3D simulation of the rotating spoke in wall-less Hall thruster

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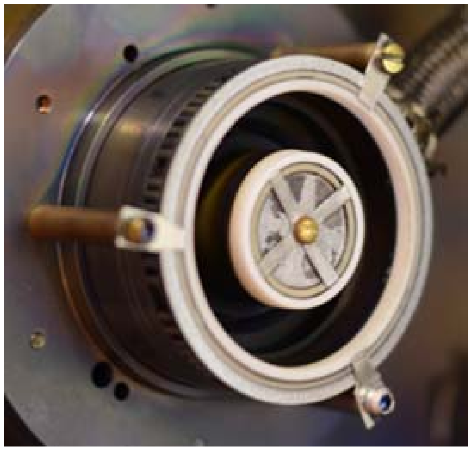
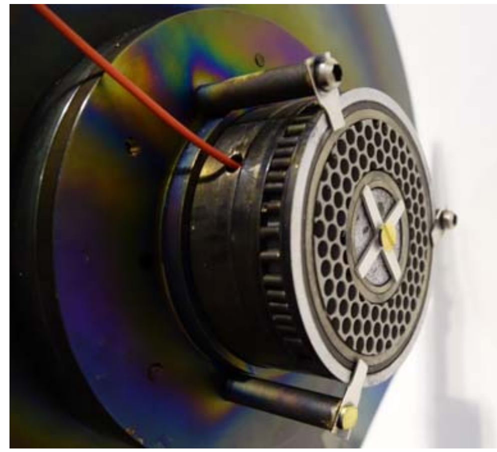
Rotating spoke observation in ISCT200 thruster

200 W permanent magnet Hall thruster

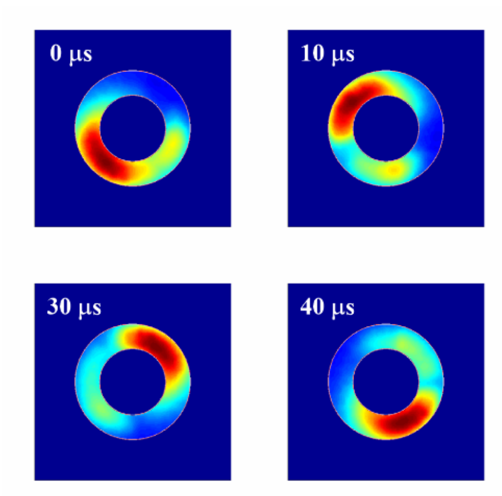


Standard configuration
BN-SiO_2 walls
B_{max} at channel exit plane



Wall-Less configuration
E field shifted ouside
Discharge in $\nabla B<0$ region

High-speed camera imaging (WL configuration)



m=1 mode dominates

110 V, 1,3 mg/s-Xe
11 kHz rotation
v_{spoke} = 1280 m/s

A wall-less Hall thruster is a perfect test platform

- localization of the plasma discharge outside the channel provides unrestricted access for diagnostics
- absence of plasma-wall interactions makes easier modeling and numerical simulation

3 dimensional Particle in Cell code with Monte-Carlo collisions

STOIC (electroSTatic Optimized particle In Cell)

Kinetic treatment of all plasma species

Neutral dynamics self-consistently resolved with direct simulation Monte Carlo (DSMC)

All relevant collisions are included

$e^- + Xe \rightarrow Xe^+ + 2e^-$	ionization
$e^- + Xe \rightarrow Xe^* + e^-$	total excitation
$e^- + Xe \rightarrow Xe + e^-$	elastic scattering
$Xe^+ + Xe \rightarrow Xe^+ + Xe$	elastic scattering
$Xe + Xe^+ \rightarrow Xe^+ + Xe$	charge exchange
e^-, Xe^+	Coulomb collisions

Monte-Carlo secondary electron emission (SEE) model at the dielectric surface

In the present simulations no SEE at the dielectric walls was accounted ($\gamma = 0$)

Cartesian geometry and the regular mesh (X,Y,Z) guarantees conservation of momentum and absence of self forces in the PIC algorithm

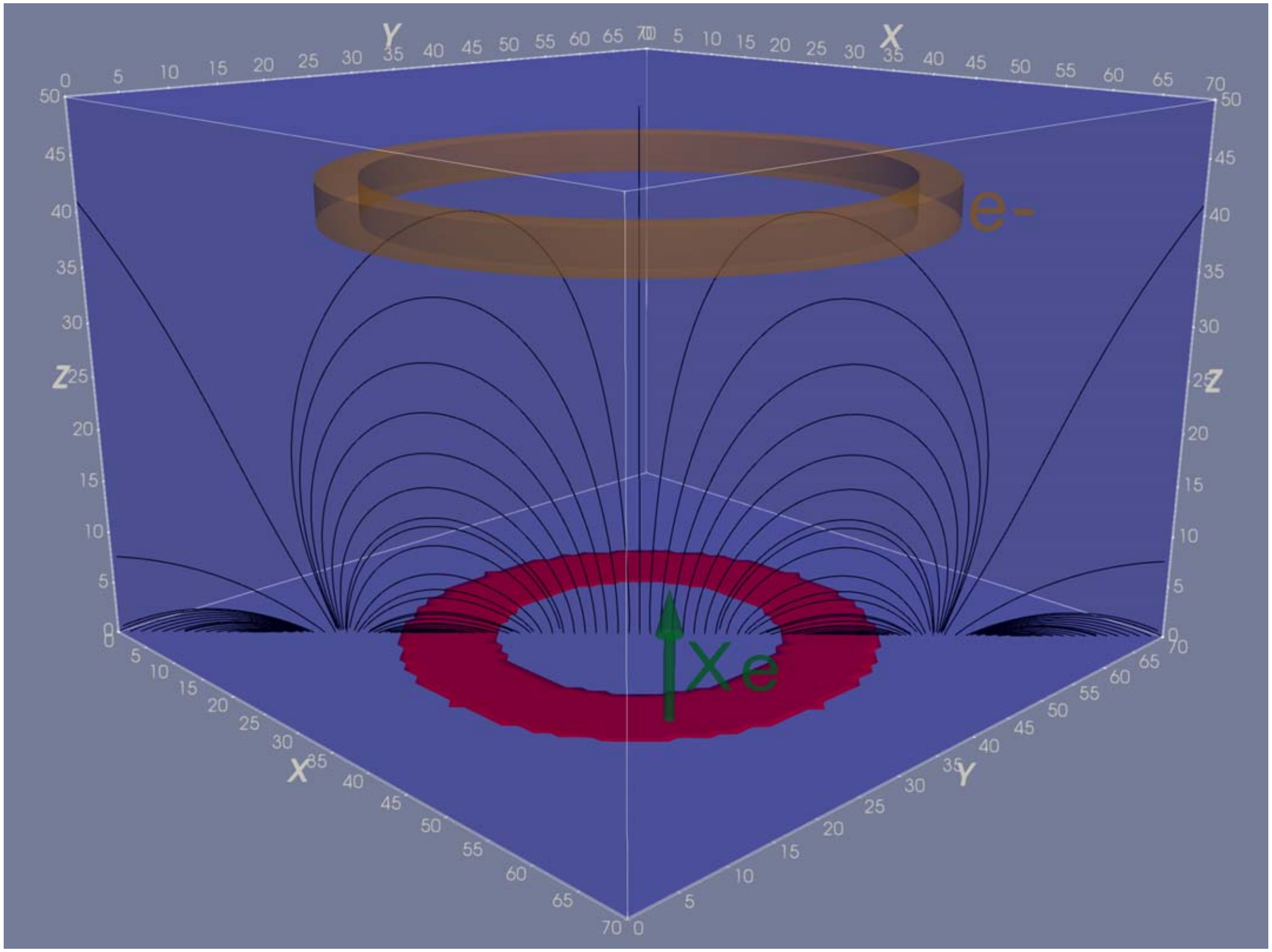
Geometry scaling

Length	$L = f\,L^*$
Magnetic field	$B = f^{-1} B^*$
Cross Sections	$Xs = f^{-1} Xs^*$

