

プラズマ中のダスト粒子挙動の シミュレーション

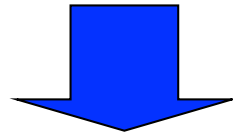
21 July, 2011

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Background-1

- **Dust** in fusion devices is one of the most critical issues, mainly related to the safety hazard.
 - Enhancement of the tritium inventory
 - Risk of explosion at an accidental air or coolant leakage
- **Dust** may be an important contributor of impurities in the main and SOL plasmas in some devices
(← The impurities may increase radiation loss)

⇒ Numerical simulation is a powerful tool nowadays for basic understanding of **dust particle formation and its transport in edge plasma condition** of fusion devices.



-Ion drag force & dust potential, etc
-Electron emission
-Improved to treat various materials

DUSTT code has been developed by Dr.A.Pigarov, UCSD cooperating UEDGE code (Dr.T.Rognlien, LLNL)

-Present work

Calculation of behaviors of C dust particles in a plasma in JT-60U configuration with DUSTT code

- Behavior of individual dust launched from different wall positions with different initial radii and different initial velocities.**
- Statistical analysis of dust particles with different initial velocities.**

1-100 micron

-Calculation of trajectories, temporal evolution in temperature, mass, electronic charge, velocity etc of dust particles in a plasma in JT-60U.

Other examples:

Behavior of ablating particles in plasmas

- Spallation particle flight from polymer bulk irradiated by plasmas
- Evaporation simulation of polymer particle

Underlying physics equations of dust particles in a plasma-1

-Equation of motion of dust particle:

$$\frac{4}{3}\pi r_d^3 \rho_d \frac{d\mathbf{v}_d}{dt} = \underbrace{\xi (F_c + F_o)}_{\text{-Ion friction forces}} + \underbrace{F_a}_{\text{-Neutral particle friction forces}} - \underbrace{eZ_d E}_{\text{-Electric field force due to charging of the dust}} + \underbrace{M_d \mathbf{g}}_{\text{-Gravity}}$$

Spinning effect
is neglected

-Ion friction forces

-Neutral particle friction forces

-Shape factor(=1.0 for sphere)

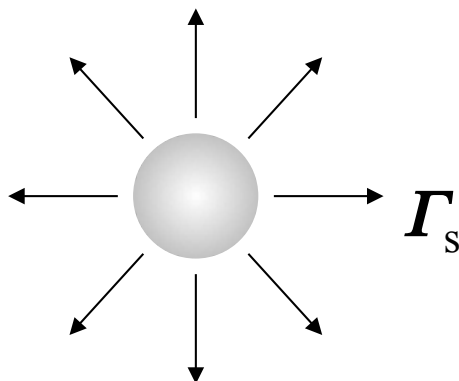
-Gravity

-Electric field force
due to charging of the dust

-Equation of mass of dust particle:

$$\frac{d}{dt} \left(\rho_d \frac{4}{3} \pi r_d^3 \right) = - \underbrace{4\pi r_d^2 m_s \Gamma_s}_{\text{-Mass flux due to physical \& chemical sputtering, RES, thermal evaporation/sublimation}}$$

-Mass flux due to
physical & chemical
sputtering, RES,
thermal evaporation/sublimation

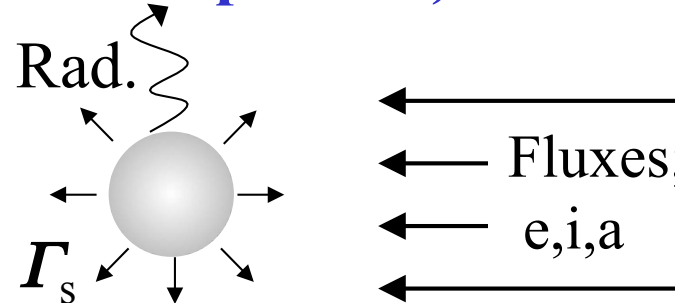


Uniform mass loss
in radial direction

→ Dust shape is always sphere.

Underlying physics equations of dust particles in a plasma-2

-Equation of energy (uniform temperature profile assumption inside a dust particle):



$$\left. \begin{aligned} &\frac{d}{dt} \left(\rho_d \frac{4}{3} \pi r_d^3 \int_0^{T_d} c_{pd} dT \right) \\ &\quad (T_d < T_m, \quad T_m < T_d) \\ &\text{-Liquid fraction} \\ &\frac{d}{dt} \left(\rho_d \frac{4}{3} \pi r_d^3 H_m \eta_\ell \right) \\ &\quad (T_d = T_m) \\ &\text{For melting process} \end{aligned} \right\} = 4\pi r_d^2 \left[\begin{aligned} &\underbrace{(P_{\text{kin},i} + P_{\text{kin},a} + P_{\text{kin},e} + P_{\text{pot}})}_{\text{-Heating power transfer from ions, electrons \& neutrals in a plasma}} \\ &\underbrace{-(P_{\text{rad}} + P_{\text{ps}} + P_{\text{cs}} + P_{\text{res}} + P_{\text{evap}} + P_{\text{e-emit}})}_{\text{-Cooling power due to thermal radiation, physical \& chemical sputtering, RES, thermal evaporation, electron emission}} \end{aligned} \right]$$

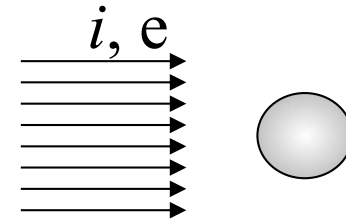
-Latent heat for melting

Calculation of floating potential of dust from quasi-equilibrium (1)

-Quasi-equilibrium condition for dust:

$$\Gamma_e = \Gamma_i + \Gamma_e^{\text{TE}} + \Gamma_e^{\text{SEE}} \quad \phi_d[\text{V}] = -\frac{T_i[\text{eV}]}{e} \chi = \frac{Z_d e^2}{r_d}$$

(Floating potential of dust)



For negative floating potential of dust

-Electron flux from thermoionic emission (Richardson-Dushman's equation):

$$\Gamma_e^{\text{TE}} = \sigma_{\text{sb}} \left(\frac{4\pi m_e (kT_d)^2}{h^3} \right) \exp\left(-\frac{W_d}{kT_d}\right)$$

-Electron flux from plasma:

$$\Gamma_e = \frac{1}{4} n_e \left(\frac{8T_e}{\pi m_e} \right)^{\frac{1}{2}} \exp\left[-\left(\frac{T_i}{T_e}\right) \chi\right]$$

-Ion flux from plasma:

$$\Gamma_i = n_i \left(\frac{2T_i}{m_i} \right)^{\frac{1}{2}} \frac{u}{4} \left\{ \left(1 + \frac{1}{2u^2} + \frac{\chi}{u^2} \right) \text{erf}(u) + \frac{e^{-u^2}}{u\sqrt{\pi}} \right\}$$

Relative drift velocity:

$$u = \frac{|\mathbf{v}_i - \mathbf{v}_d|}{v_n} = \frac{|\mathbf{v}_i - \mathbf{v}_d|}{\left(\frac{2T_i}{m_i} \right)^{1/2}}$$

If Γ_e^{TE} or Γ_e^{SEE} is high,
the floating potential
of dust can be positive.

Calculation of floating potential of dust from quasi-equilibrium (2)

-Quasi-equilibrium condition for dust:

$$\Gamma_e = \Gamma_i + \Gamma_e^{\text{TE}} + \Gamma_e^{\text{SEE}}$$

$$\phi_d[\text{V}] = -\frac{T_i[\text{eV}]}{e} \chi = \frac{Z_d e^2}{r_d}$$

For positive floating potential of dust

-Electron flux from thermoionic emission (Richardson-Dushman's equation):

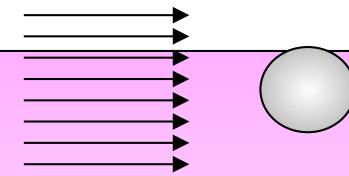
$$\Gamma_e^{\text{TE}} = \sigma_{\text{sb}} \left(\frac{4\pi m_e (kT_d)^2}{h^3} \right) \exp\left(-\frac{W_d}{kT_d}\right)$$

-Electron flux from plasma:

$$\Gamma_e = \frac{1}{4} n_e \left(\frac{8T_e}{\pi m_e} \right)^{\frac{1}{2}} \left[1 - \left(\frac{T_i}{T_e} \right) \chi \right]$$

-Ion flux from plasma:

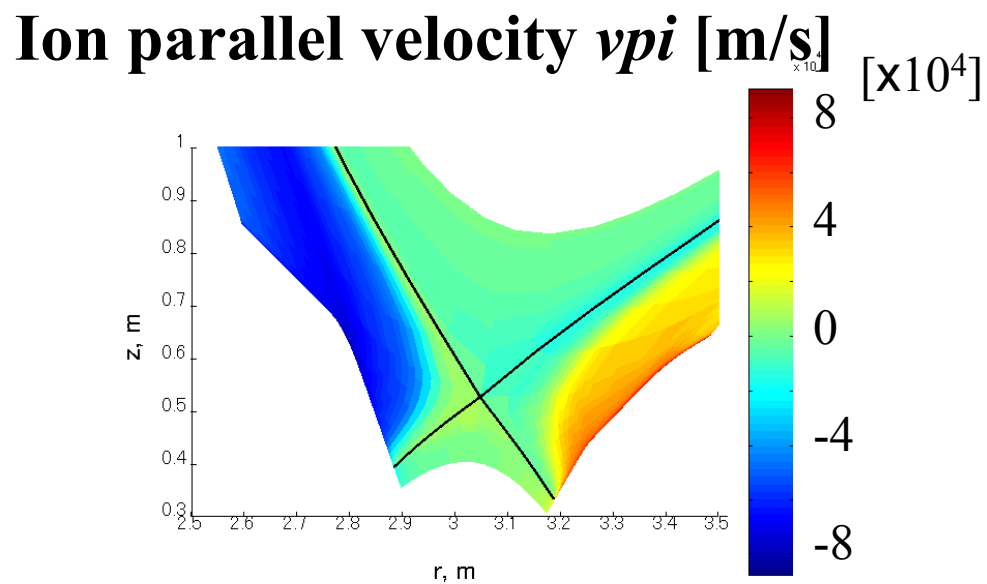
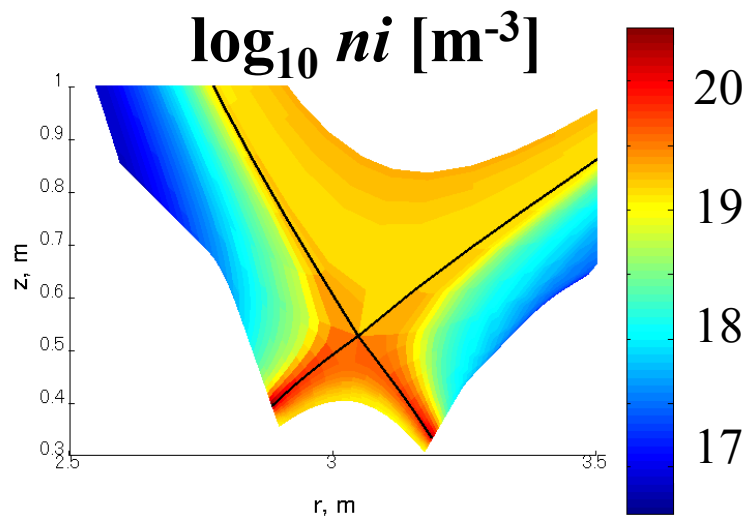
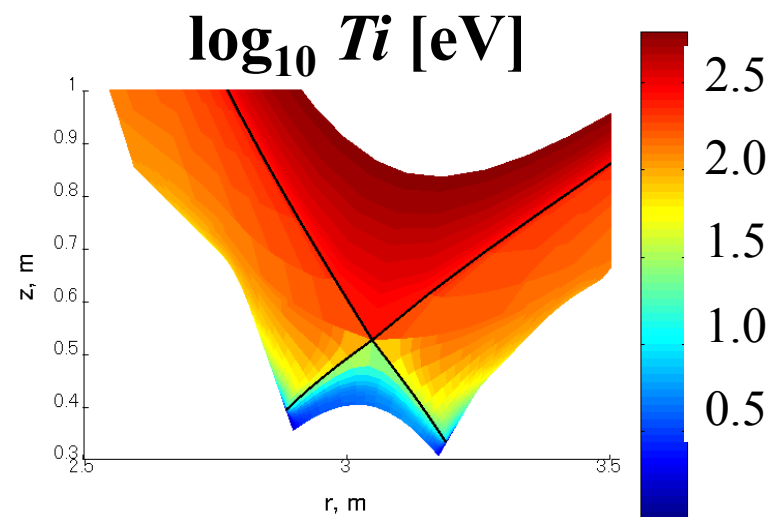
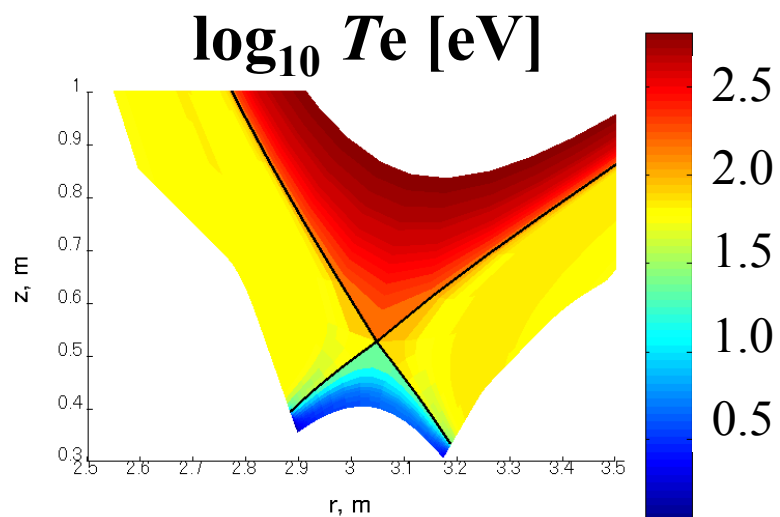
$$\Gamma_i = n_i \left(\frac{2T_i}{m_i} \right)^{\frac{1}{2}} \frac{u}{8} \left\{ \left(1 + \frac{1}{2u^2} + \frac{\chi}{u^2} \right) \left[\text{erf}(u + \sqrt{-\chi}) + \text{erf}(u - \sqrt{-\chi}) \right] + \frac{1}{u^2 \sqrt{\pi}} \left[(u + \sqrt{-\chi}) \exp[-(u - \sqrt{-\chi})^2] + (u - \sqrt{-\chi}) \exp[-(u + \sqrt{-\chi})^2] \right] \right\}$$



