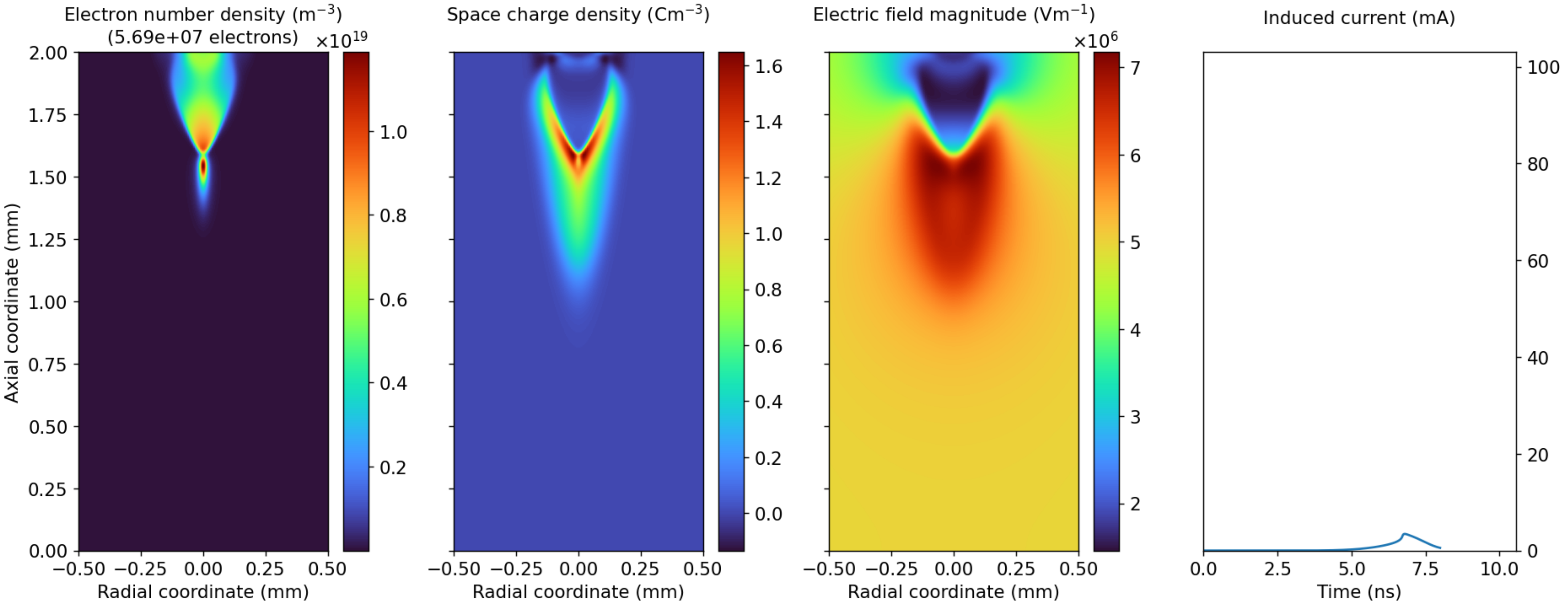


**Fluid model (bulk)**
**E/N = 200 Td**
**$n_{BG} = 10^4\ m^{-3}$**