Scaling factor f = 0.1 is used in the present simulations

70x70x50 grid is used

Simulation geometry



Lx = Ly = 70 mm

Lz = 50 mm

Ua = 100 – 250 V

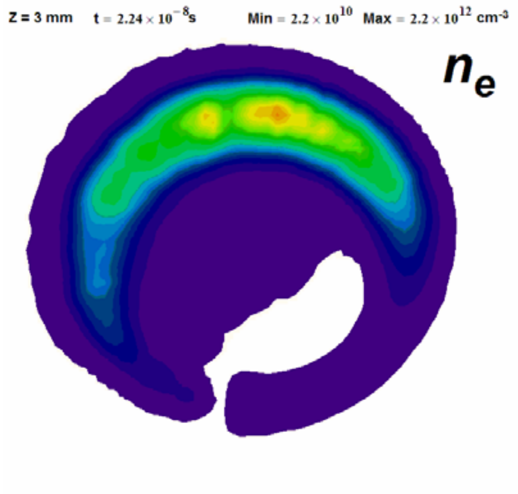
Ug = 0 V

Γ_{Xe} = 0.8 – 1.1 mg/s

Ring anode is mapped with square cells

Simulation results

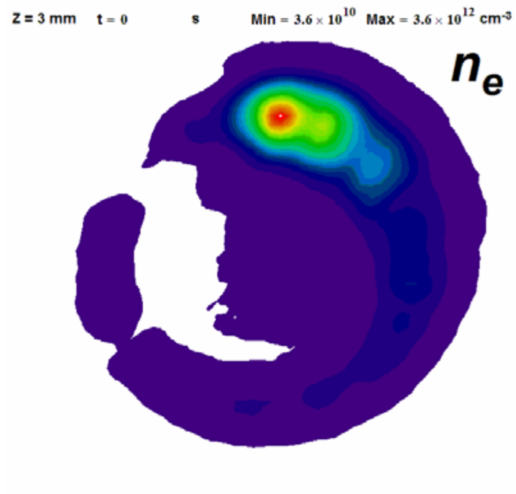
225 V, 1 mg/s



f= 56 kHz, v = 6.3 km/s

ExB direction

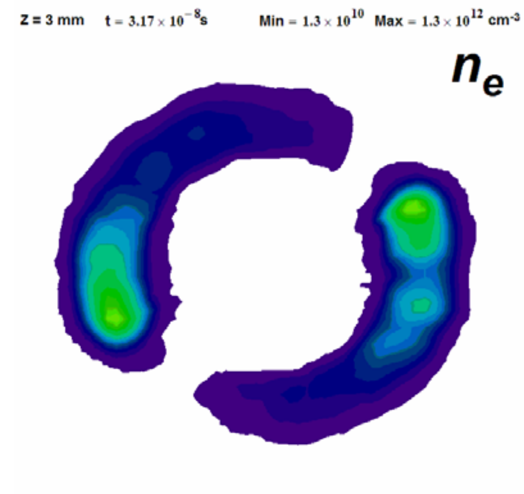
175 V, 1 mg/s



f= 34 kHz, v = 3.8 km/s

-***ExB*** direction

120 V, 1.3 mg/s

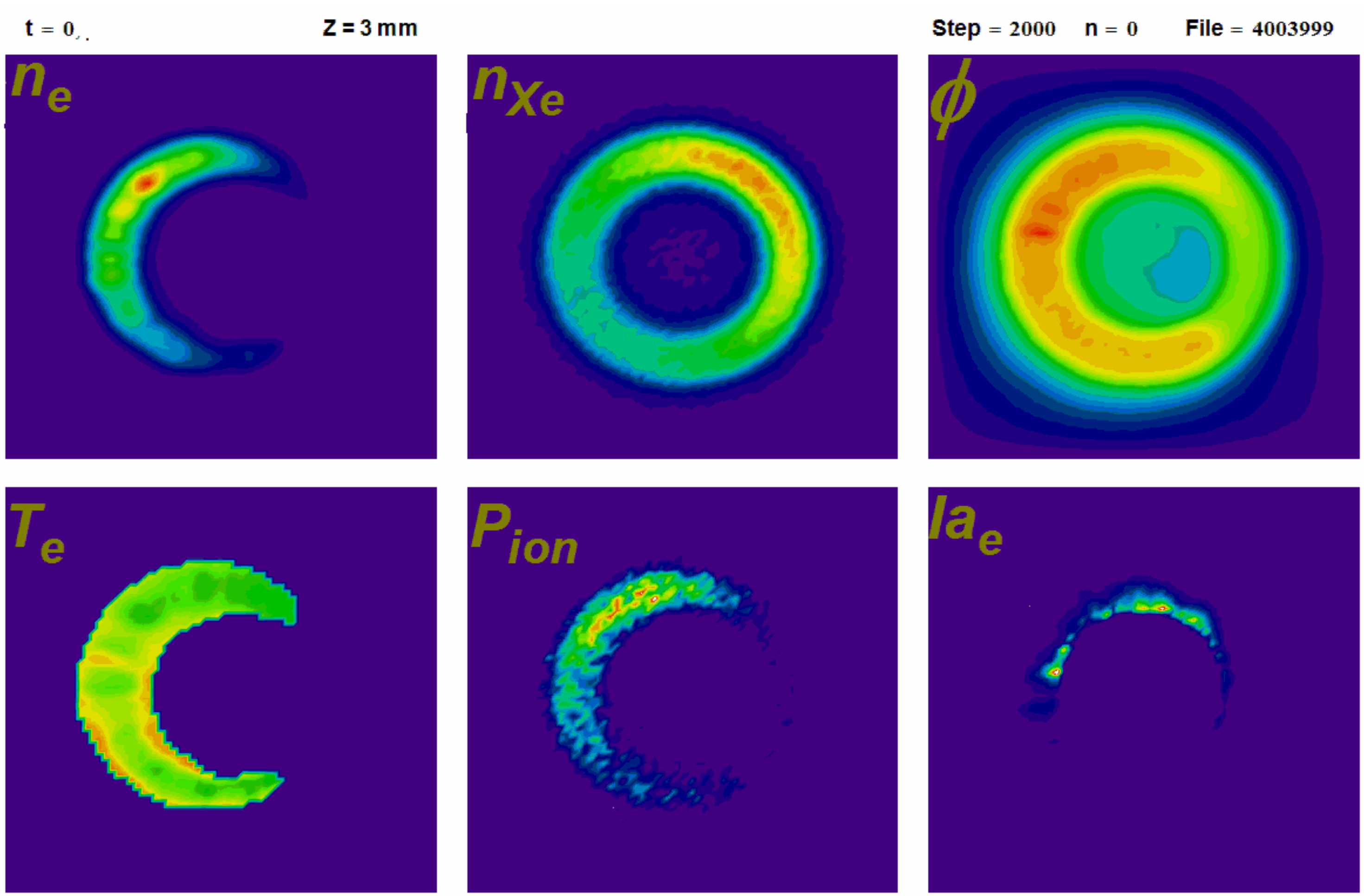


f= 39 kHz, v = 4.5 km/s

-***ExB*** direction

m = 1 and m = 2 spokes rotating both in ***ExB*** direction (clockwise) and -***ExB*** direction, with velocities ~ 3-6 km/s were observed in the simulations

Spoke dynamics, 225 V, 1 mg/s

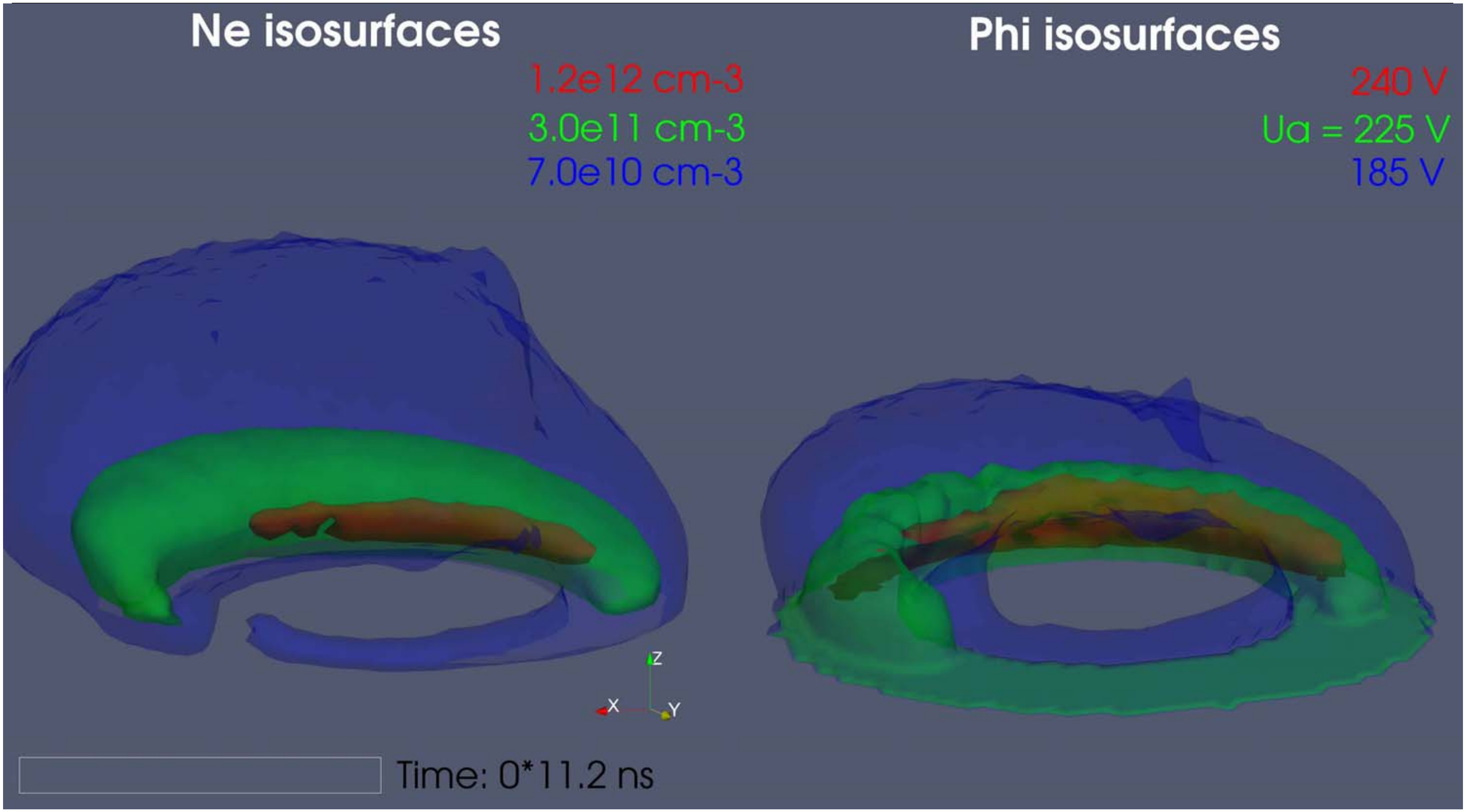


Spoke rotation associated with strong oscillations (~200V/cm, λ~2-4mm) of the azimuthal E-field and the azymuthal depletion of neutrals

Macroscopic azimuthal E-fields at spoke front/back cause drift to/from anode

Dynamics of the anode current indicates additional transport mechanism at spoke front

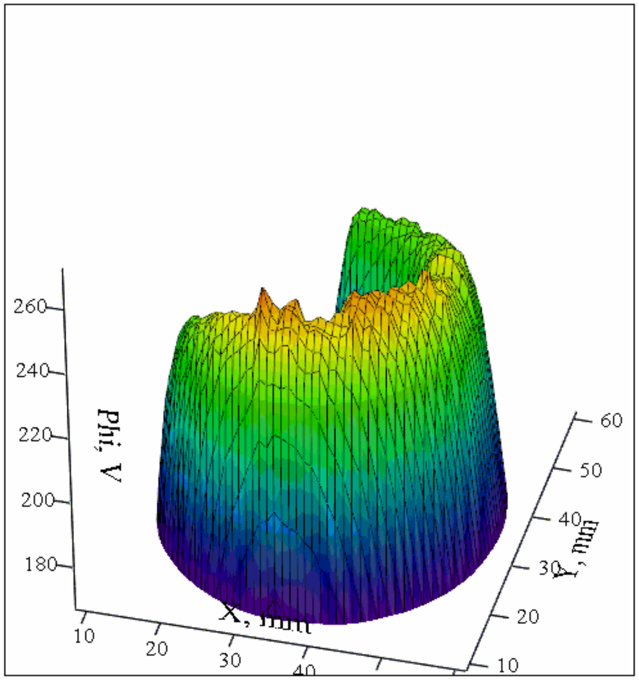
Electron density and potential dynamics

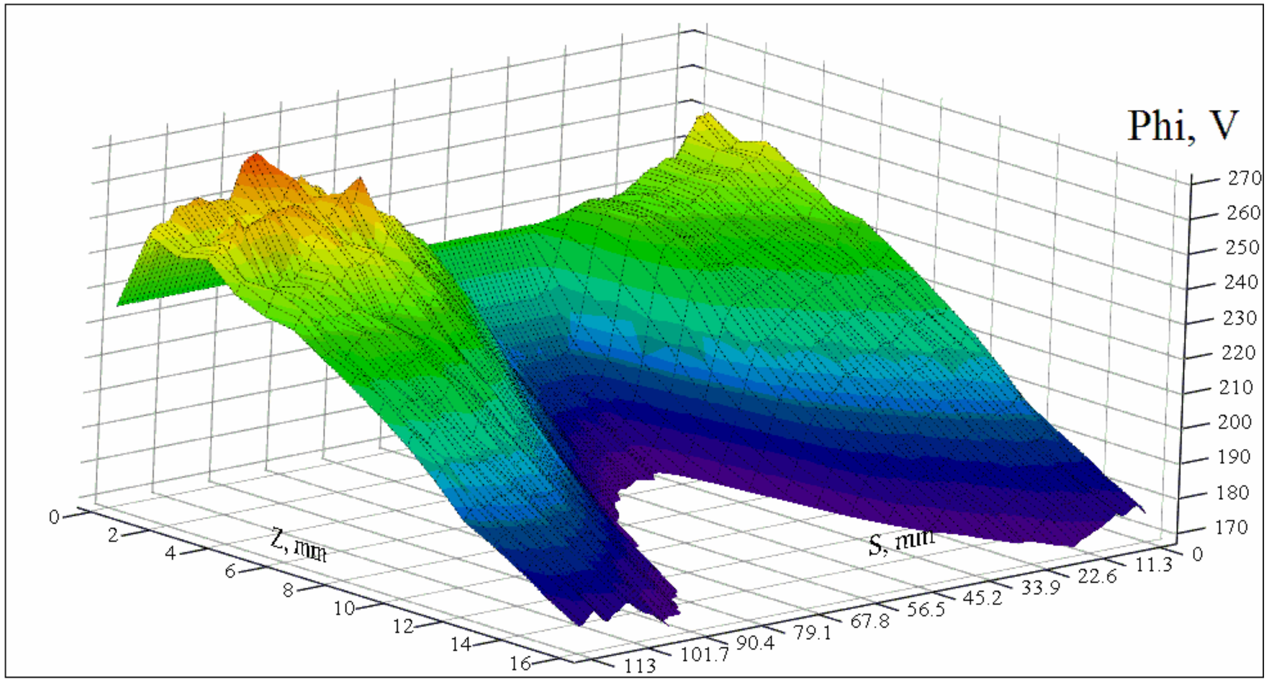


Average axial E-field inside the spoke ~10V/cm is much smaller than axial field outside the spoke ~100V/cm, and spoke HF oscillations amplitude ~200V/cm