Relative drift velocity:

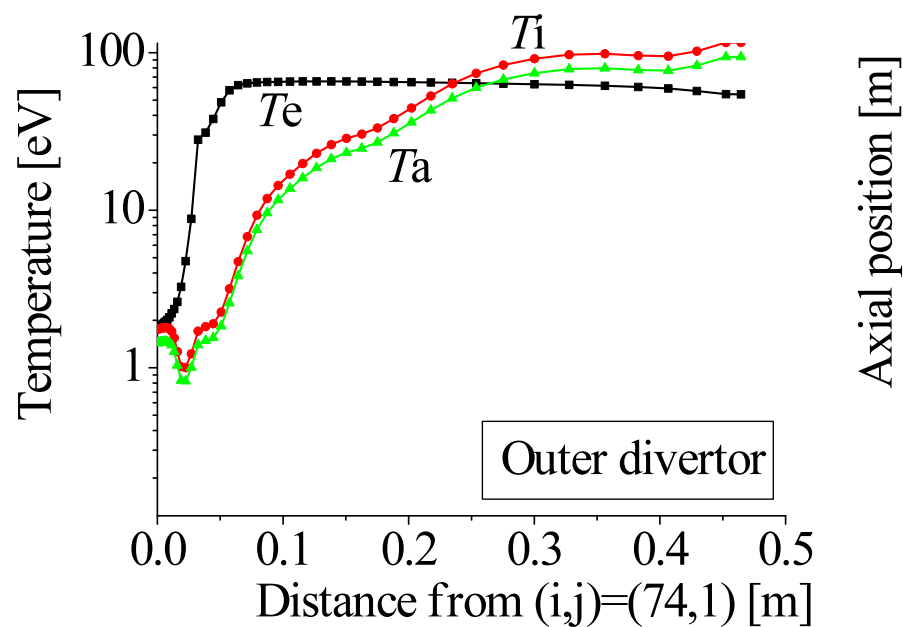
$$u = \frac{|\mathbf{v}_i - \mathbf{v}_d|}{v_n} = \frac{|\mathbf{v}_i - \mathbf{v}_d|}{\left(\frac{2T_i}{m_i} \right)^{1/2}}$$

Parameters of background plasma calculated with UEDGE code

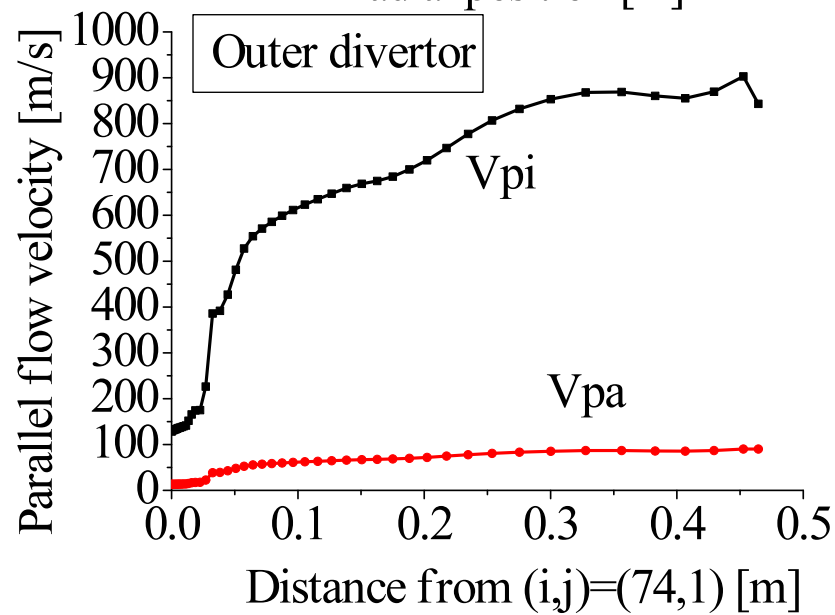
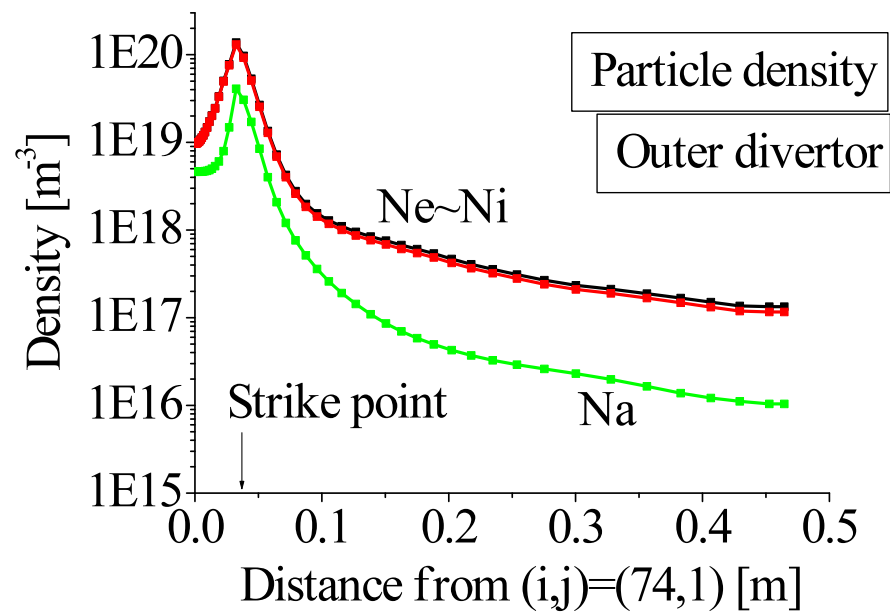
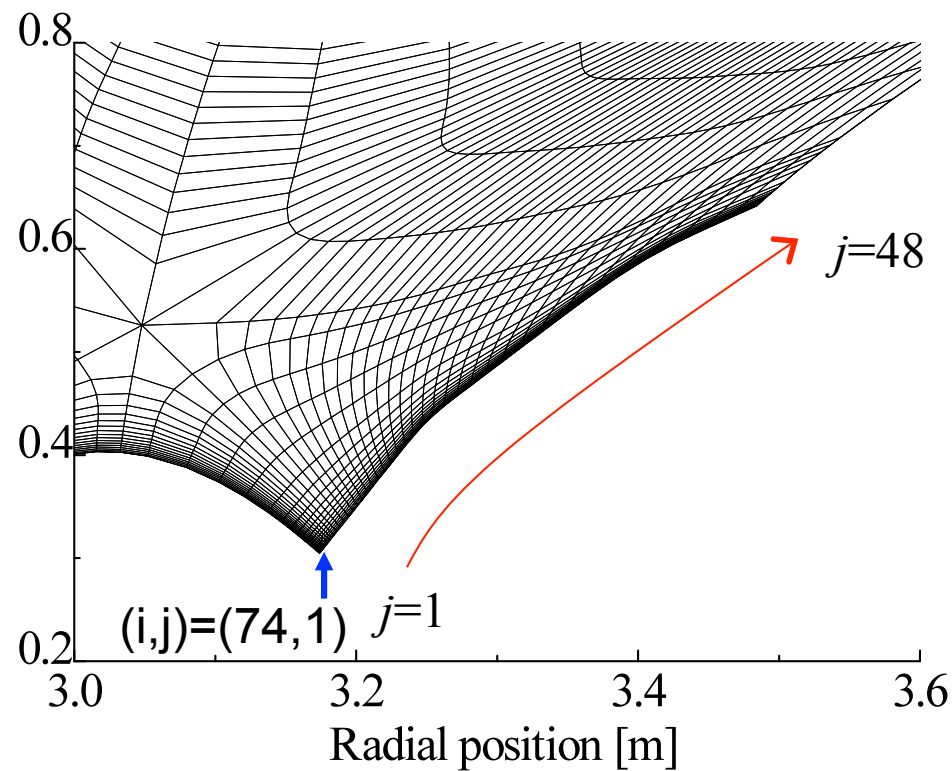