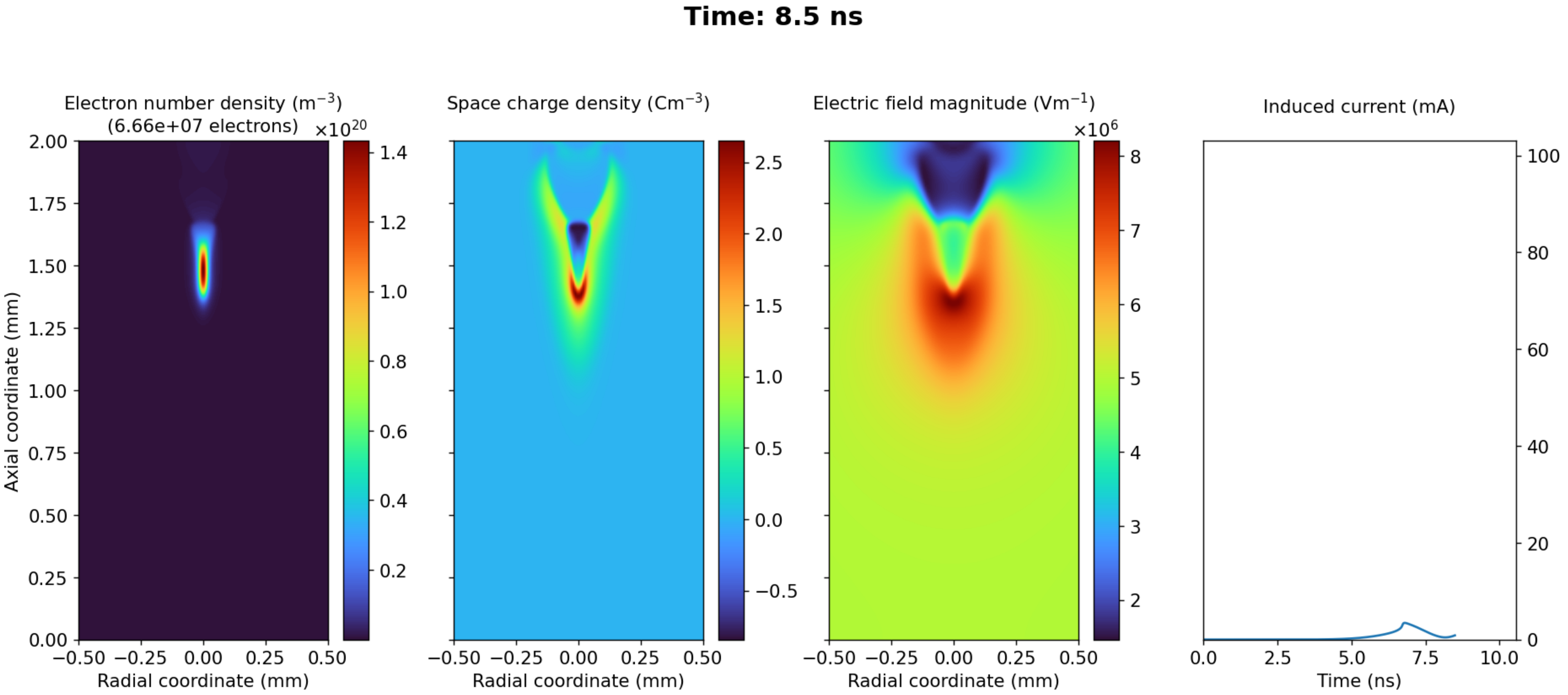


# Fluid model (bulk)
# E/N = 200 Td
# $n_{BG} = 10^4$ m$^{-3}$

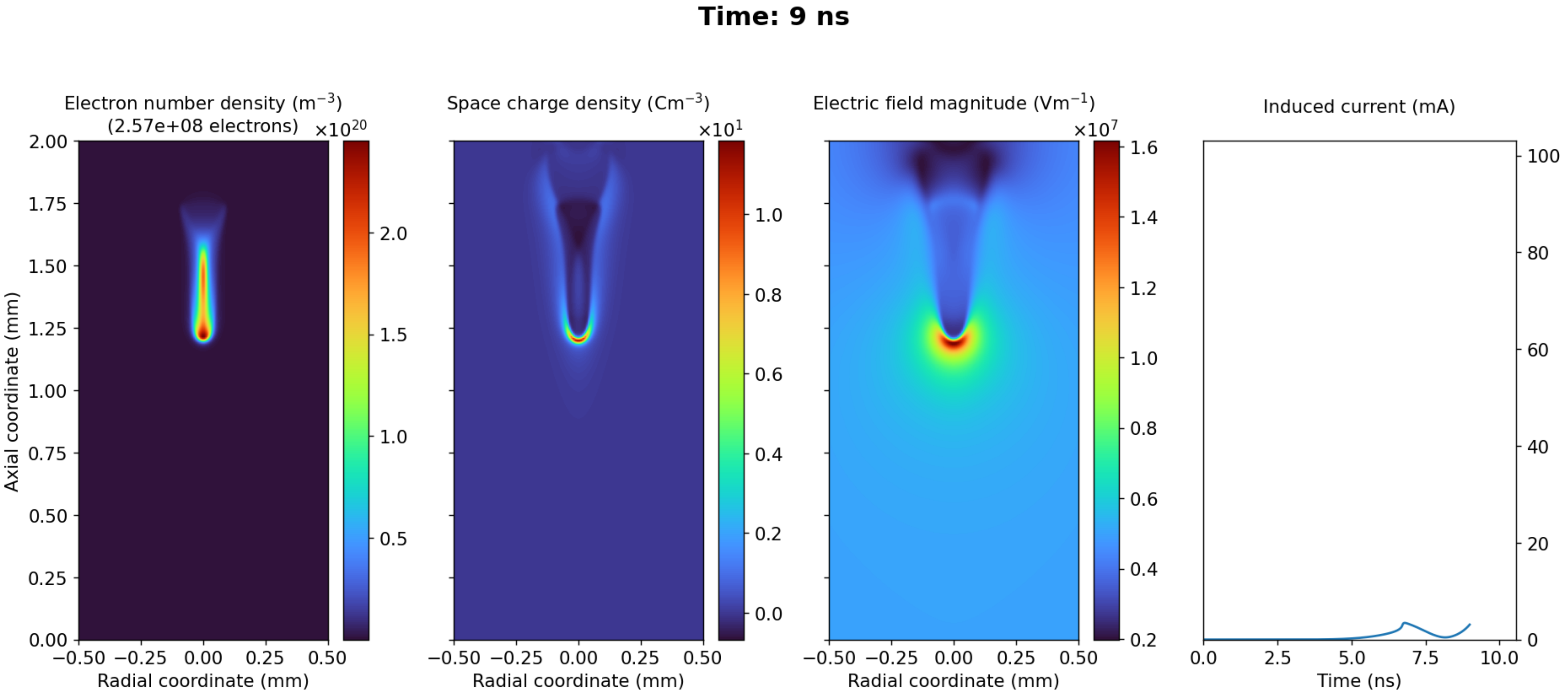