Cavity in equipotentials should lead to vortex in electron drift

Potential dynamics, 225 V, 1 mg/s



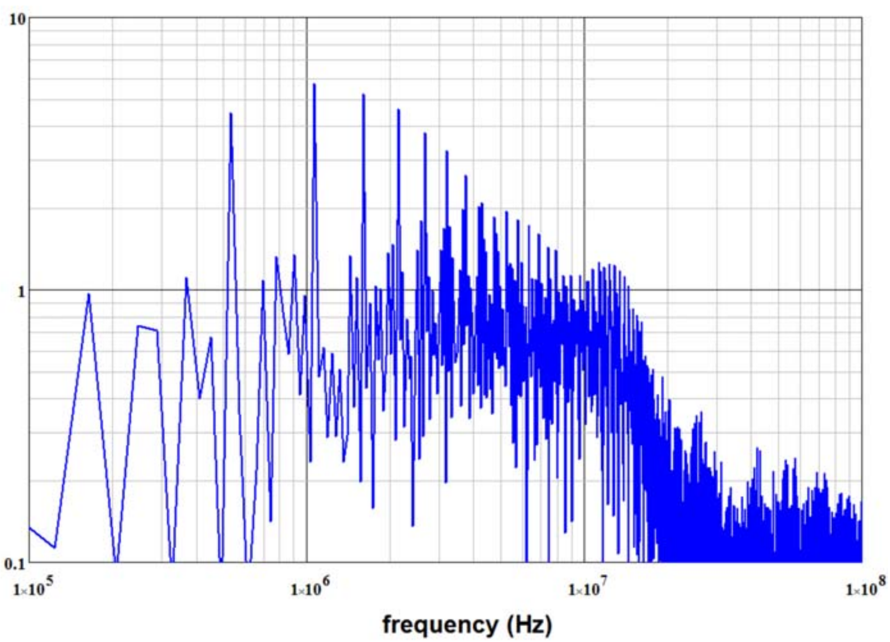


Average (background) E-field inside the spoke < 20 V/cm

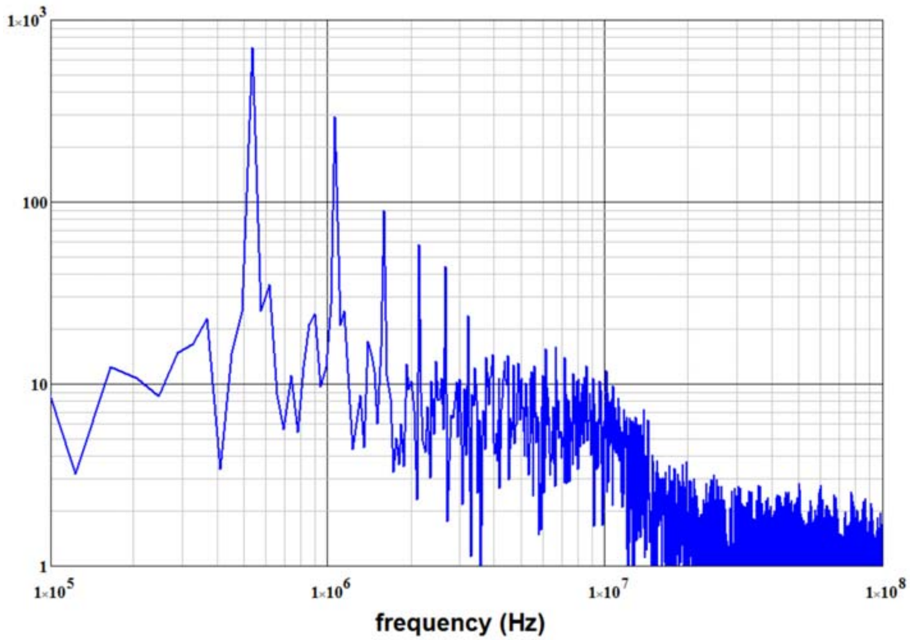
High-frequency short scale (~2mm) oscillations ~ 200 V/cm

Frequency spectrum of the spoke oscillations

electron density

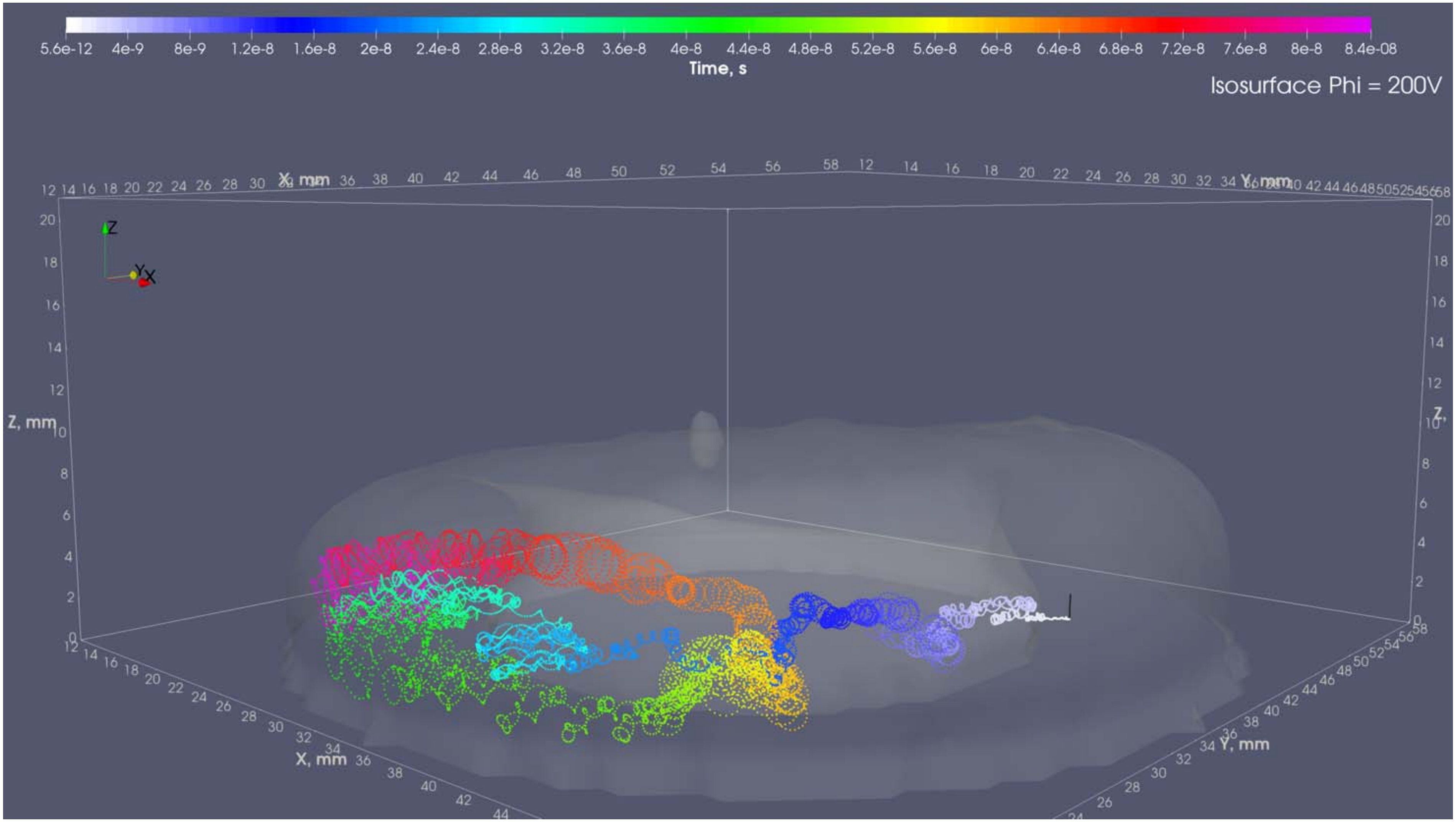


azimuthal electric field

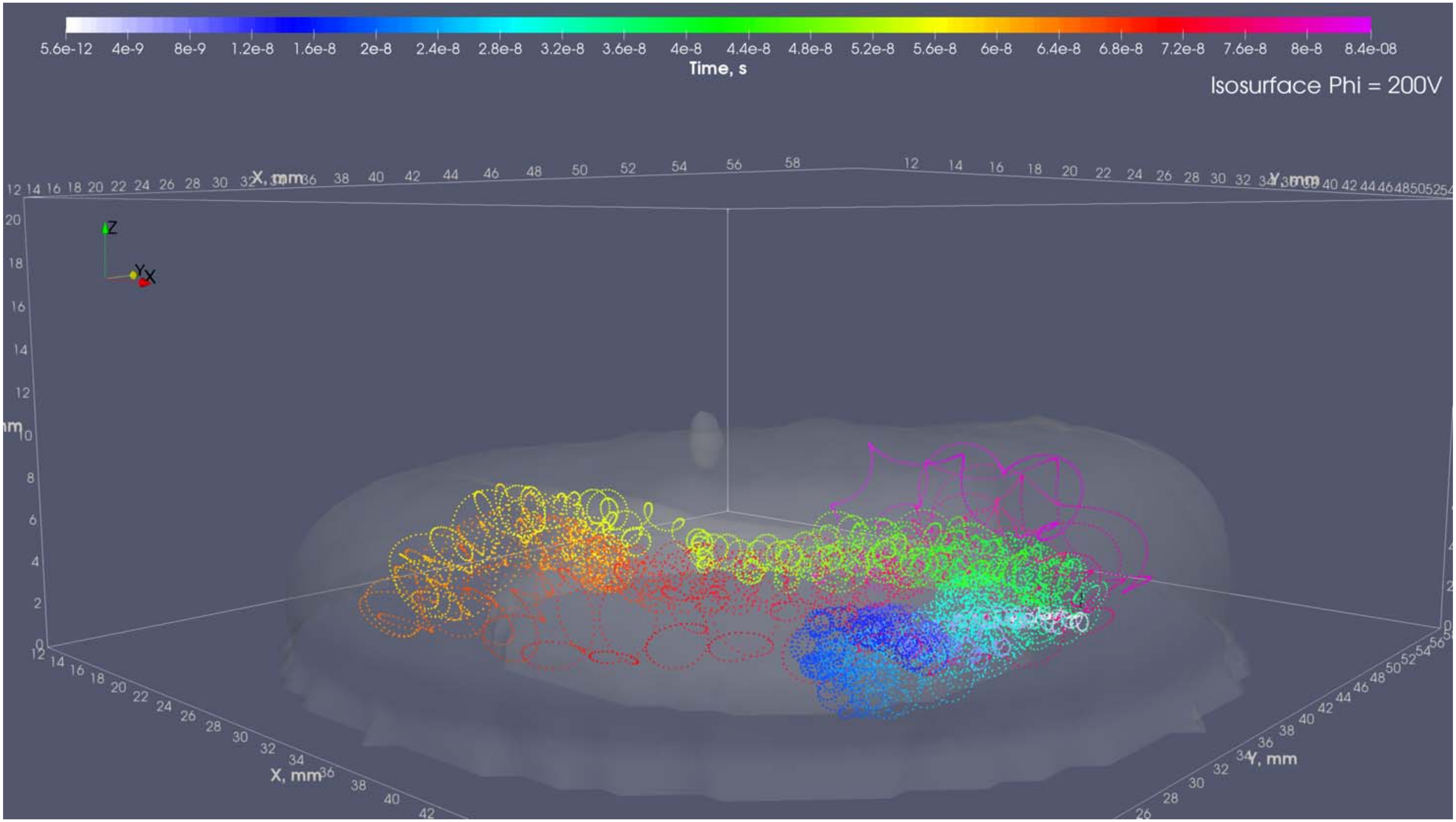


High-frequency oscillations ~ 10 MHz – heating and transport inside the spoke?