Calculated by Dr. Pigarov, UCSD

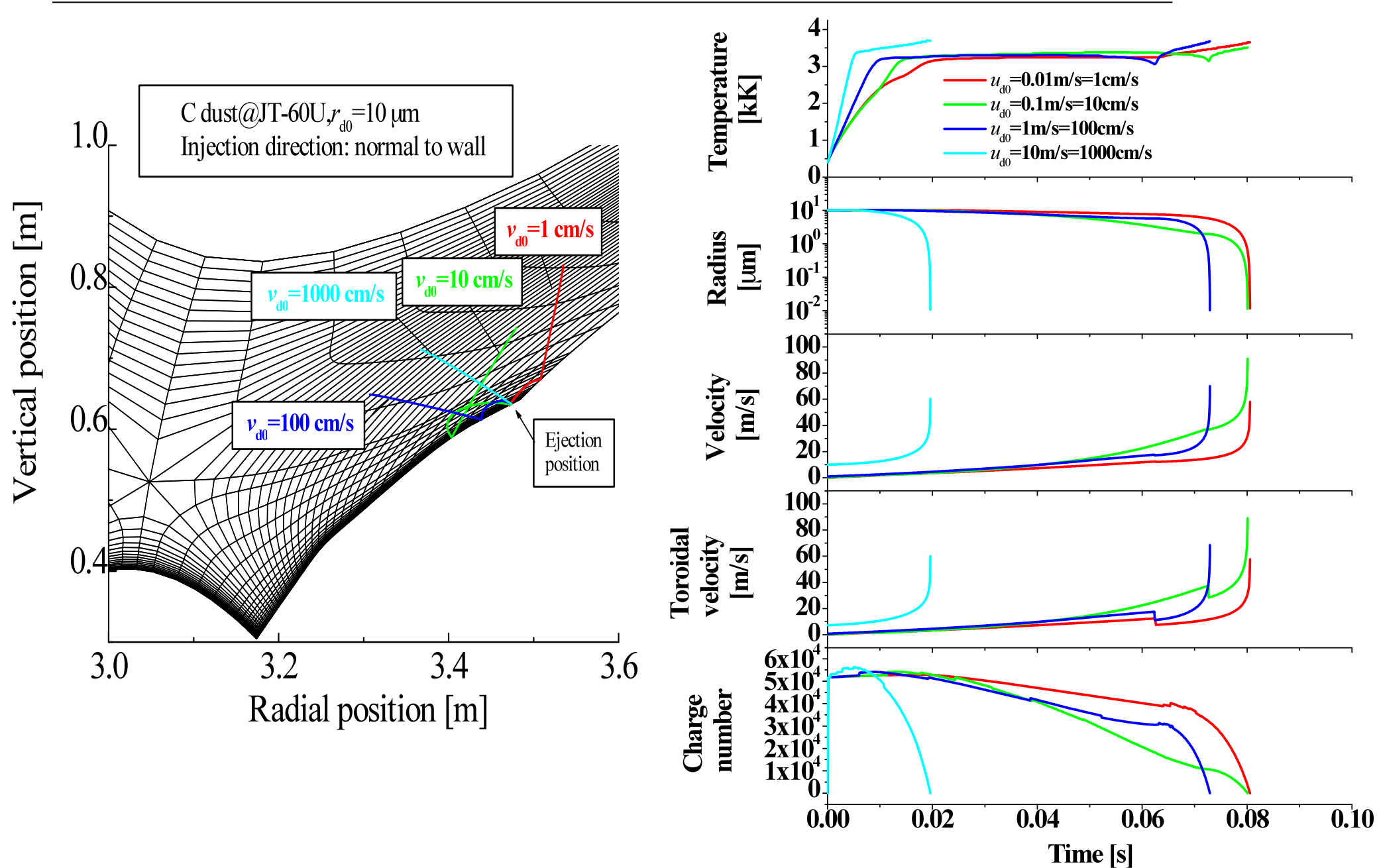
Outer-divertor



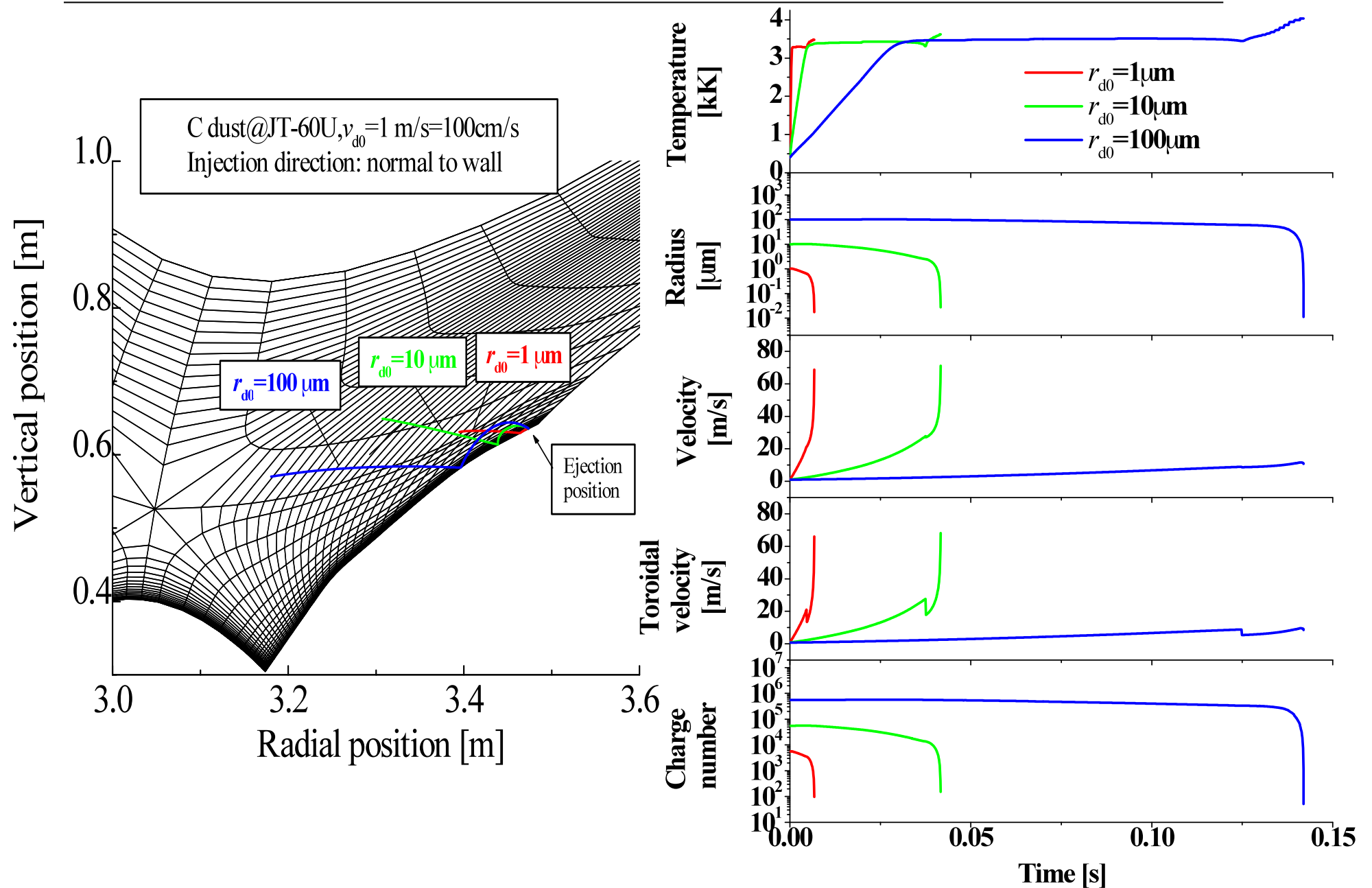
Axial position [m]



Trajectories of the dust from outer region for different initial dust velocities -#O1

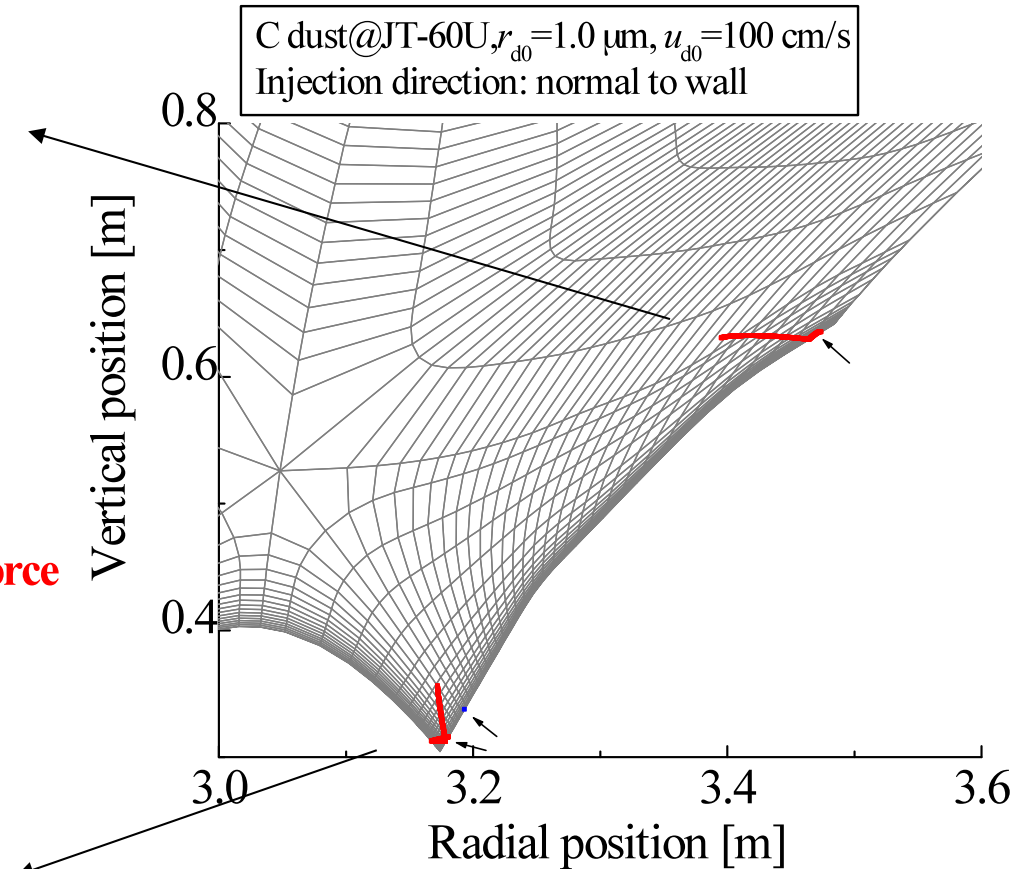
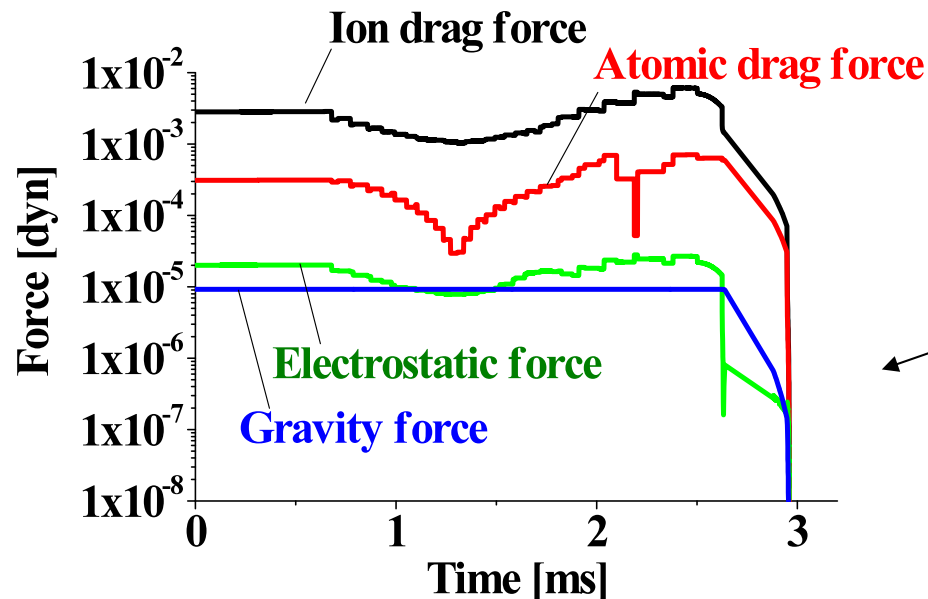
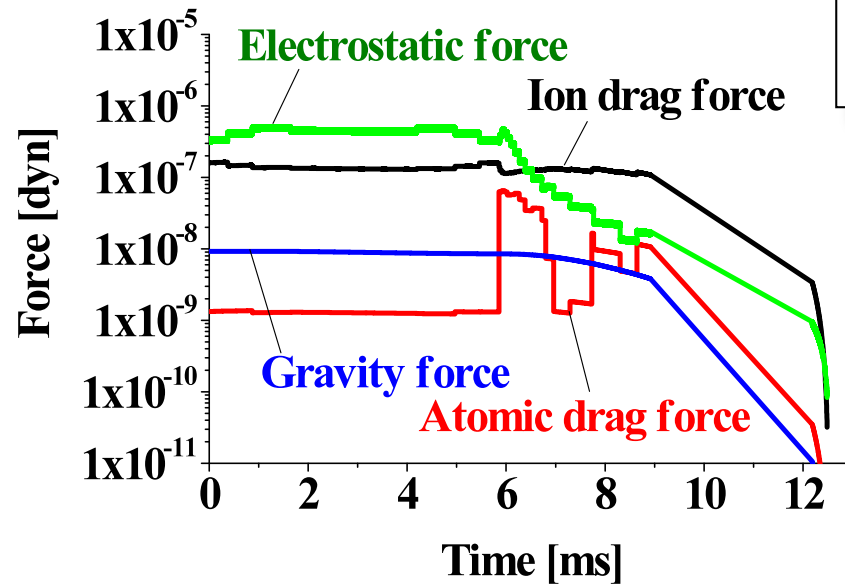