**Time: 8 ns**



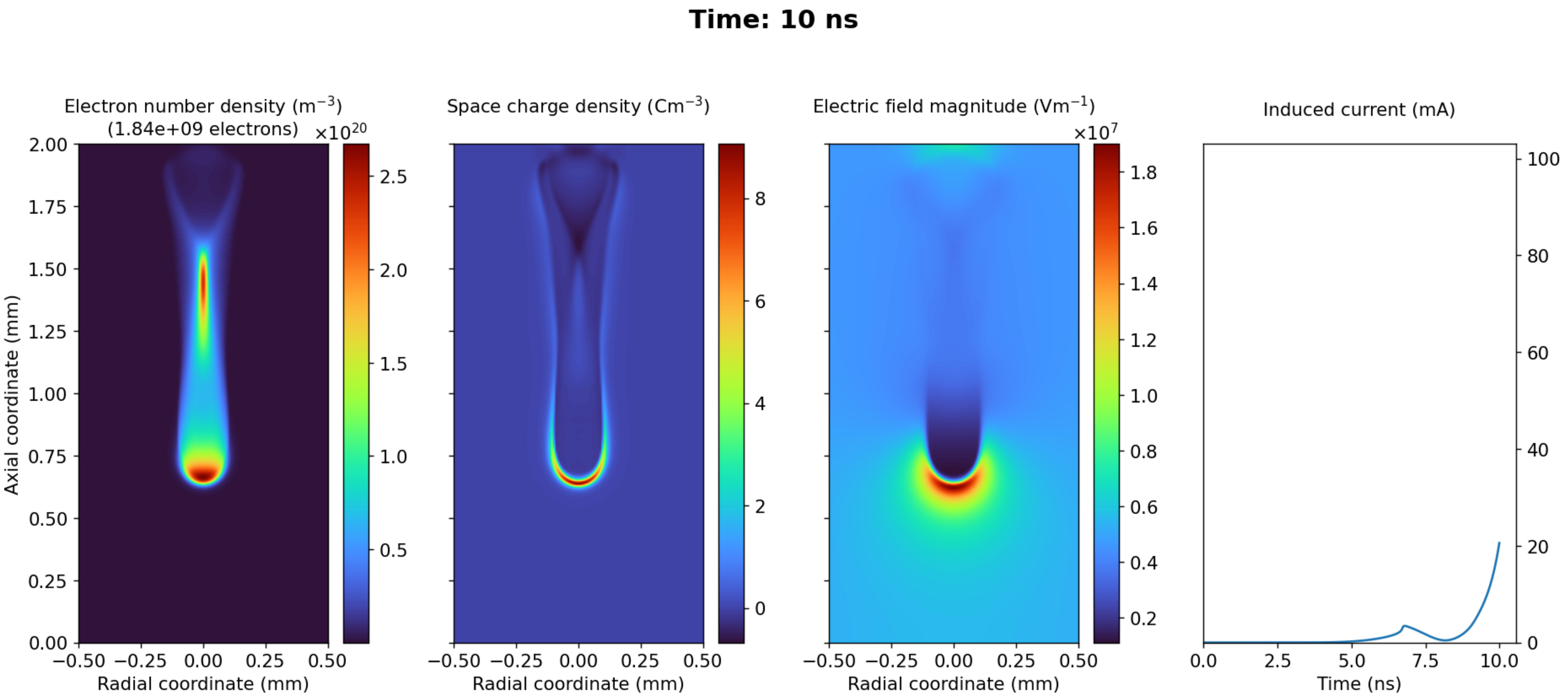
# Fluid model (bulk)
# E/N = 200 Td
# $n_{BG} = 10^4\ m^{-3}$