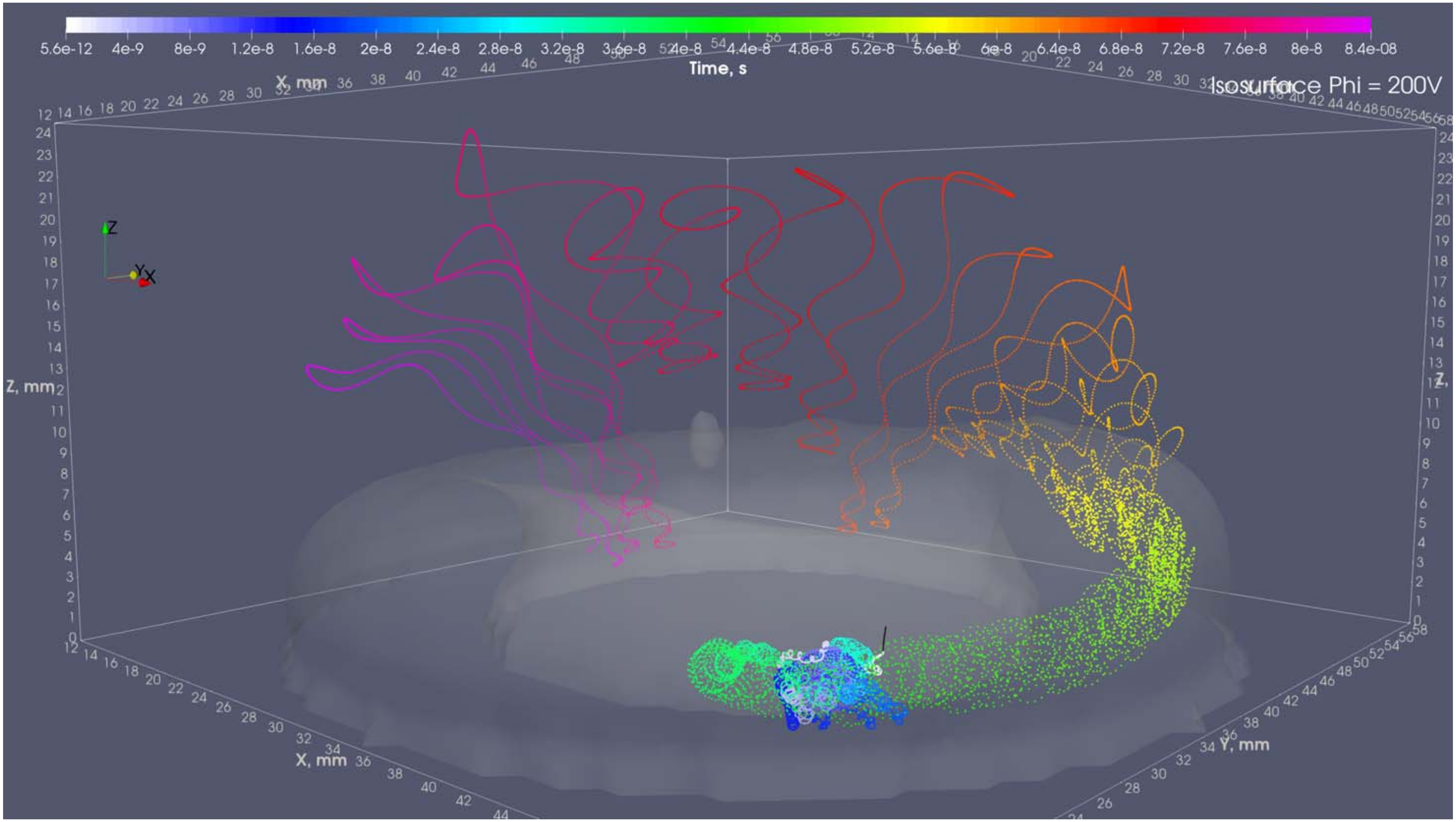
Electron trajectories inside the spoke



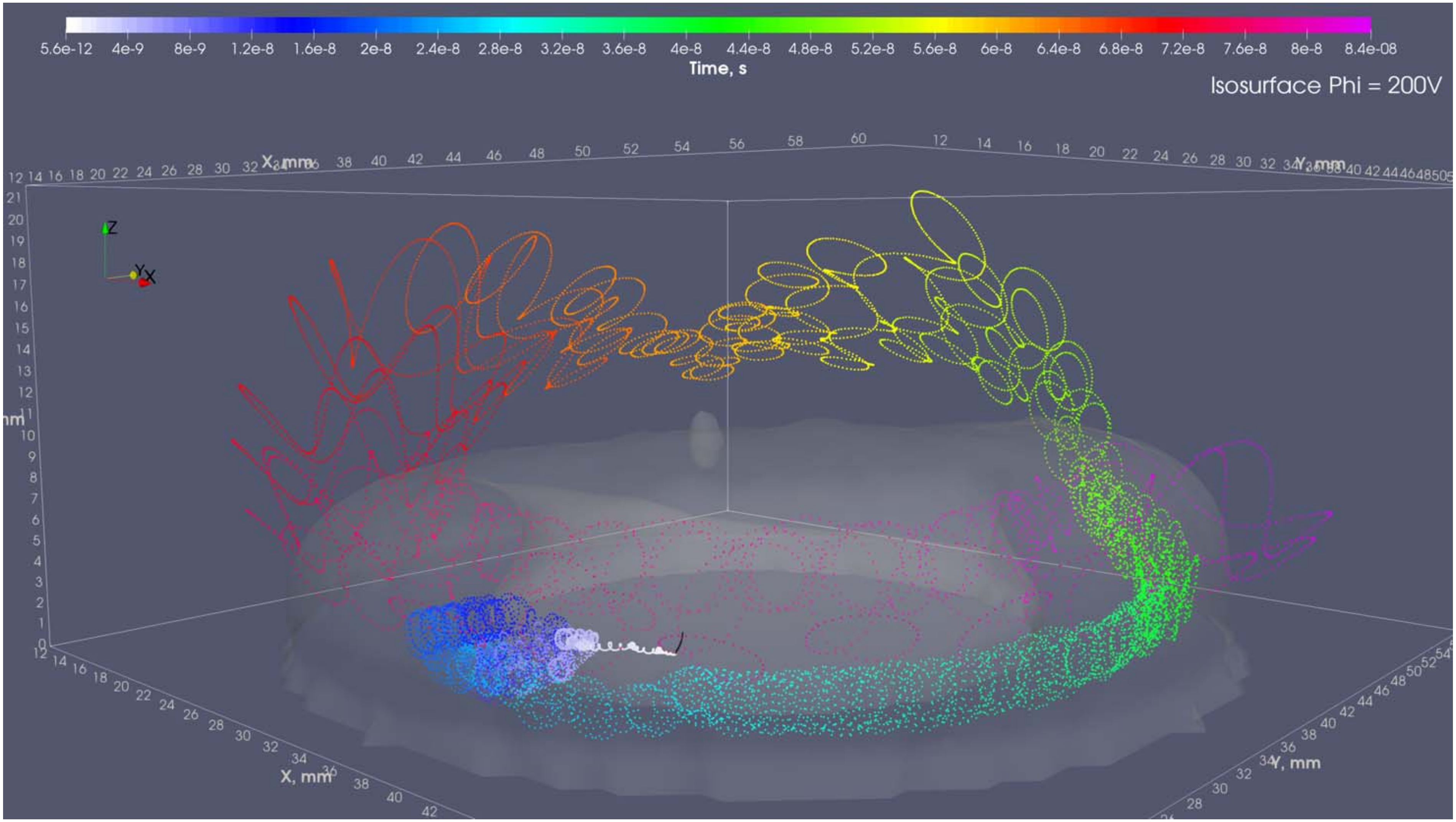
Electron trajectories inside the spoke



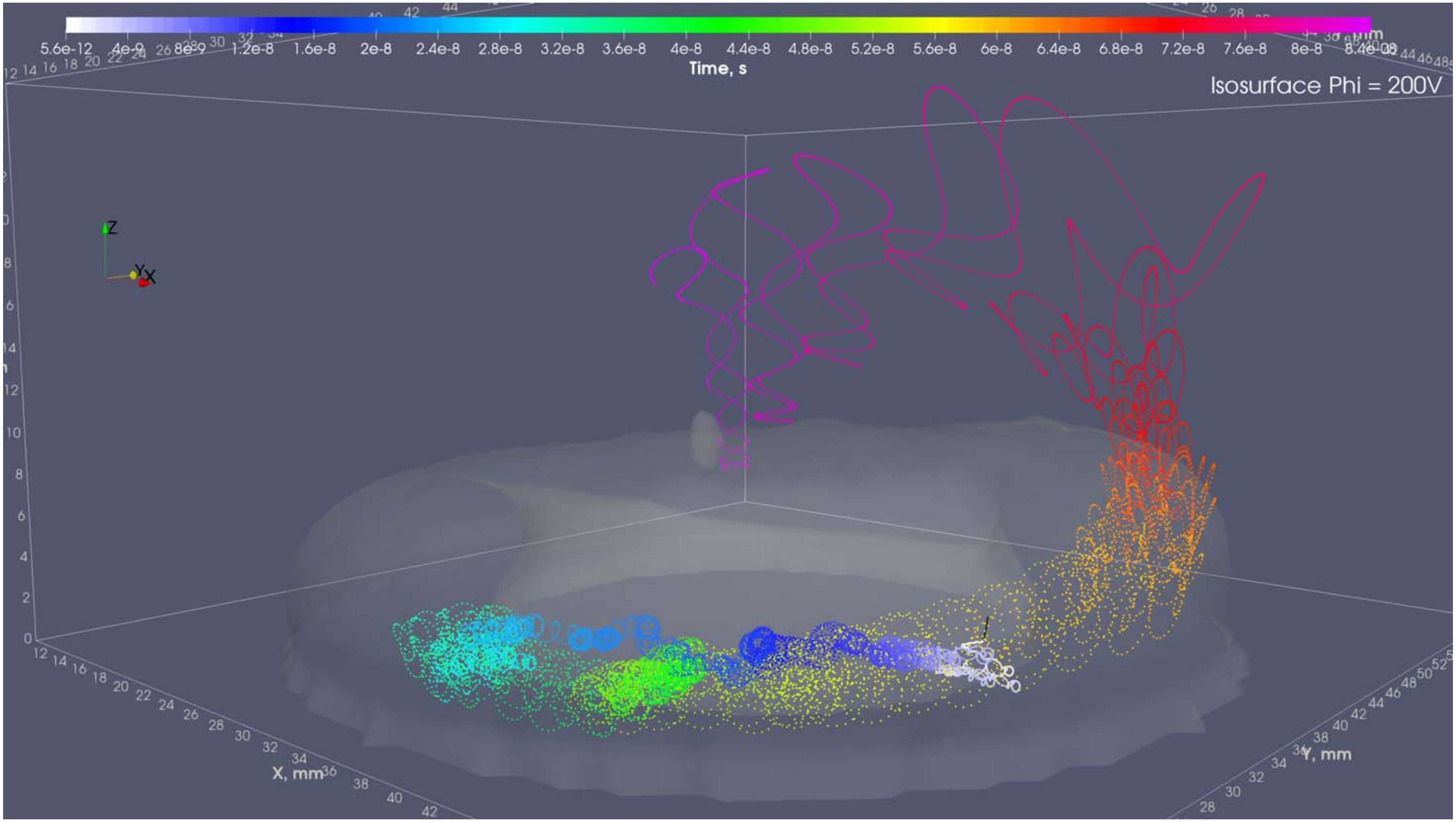
Electron trajectories inside the spoke



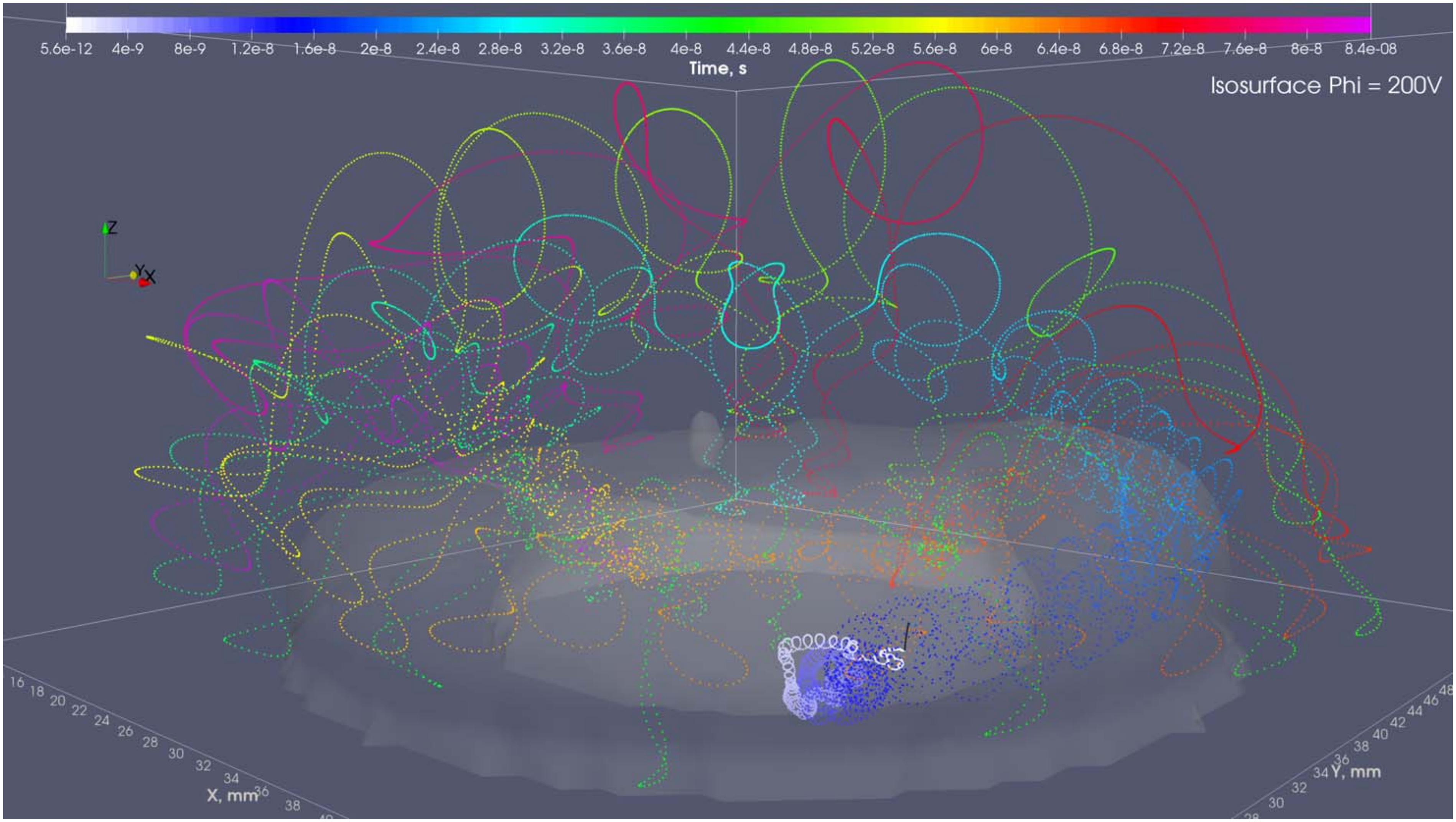
Electron trajectories inside the spoke



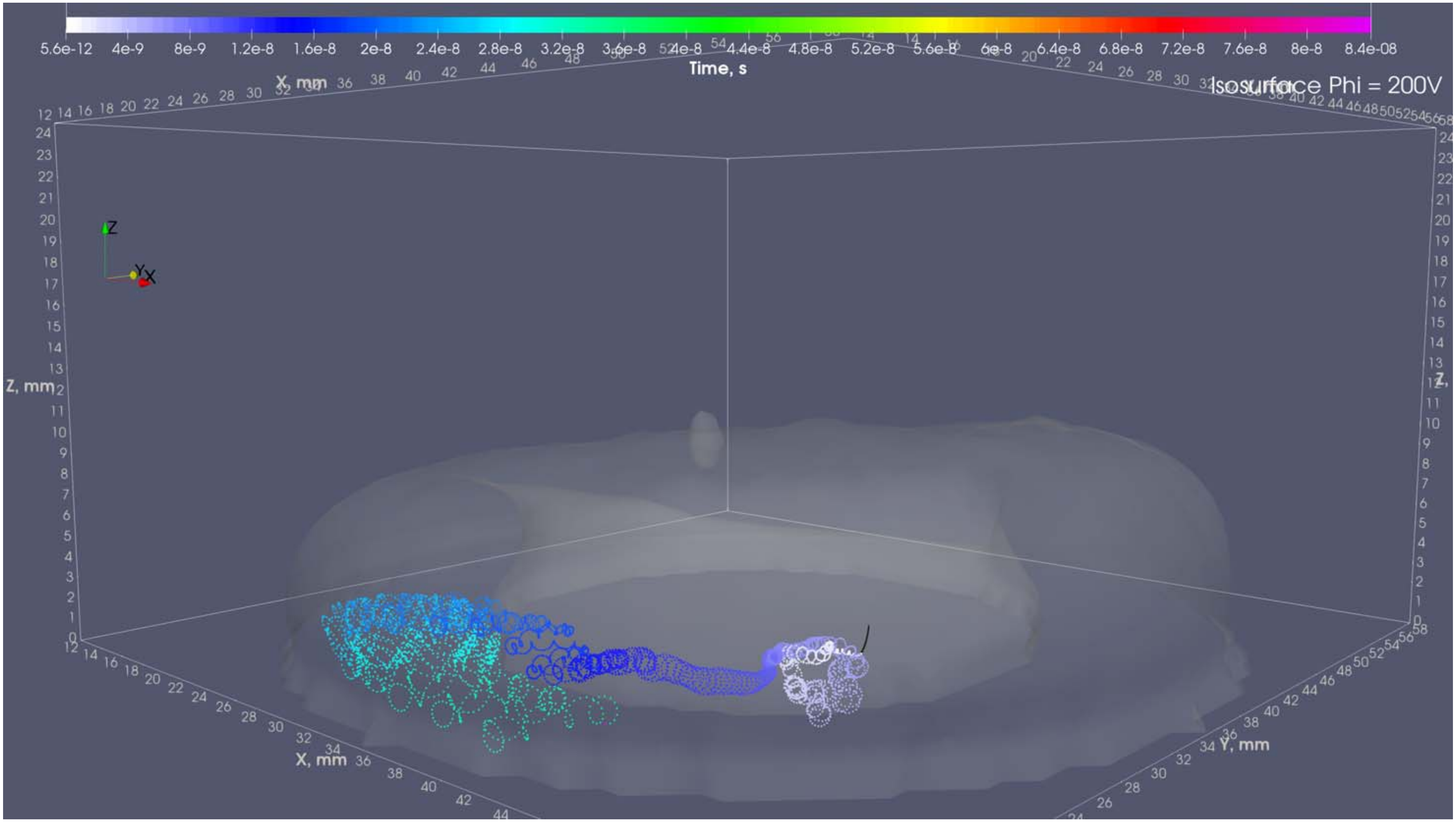