Trajectories of the dust from outer region for different initial dust radii -#O3



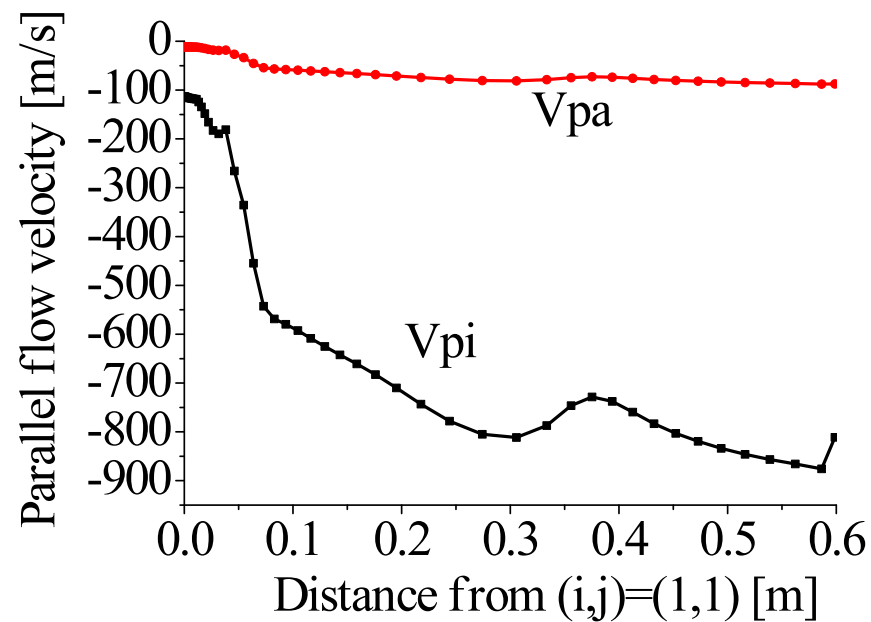
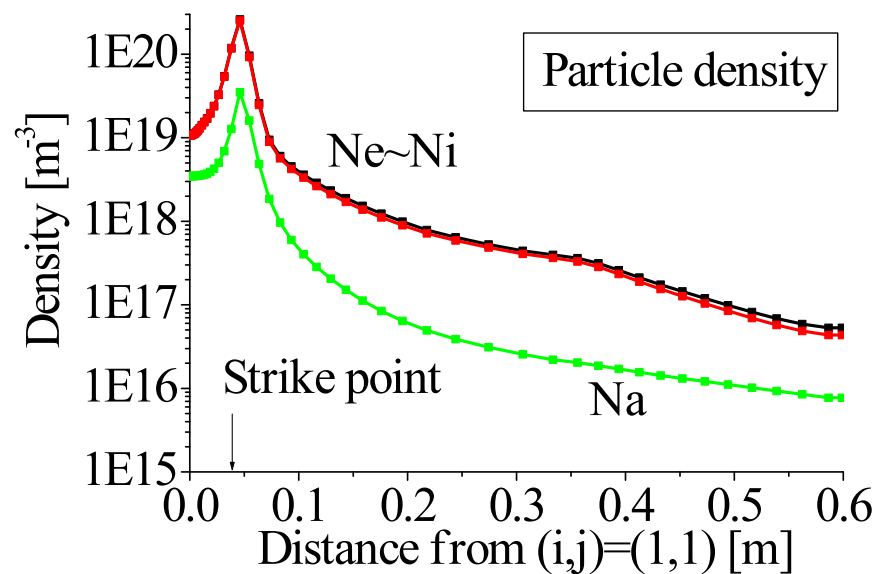
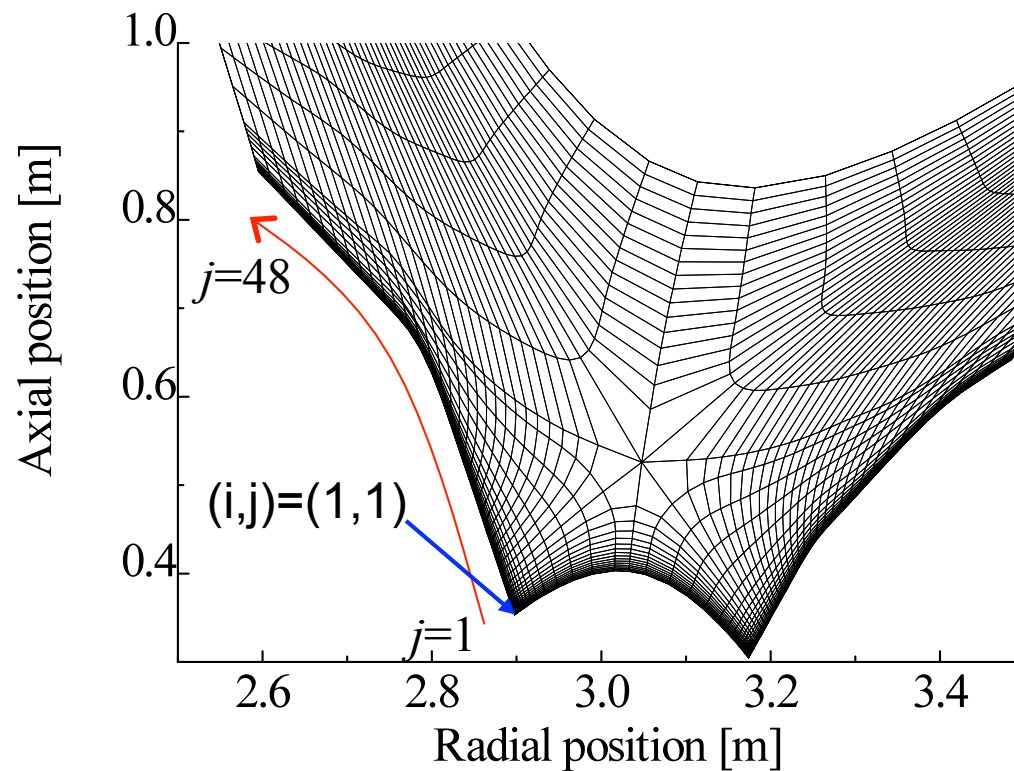
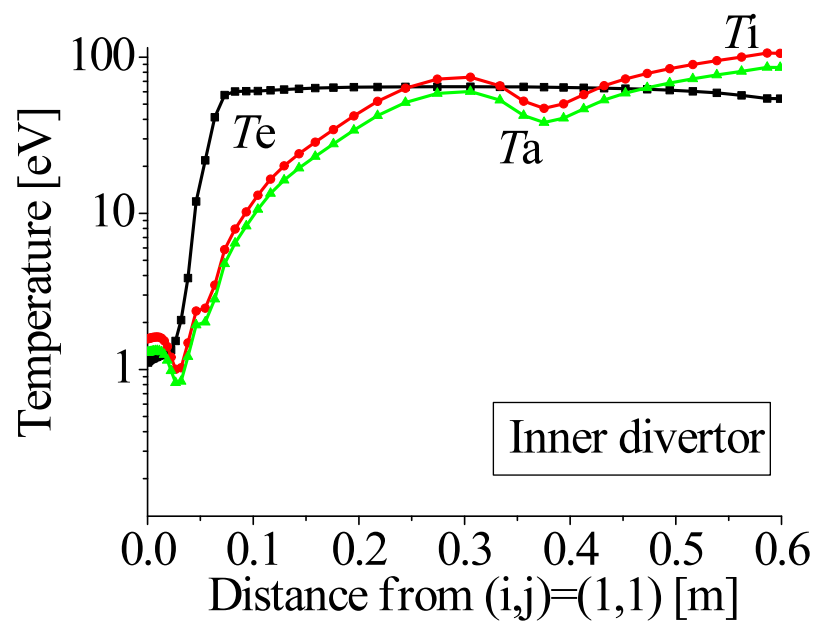
Applied forces onto the dust