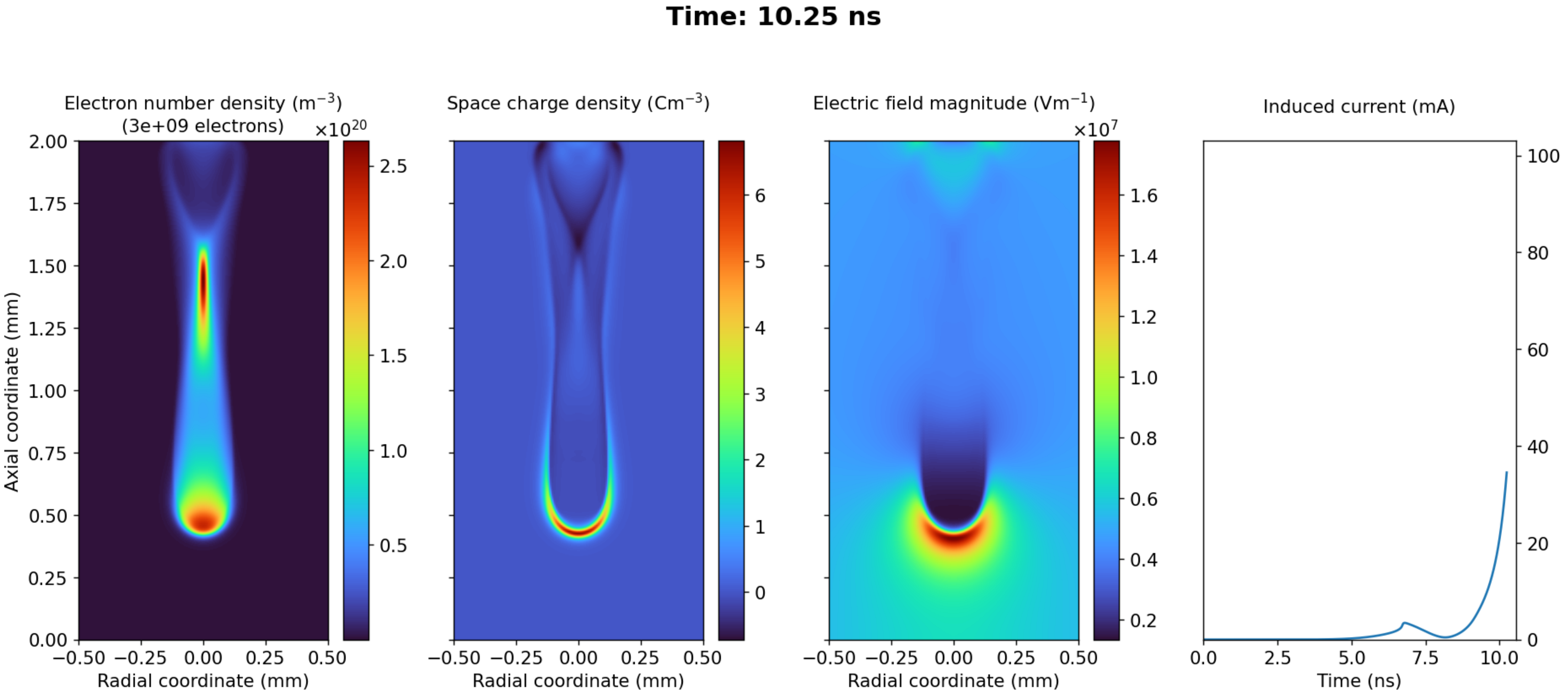
# Fluid model (bulk)
# E/N = 200 Td
# $n_{BG} = 10^4\ m^{-3}$