Electron trajectories inside the spoke



Electron trajectories inside the spoke

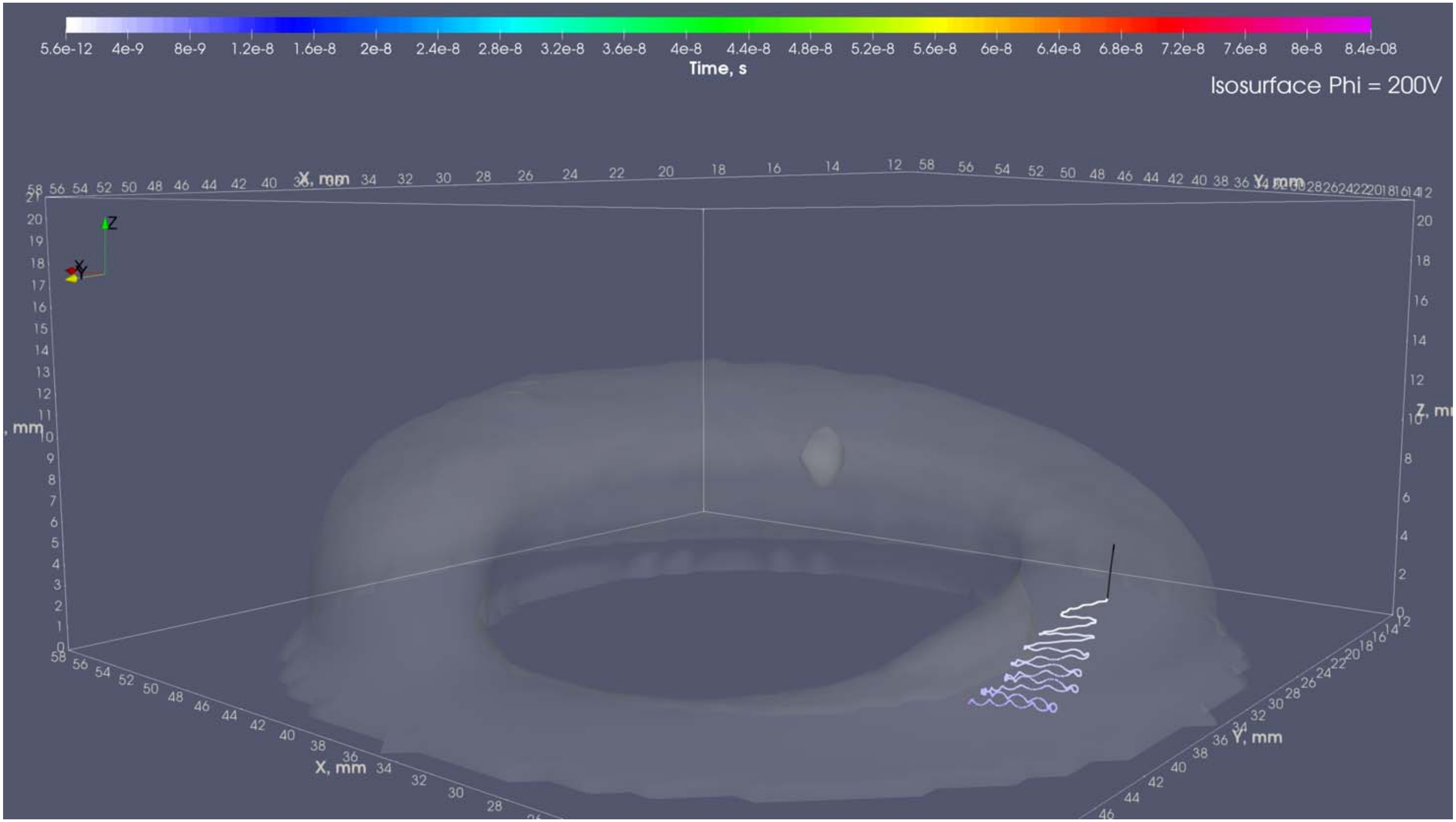


Electron trajectories inside the spoke

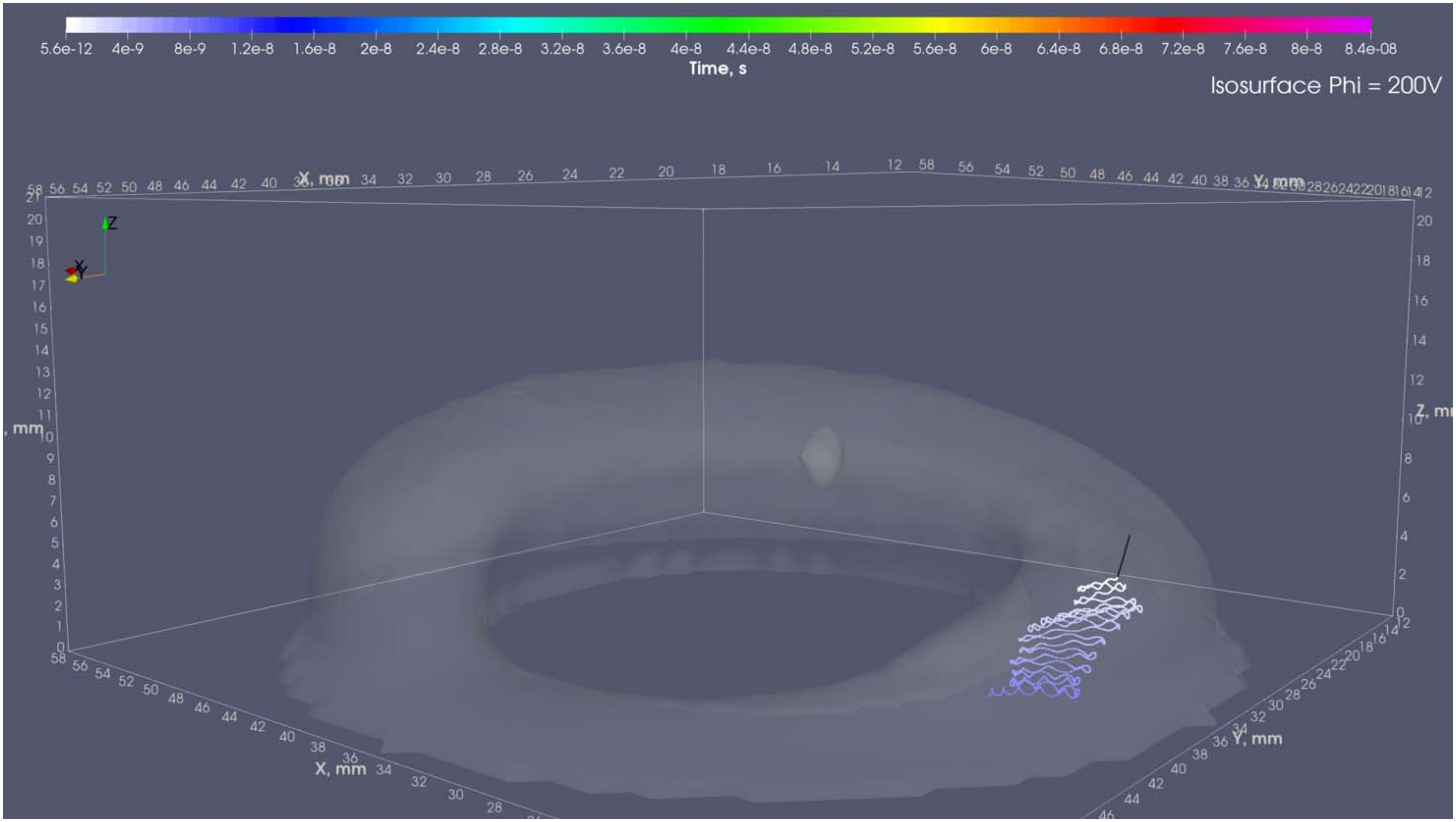


Electron motion inside the spoke dominated by diffusion of the guiding centers in HF fields, not a regular drift in a macroscopic E-field.