-Initially, electrostatic force is dominant, and then is ion drag force

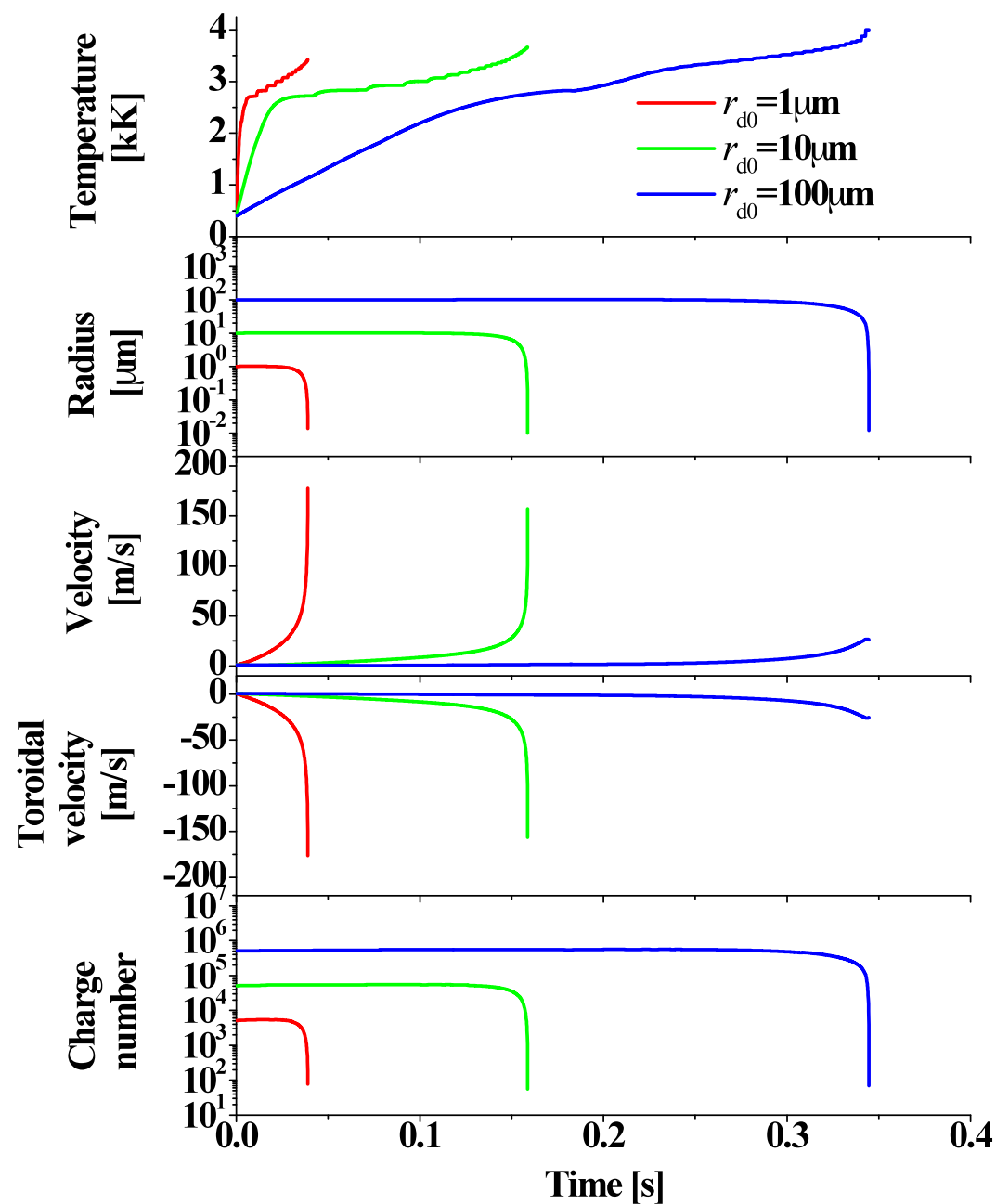
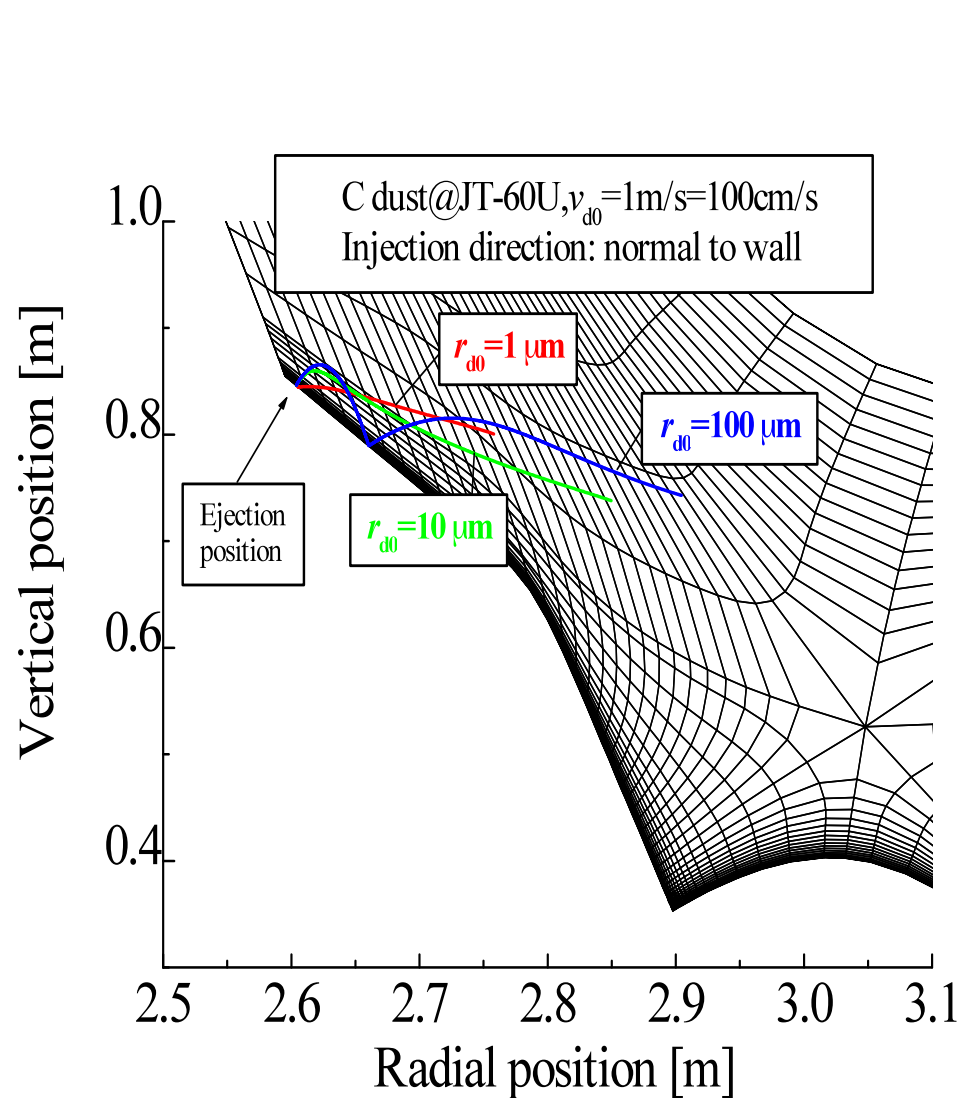


-Dominant force is ion drag force, and atomic drag force.

Inner-divertor

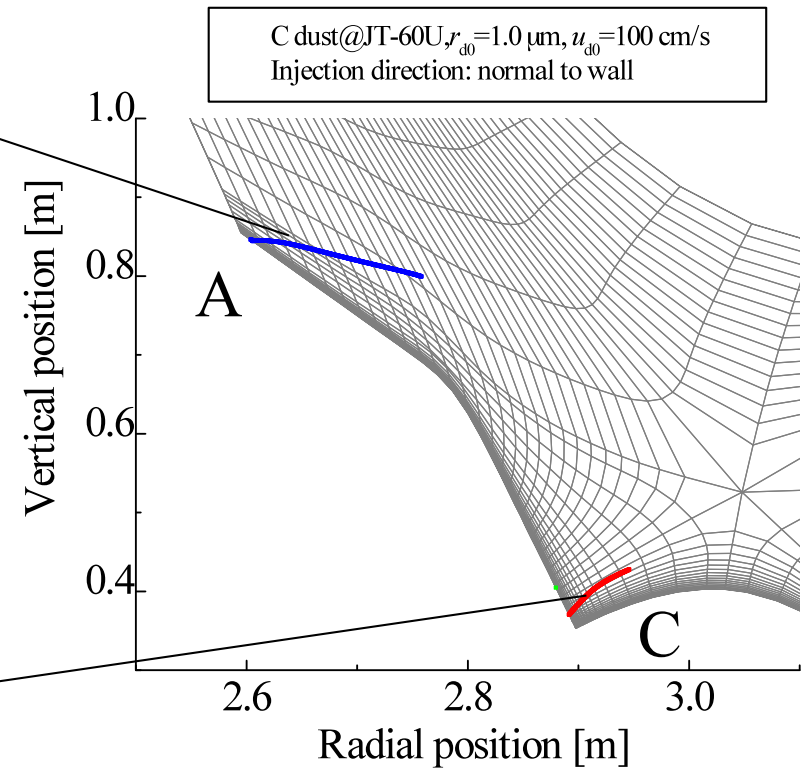
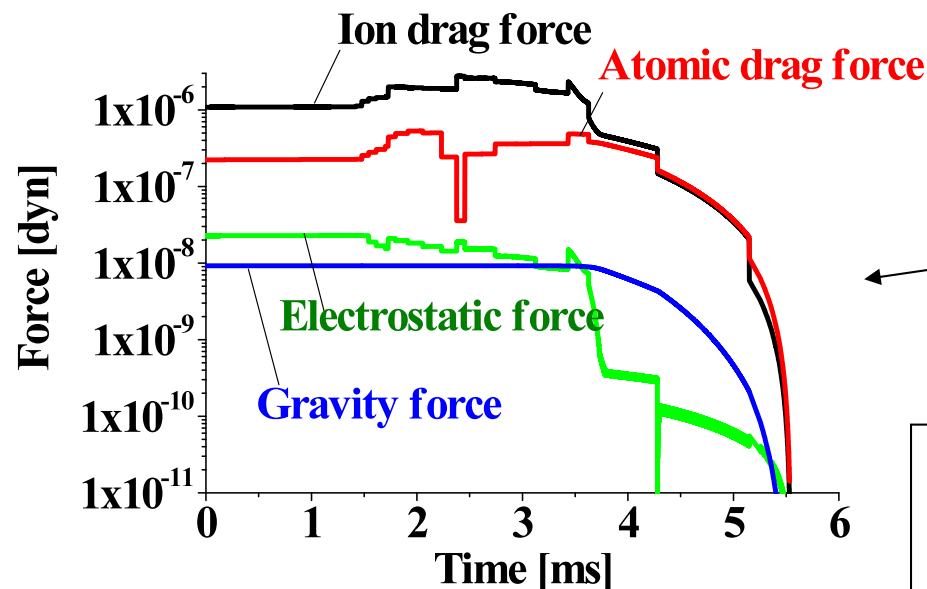
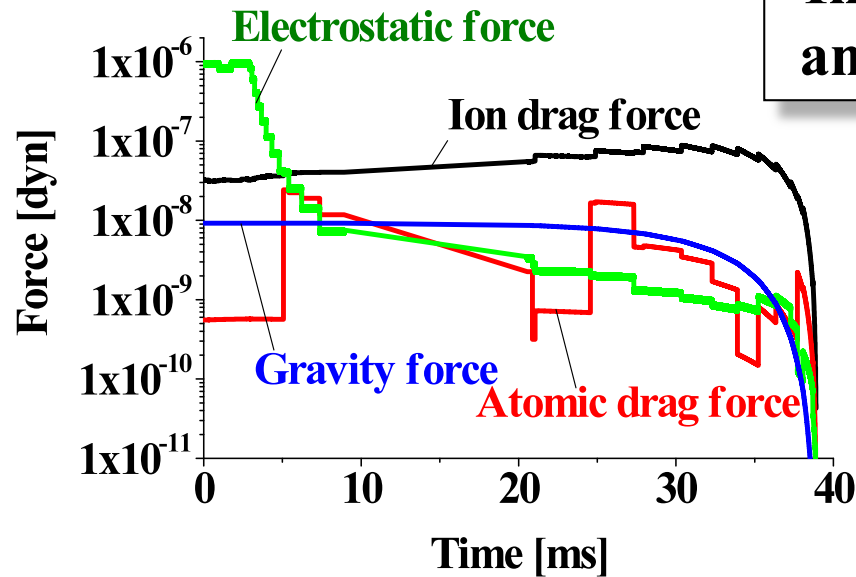