# Fluid model (bulk)
# E/N = 200 Td
# $n_{BG} = 10^4\ m^{-3}$



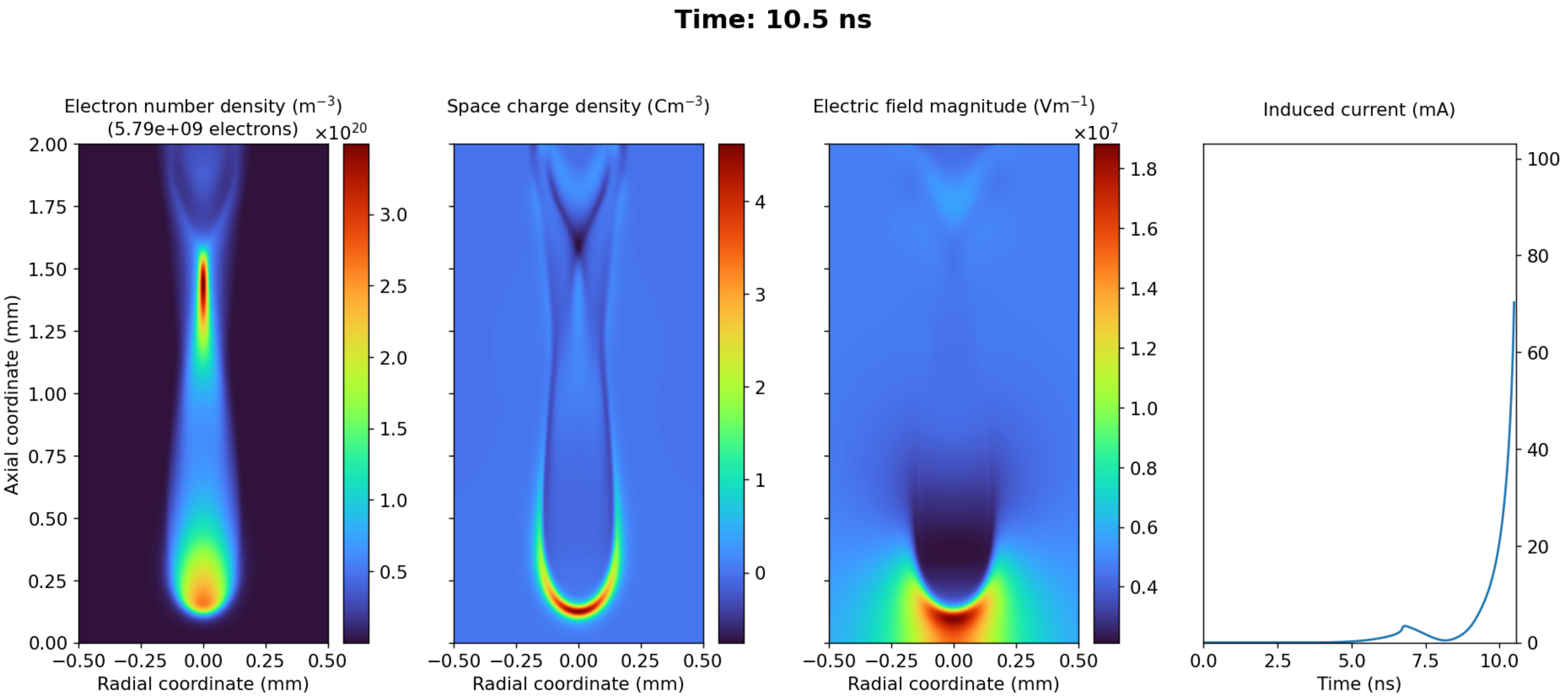
# Fluid model (bulk)
# E/N = 200 Td
# $n_{BG} = 10^4\ m^{-3}$