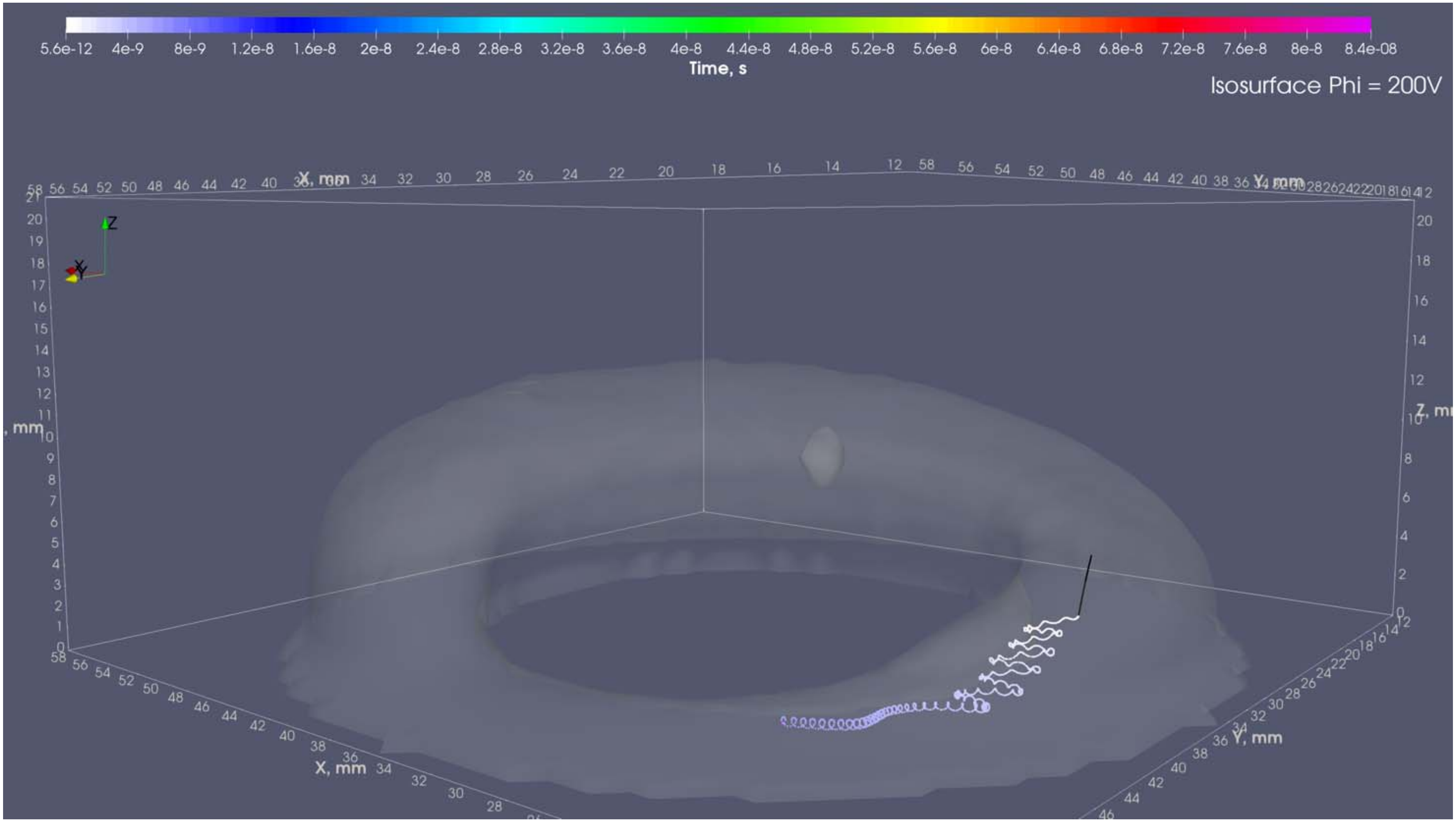
Electron trajectories at spoke front



Electron trajectories at spoke front

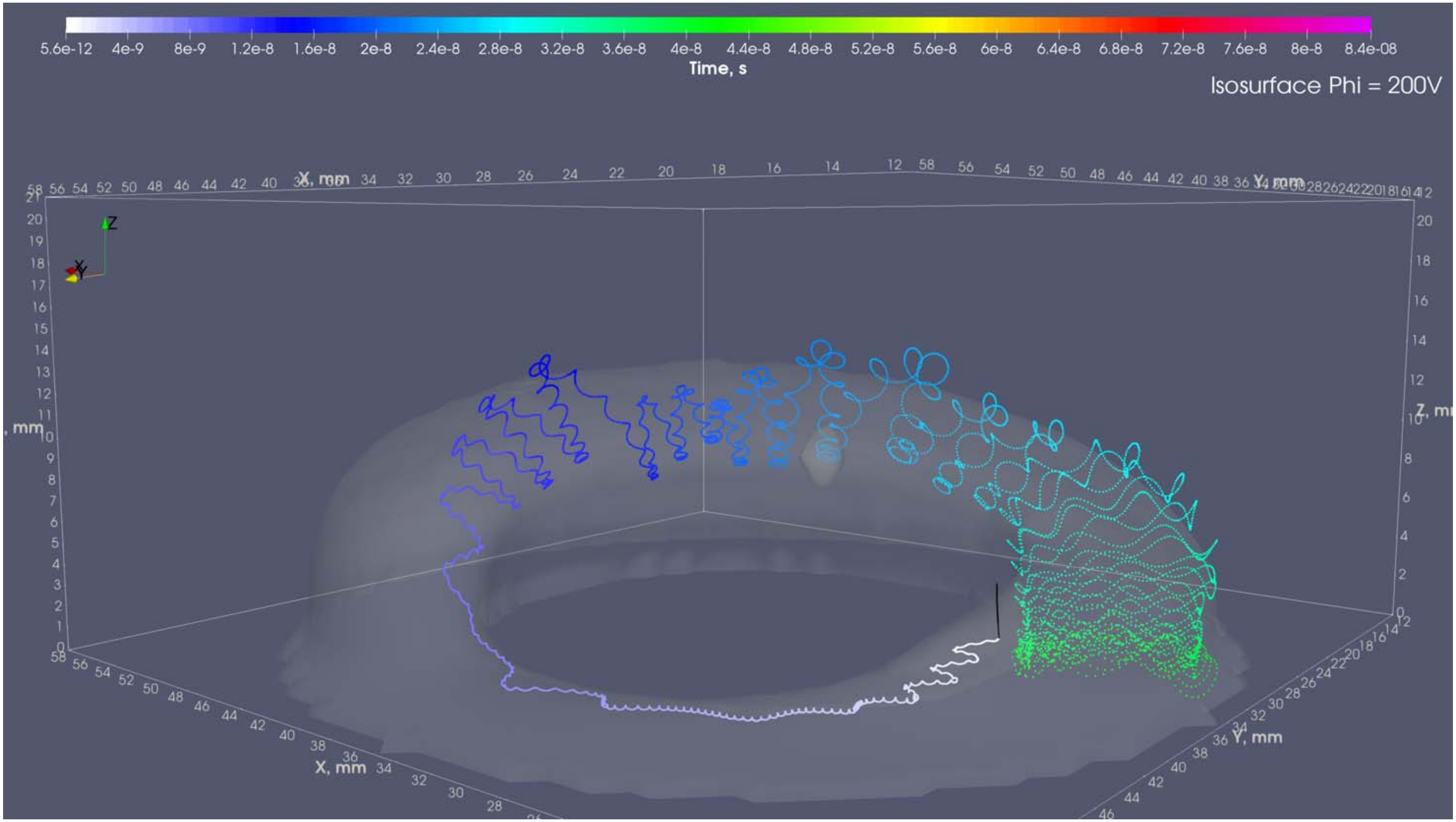


Electron trajectories at spoke front

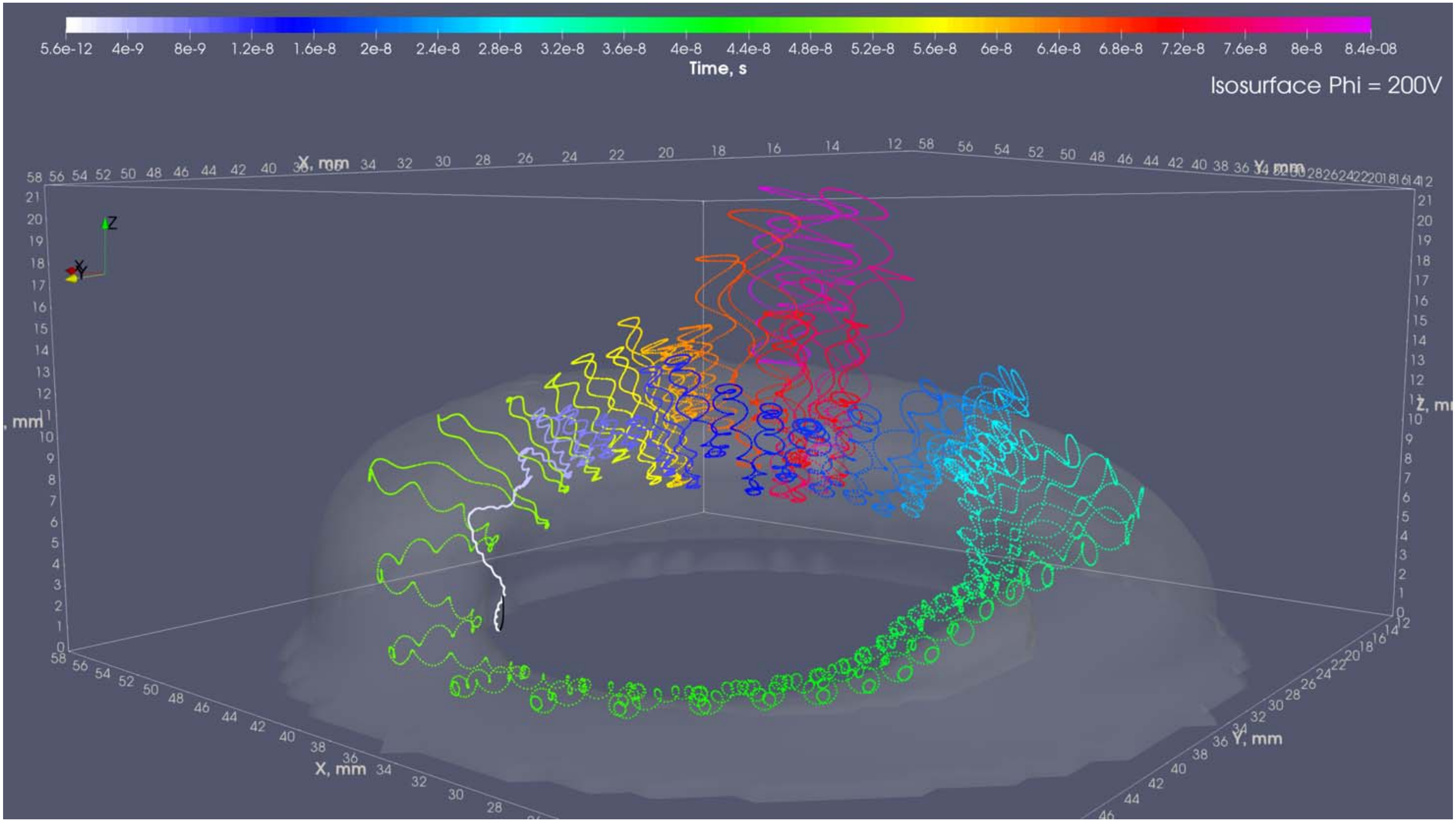


Electron motion at spoke front - ExB drift clockwise and down toward the anode. Spoke contribution to the anode current