Trajectories of the dust from inner region for different initial dust radii -#13

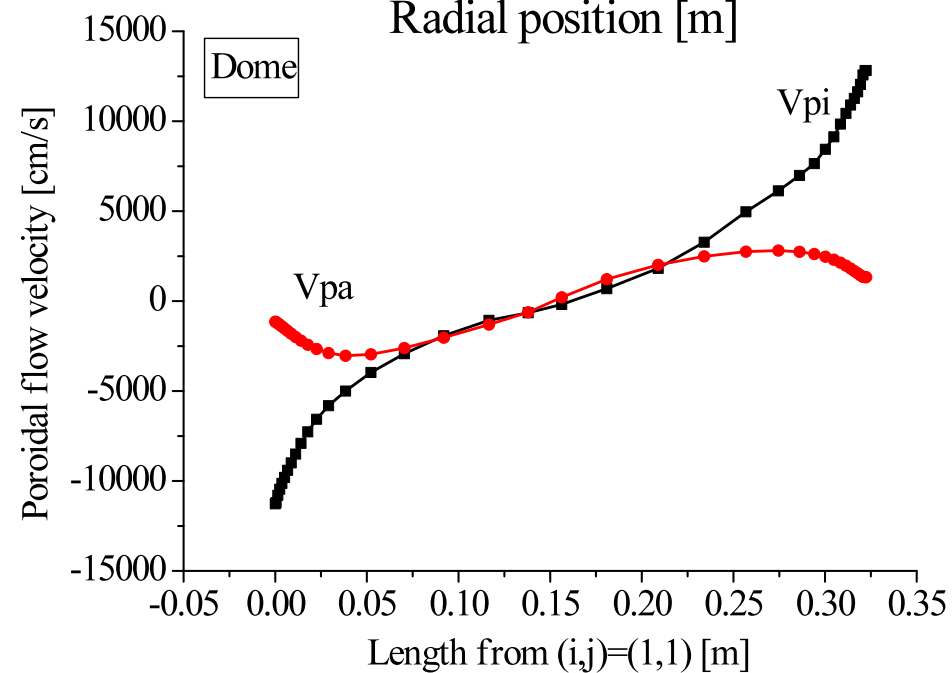
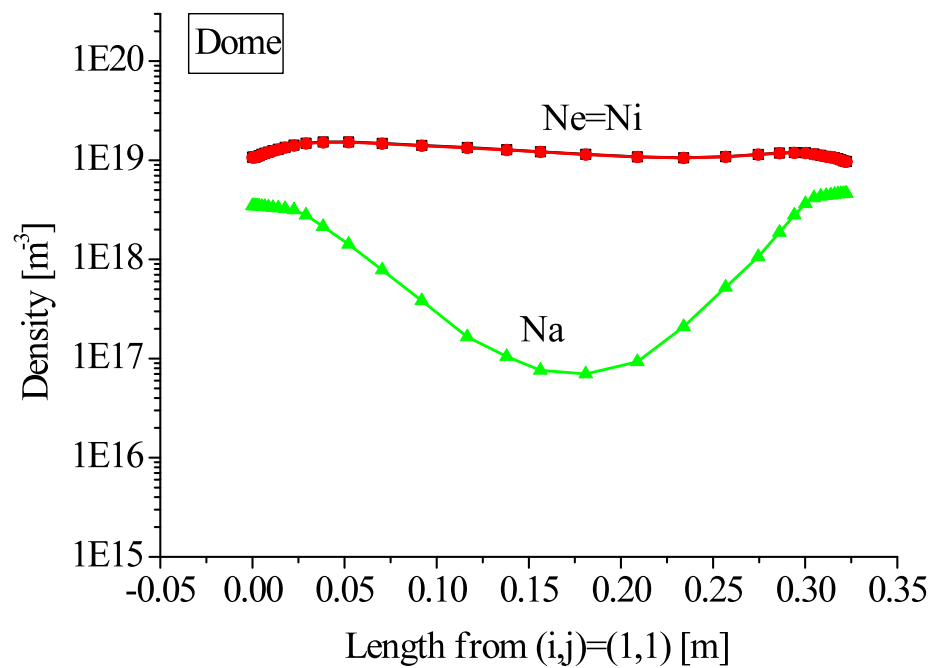
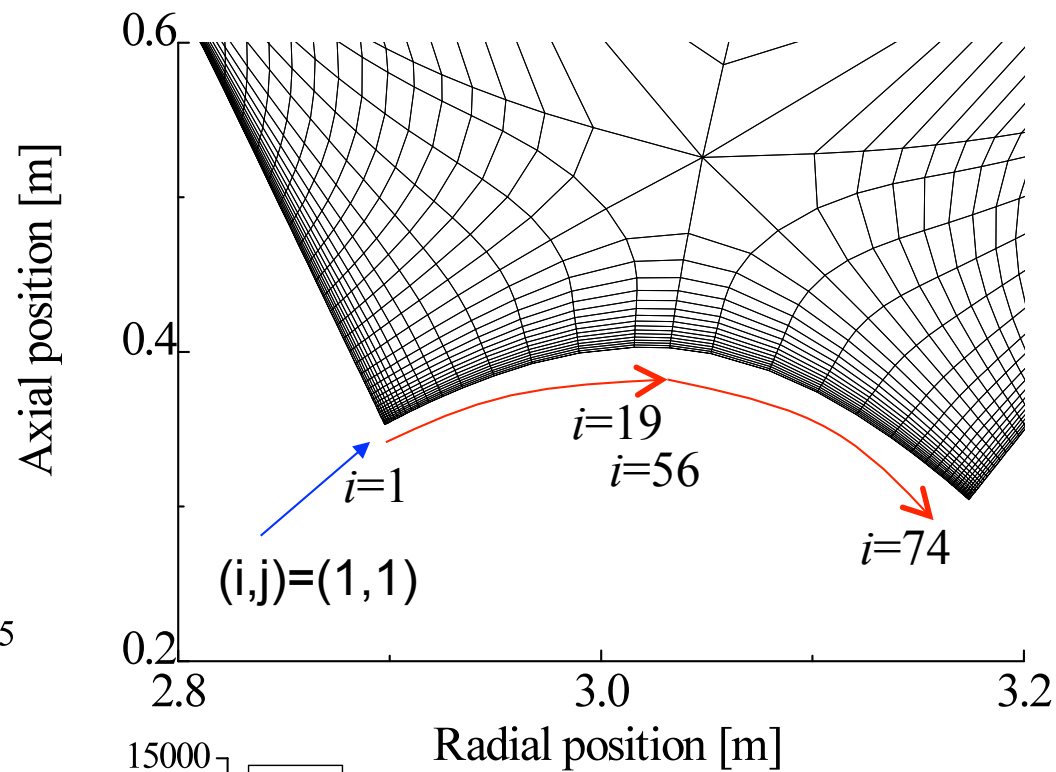
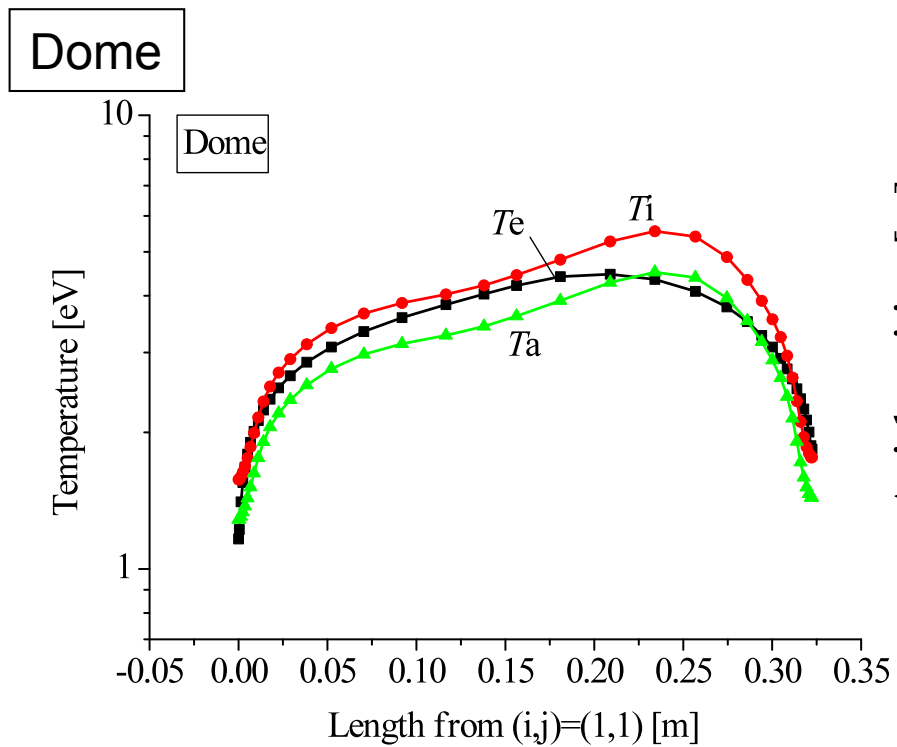


Applied forces onto the dust

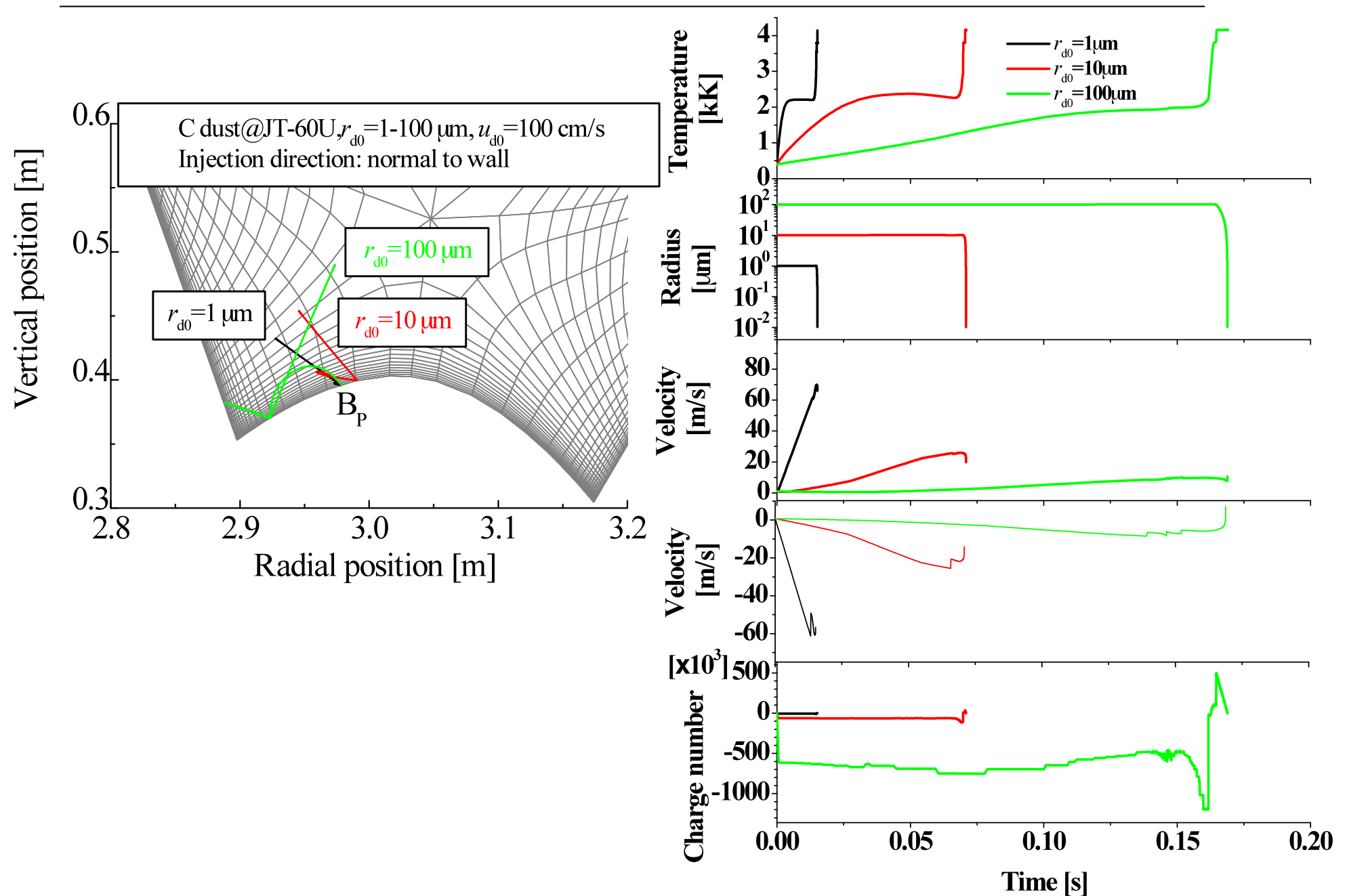
-Initially, electrostatic force is dominant, and then is ion drag force



-Dominant force is ion drag force, and atomic drag force.