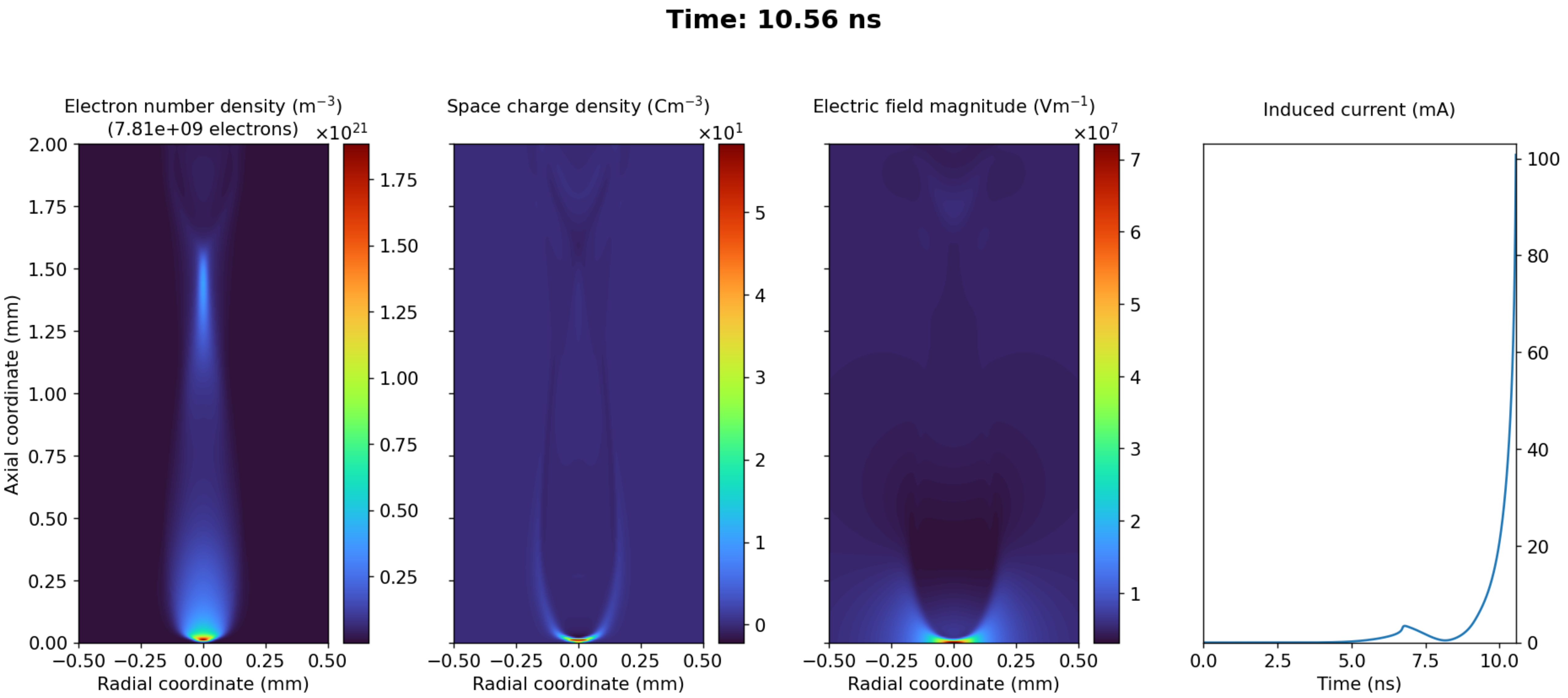
**Fluid model (bulk)**

**E/N = 200 Td**

**$n_{BG} = 10^4\ m^{-3}$**



# Fluid model (bulk)
# E/N = 200 Td
# $n_{BG} = 10^4\ m^{-3}$



# Conclusion and further work

- We have developed a 2.5D PIC/MCC and a 2D fluid model of RPCs.
- Both models assume axial symmetry.
- The models were employed to study the signal induction, space charge effects and avalanche to streamer transition in RPCs under LHC-like conditions and to demonstrate how different gas mixtures, input data and background ionization affect the streamer dynamics and induced signals.
- PIC/MCC model will be used to obtain RPC efficiency, time response functions and charge spectra. Both models will be used to study the positive streamer inception.
- Efficiency curves calculated using microscopic MC for LHC-like RPCs strongly disagree with the measured data. Calculations should be repeated using a realistic threshold level.

# Acknowledgements

**This work is supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia and Institute of Physics Belgrade, and the Science Fund of the Republic of Serbia, Grant No. 7749560, Exploring ultra-low global warming potential gases for insulation in high-voltage technology: Experiments and modelling—EGWIn**

EGWIn

Science Fund
of the Republic of Serbia