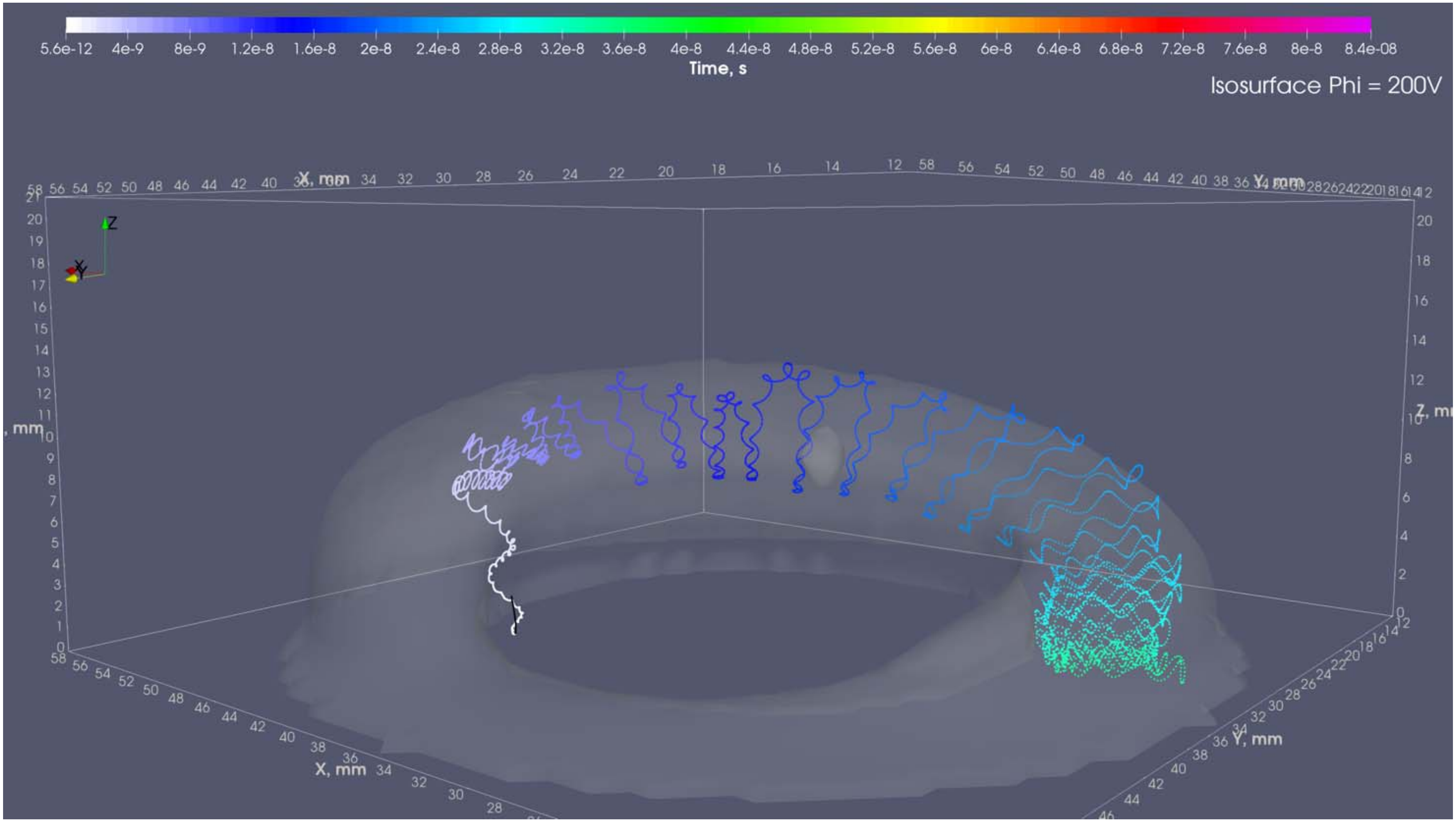
Electron trajectories at spoke back



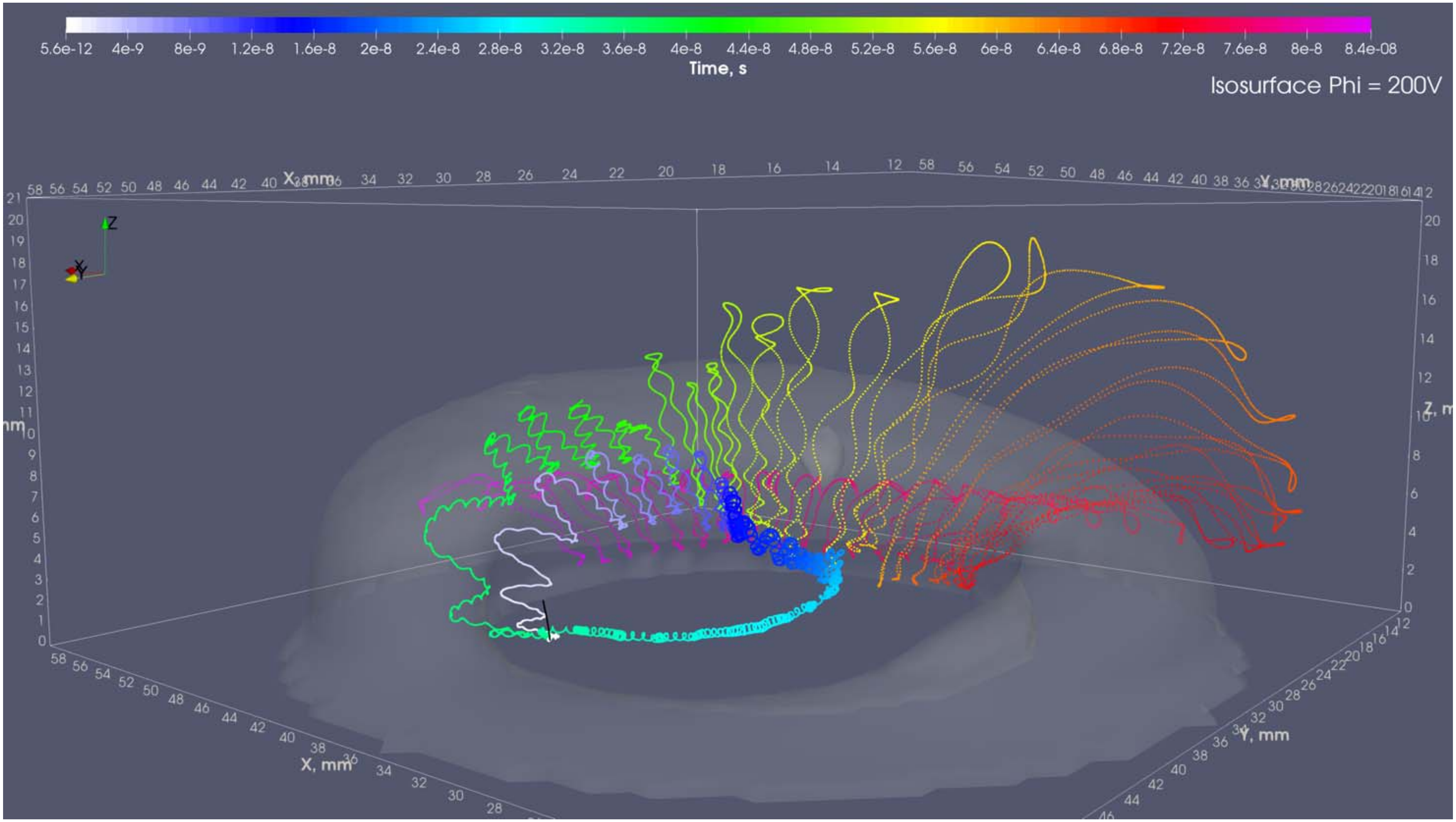
Electron trajectories at spoke back



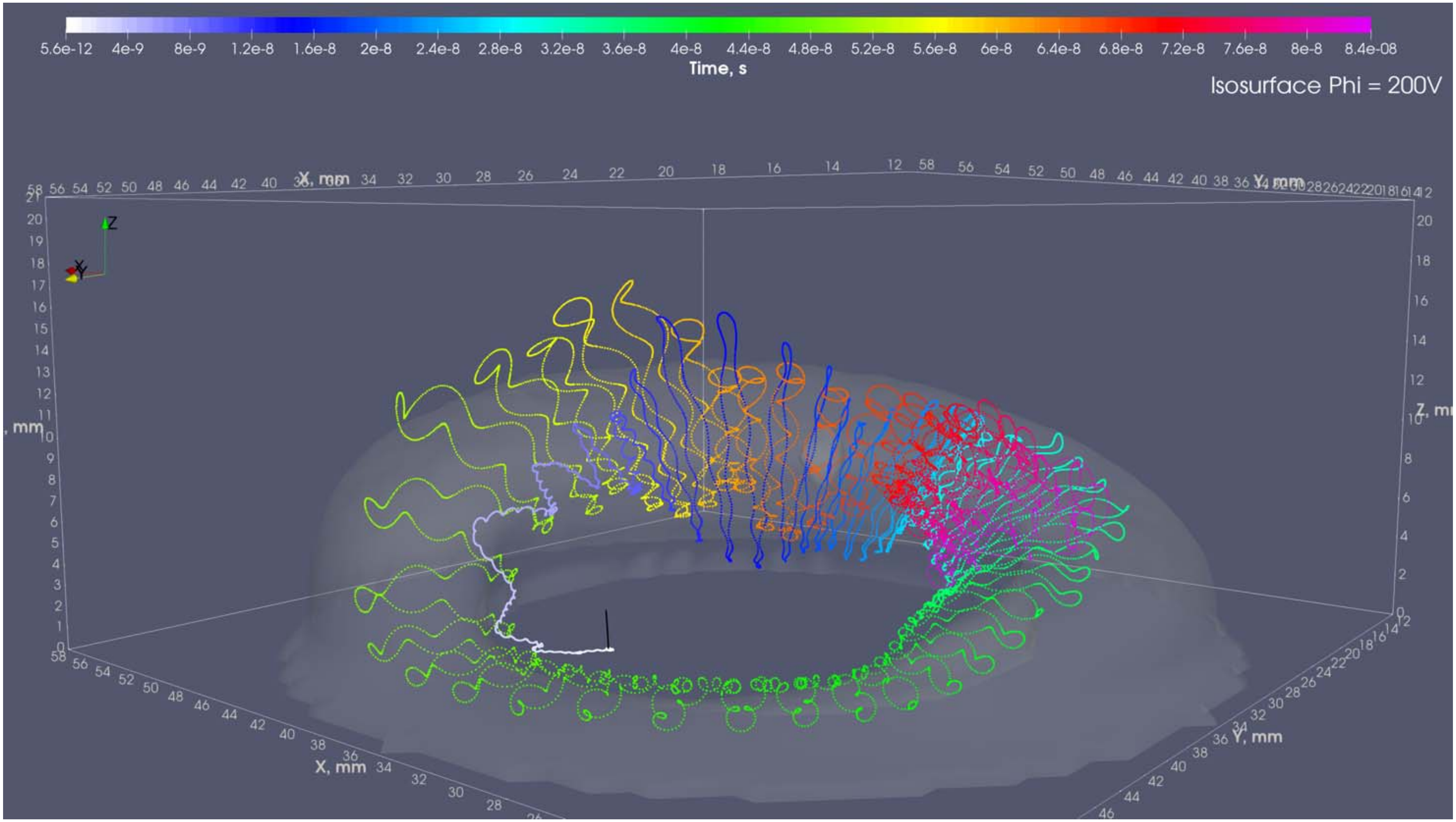
Electron trajectories at spoke back



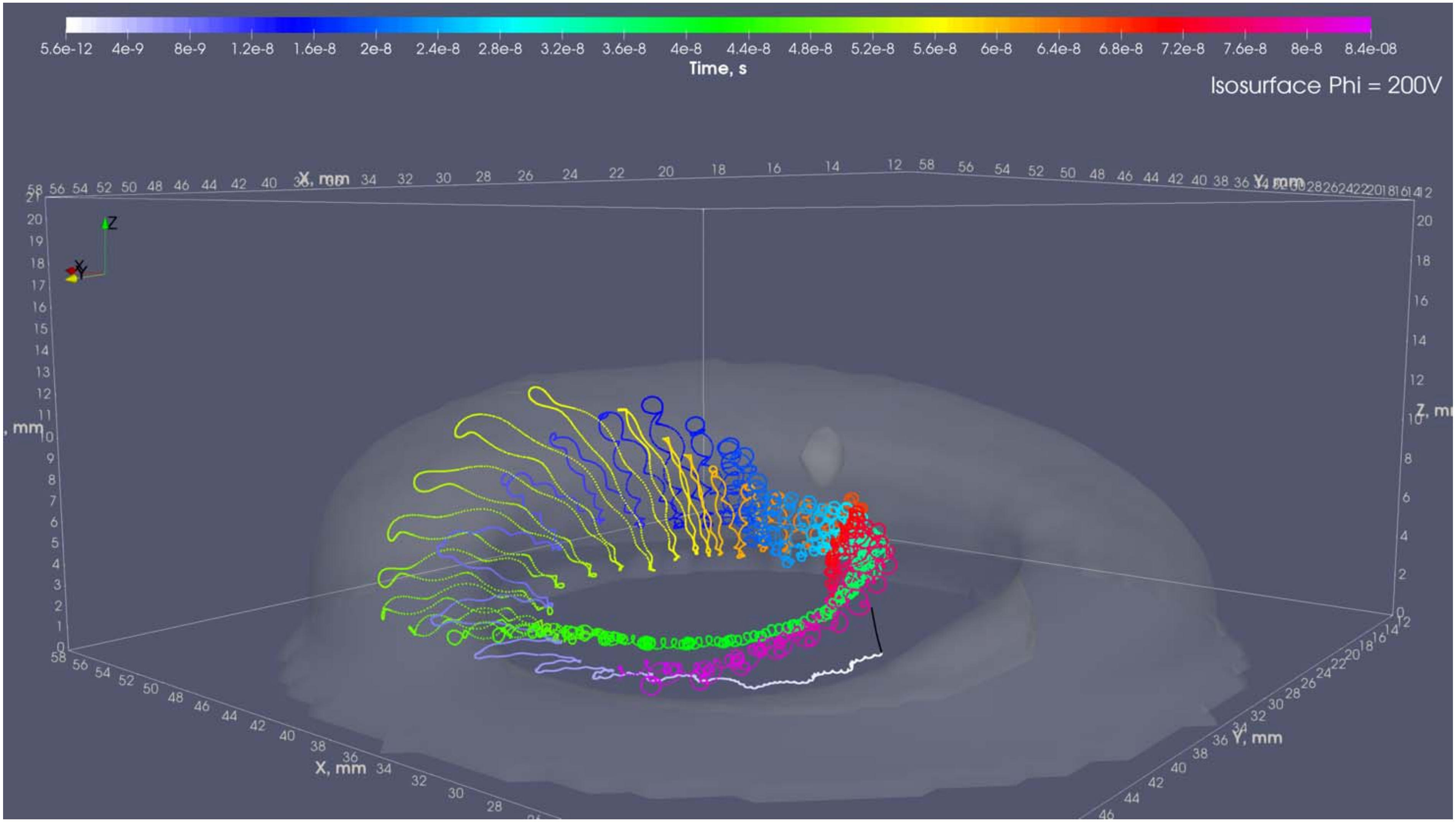
Electron trajectories at spoke back



Electron trajectories at spoke back



Electron trajectories at spoke back



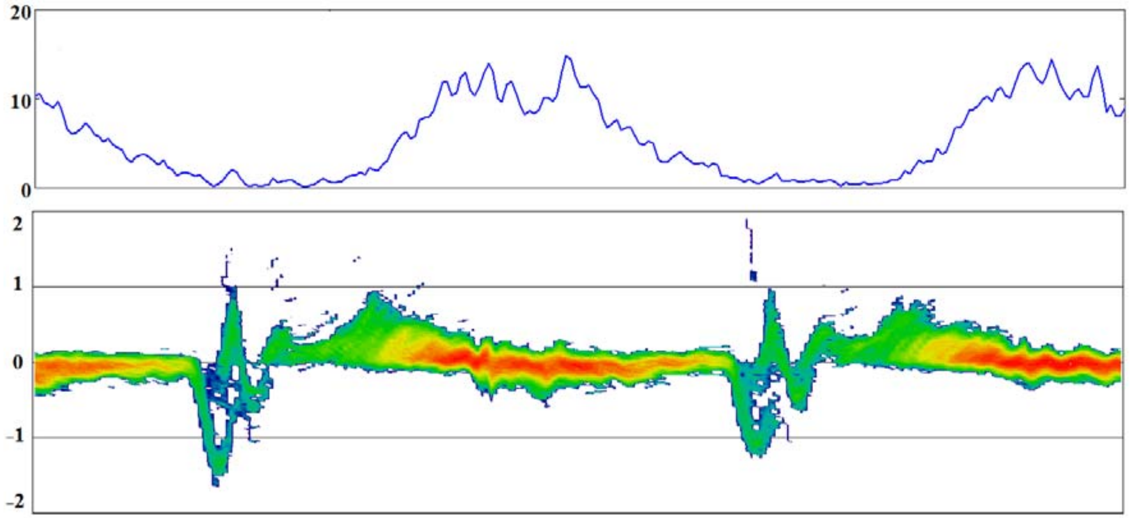
Electron motion at spoke back - ExB drift clockwise and up
Variety of the drift orbits

Conclusions

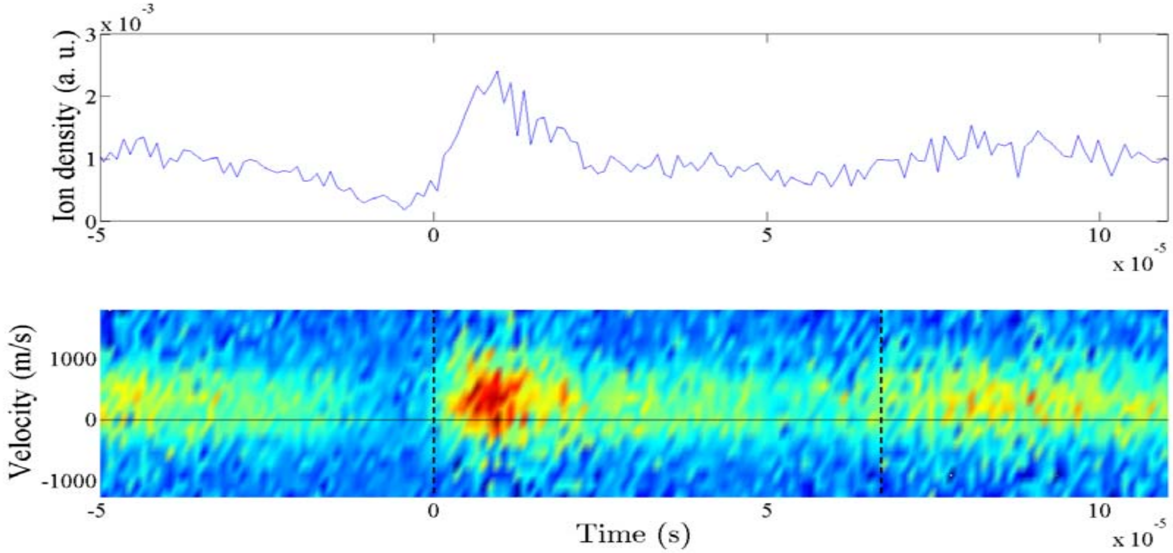
- **Full 3D PIC MCC model for ISCT200 is developed**
- **The model is able to resolve the anomalous electron transport due to azimuthal E-field fluctuations**
- **The spoke rotating with v ~4-5 km/s is observed in the simulations**
- **Spoke rotation is associated with azimuthal depletion of the neutral gas and azimuthal E-field oscillations f ~ 10 MHz**
- **Electron conductivity inside the spoke is dominated by diffusion of the guiding centers in the HF E-fields**
- **Electron conductivity at the spoke front - ExB drift in the macroscopic spoke E-field**
- **Further joint simulation and experiment efforts are necessary for clarification of the phenomena underlying the spoke formation and the dynamics**

Time-varying ion VDF (azimuthal component) at 110 V

PIC simulation



Time-resolved LIF measurements



Ions accelerated azimuthally in opposite directions by spoke front/back E-fields