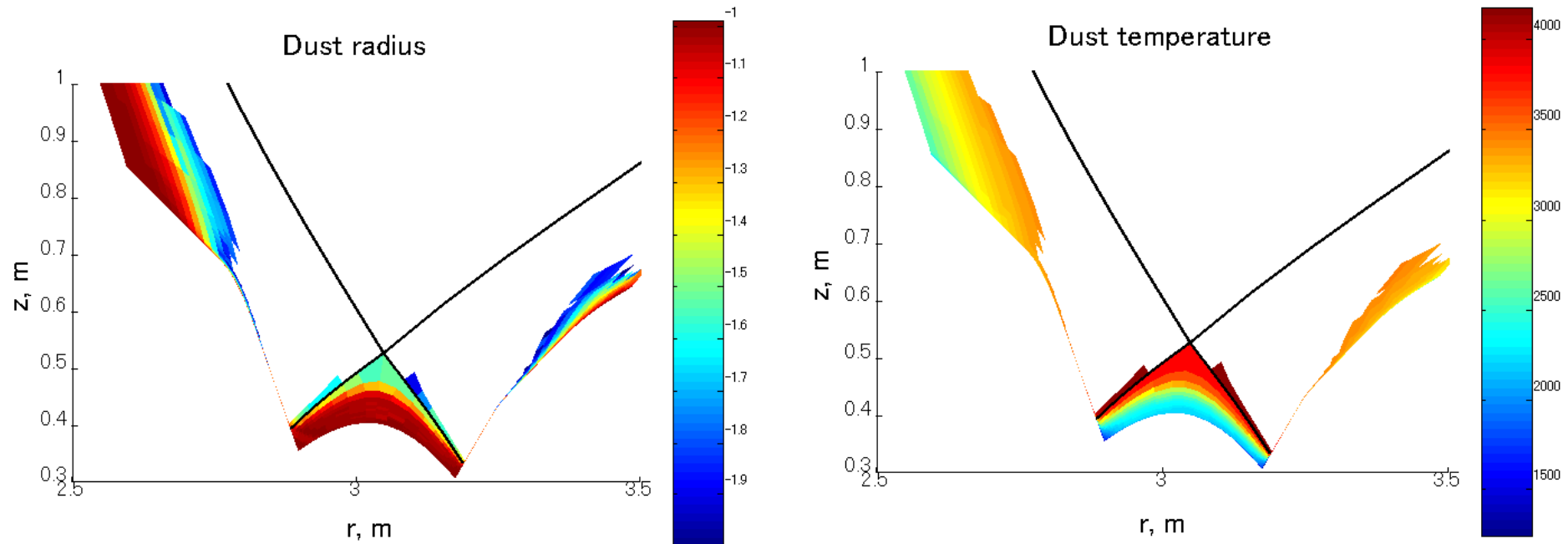


Trajectories of the dust from private region for different initial dust velocities -#P1



Statistical analysis of dust behavior-1

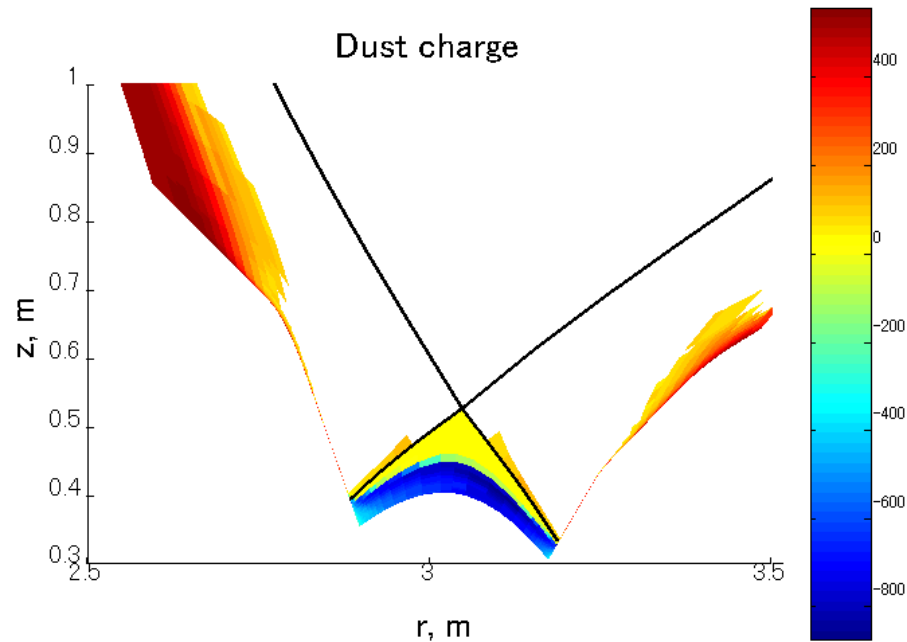
-Different position & initial velocity



- Near the strike point, a dust particle is rapidly heated and sublimated, which causes short penetration length.**
- A dust particle from private zone is slowly heated.**

Statistical analysis of dust behavior-3

-Different position & initial velocity



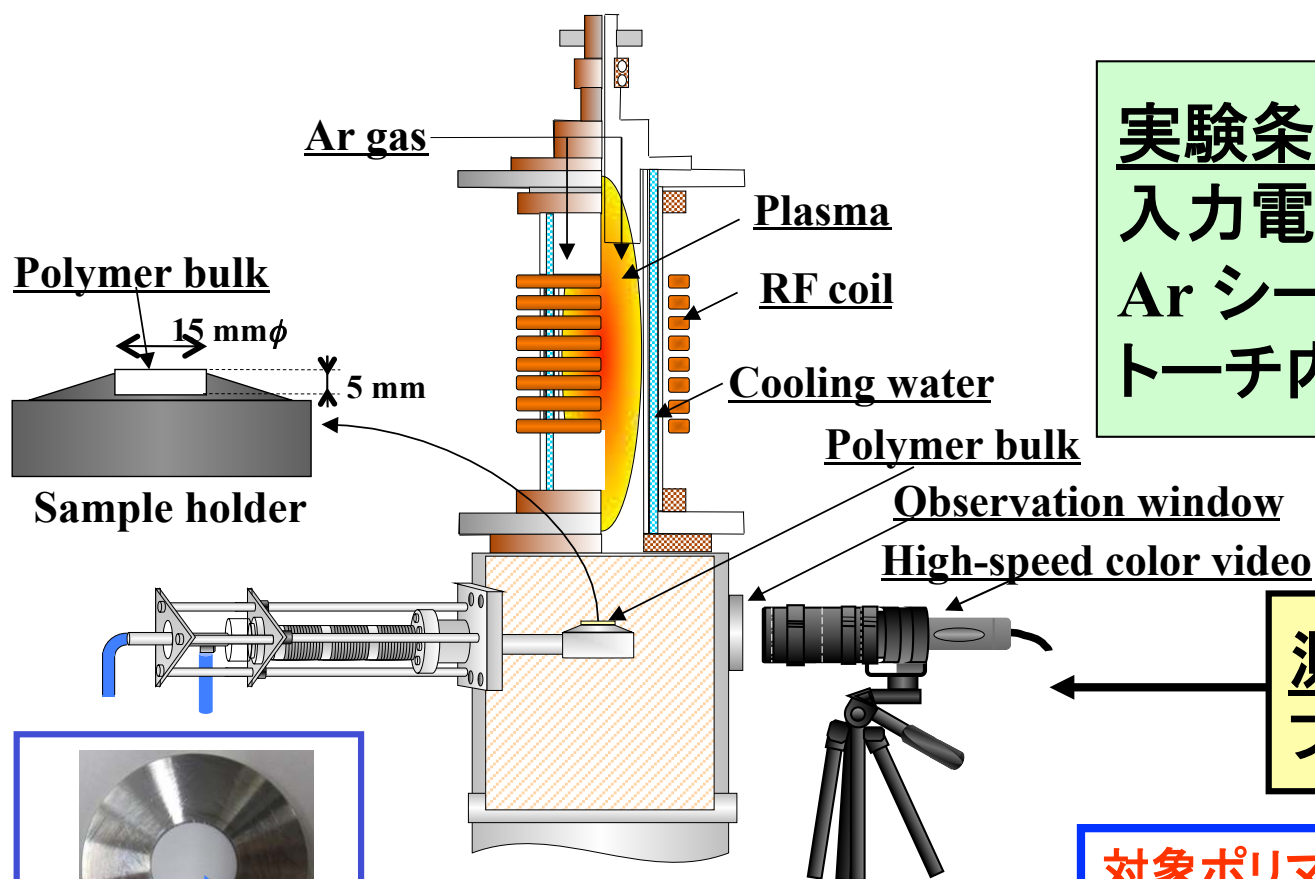
- Near the outer strike point and outer wall, a dust particle is accelerated in toroidal direction counter-clockwise. This arises from ion drag force due to ion flow.
- Near the inner strike point, clockwise acceleration occurs on a dust particle.

**Fundamental study on dust particle behavior
Using polymer spallation particles.**

-Polymer Ablation for Application to Arc Quenching



実験条件, 実験装置及び対象バルク材料



実験条件

入力電力 8.54 kW
Ar シースガス流量 30 slpm
トーチ内圧力 760 Torr

測定条件

フレームレート 1000 fps

実験系

・ 電力用遮断器

・ 配線用遮断器
・ アークホーン

・ 宇宙分野(熱遮蔽)

対象ポリマー材料

PTFE(テフロン) $[-C_2F_4-]_n$
PE(ポリエチレン) $[-C_2H_4-]_n$
POM(デルリン) $[-CH_2O-]_n$
PMMA(アクリル) $[-C_5H_8O_2-]_n$
PA66(ナイロン66) $[-C_{12}H_{22}O_2N_2-]_n$
PA6(ナイロン6) $[-C_6H_{11}ON-]_n$
PF(フェノール樹脂) $[-C_7H_6-]_n$



高速度カラービデオカメラ撮影結果



(a) PTFE
 $[-C_2F_4-]_n$



(b) PE
 $[-C_2H_4-]_n$



(c) POM
 $[-CH_2O-]_n$



(d) PMMA
 $[-C_5H_8O_2-]_n$



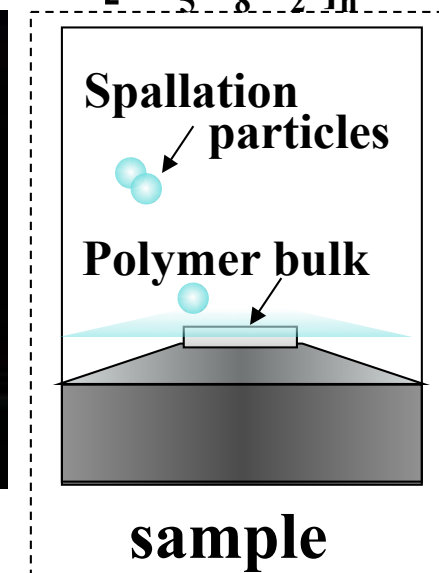
(e) PA66
 $[-C_{12}H_{22}O_2N_2-]_n$



(f) PA6
 $[-C_6H_{11}ON-]_n$



(g) PF
 $[-C_7H_6-]_n$

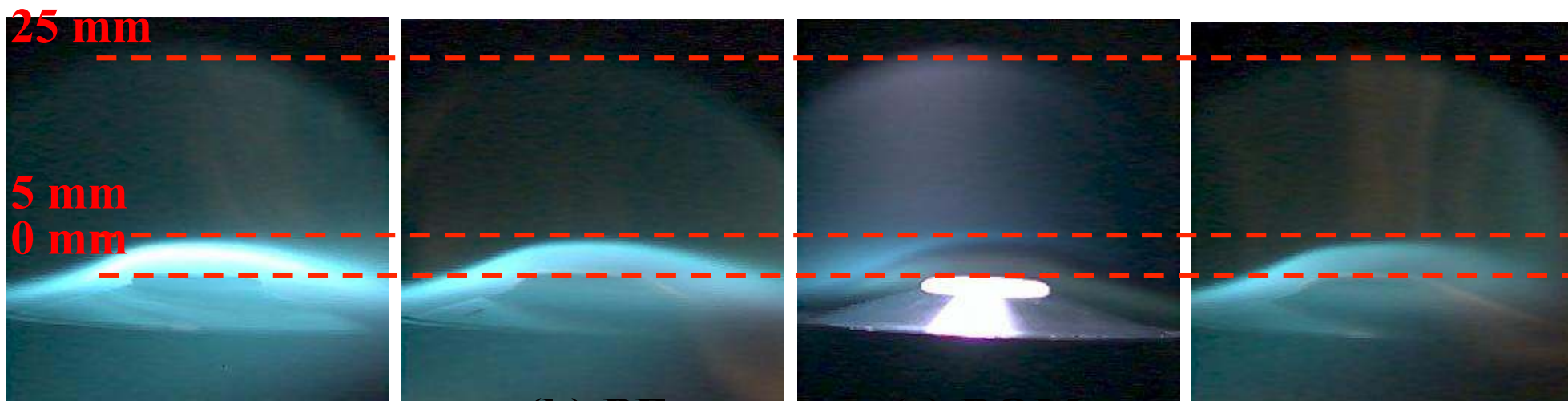


* 露光時間 $50\mu s$ (POMとPFは $250\mu s$)

* 再生速度は 15 fps フレームレート 1000 fps



高速度カラービデオカメラ撮影結果

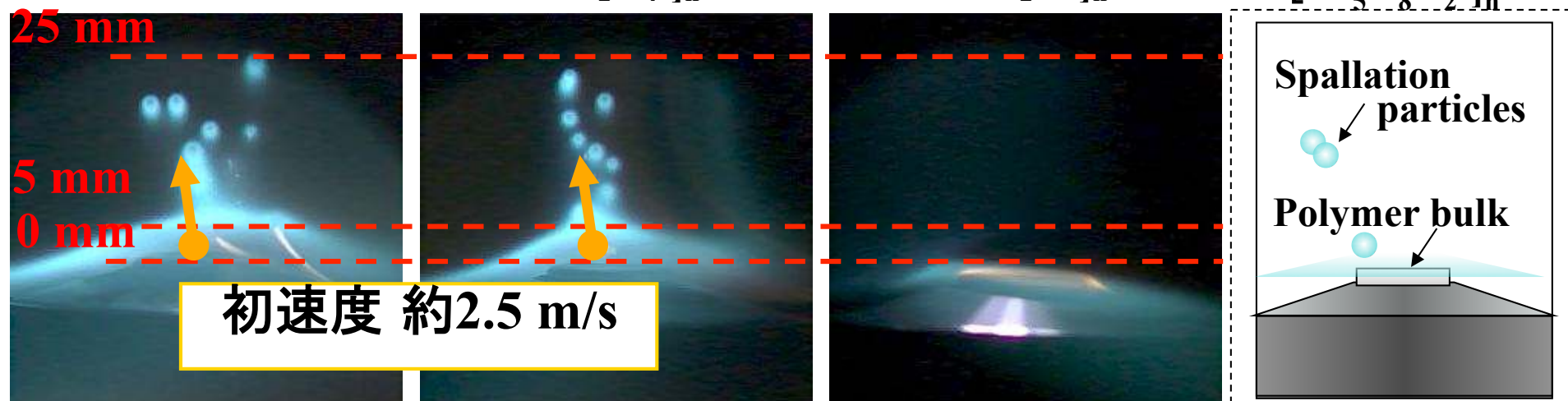


(a) PTFE
 $[-C_2F_4-]_n$

(b) PE
 $[-C_2H_4-]_n$

(c) POM
 $[-CH_2O-]_n$

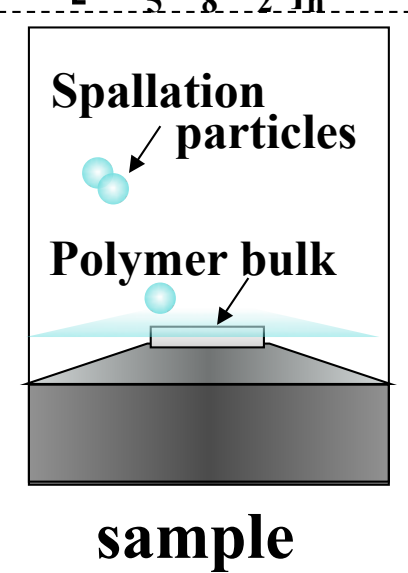
(d) PMMA
 $[-C_5H_8O_2-]_n$



(e) PA66
 $[-C_{12}H_{22}O_2N_2-]_n$

(f) PA6
 $[-C_6H_{11}ON-]_n$

(g) PF
 $[-C_7H_6-]_n$



* 露光時間50 μ s (POMとPFは250 μ s)

* 再生速度は15 fps フレームレート 1000 fps



スプレーシートの粒子の飛翔の様相

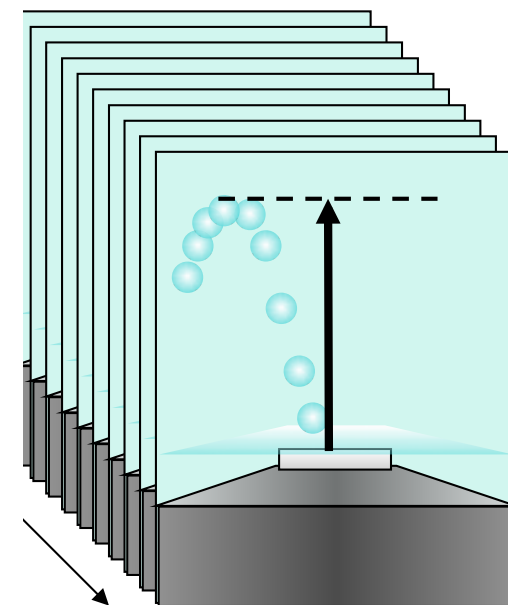
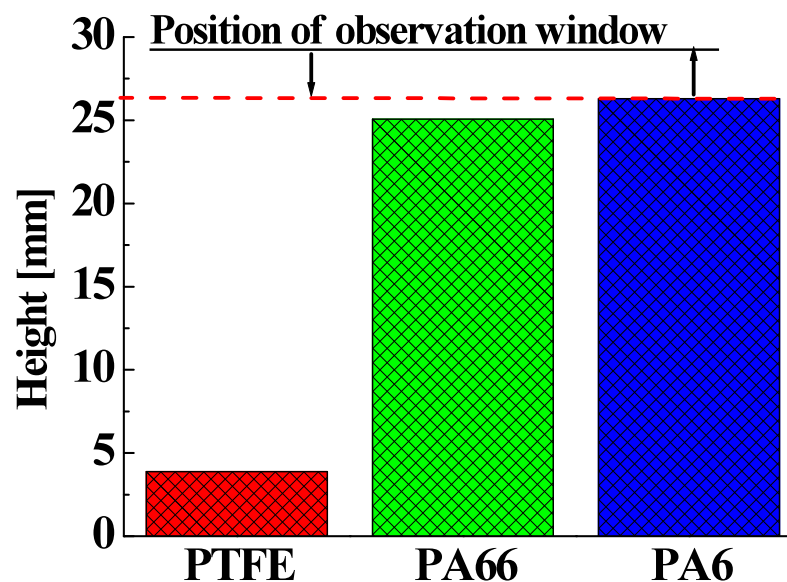
⇒ 100枚(0.1秒)

⇒ 各ピクセル

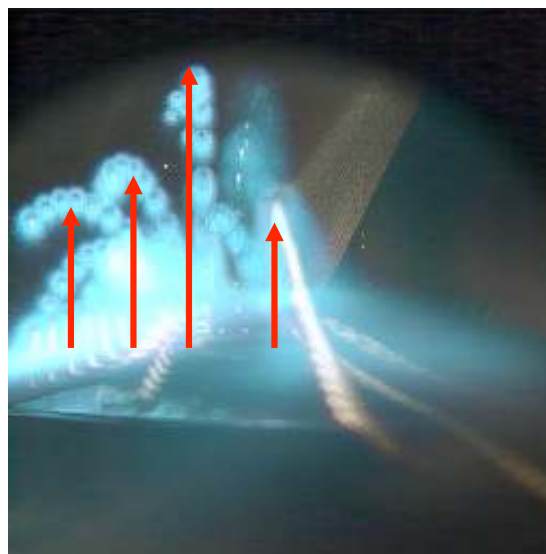
→ 飛翔粒子が

→ 飛翔粒子が

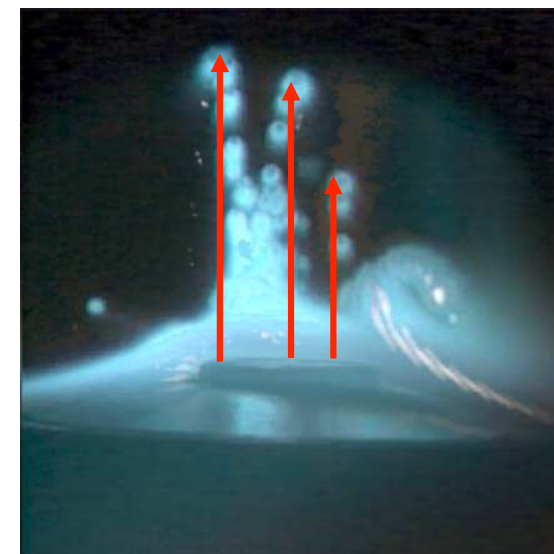
→ ポリマー表面



(a) PTFE
 $[-C_2F_4-]_n$



(b) PA66
 $[-C_{12}H_{22}O_2N_2-]_n$



(c) PA6
 $[-C_6H_{11}ON-]_n$

☐ スポレーション粒子飛翔軌跡の数値解析

運動方程式

$$\frac{dv_d}{dt} = -\frac{3}{4} C_D (v_d - u) |v_d - u| \frac{\rho}{\rho_p (2r_p)} + g$$

粒子に加わる力 ⇒ **ドラッグ力** **重力**

エネルギー保存式

Innershells

$$\rho_p C_{pp} \frac{\partial T_p(r,t)}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \kappa_p \frac{\partial T_p(r,t)}{\partial r} \right) \quad (T_p < T_{\text{melt}}, T_{\text{melt}} < T_p < T_{\text{boil}})$$

$$\rho_p H_m \frac{\partial \chi_p(r,t)}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \kappa_p \frac{\partial T_p(r,t)}{\partial r} \right) \quad (T_p = T_{\text{melt}})$$

Outershell

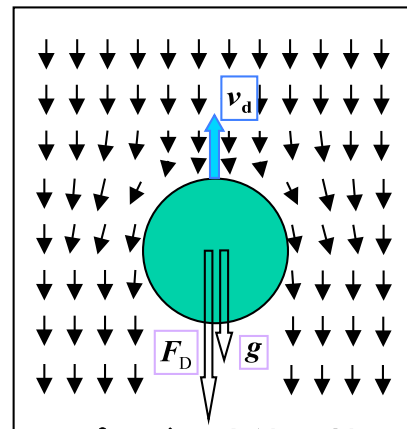
$$\frac{4\pi}{3} \rho_p C_{pp} (r_p^3 - r_{p-1}^3) \frac{\partial T_p(r,t)}{\partial t} = Q \quad (T_p < T_{\text{melt}}, T_{\text{melt}} < T_p < T_{\text{boil}})$$

$$\frac{4\pi}{3} \rho_p H_m (r_p^3 - r_{p-1}^3) \frac{\partial \chi_p(r,t)}{\partial t} = Q \quad (T_p = T_{\text{melt}})$$

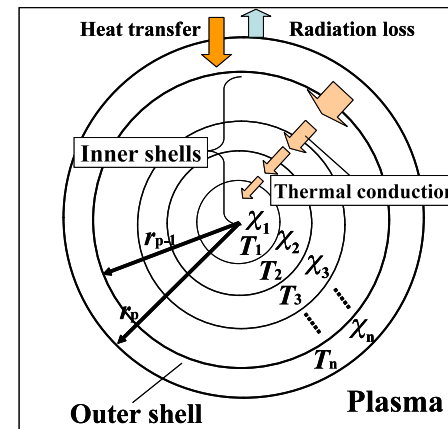
$$Q = 4\pi r_p^2 (h_c (T - T_p) - \sigma_s \varepsilon (T_p^4 - T_a^4)) - 4\pi r_{p-1}^2 \kappa_p \frac{\partial T_p(r,t)}{\partial r} \Big|_{r=r_{p-1}}$$

質量保存式

$$\frac{\partial r_p}{\partial t} = -\frac{Q}{4\pi \rho_p H_v r_p^2} \quad (T_p \geq T_{\text{boil}})$$



熱プラズマ流体の抗力



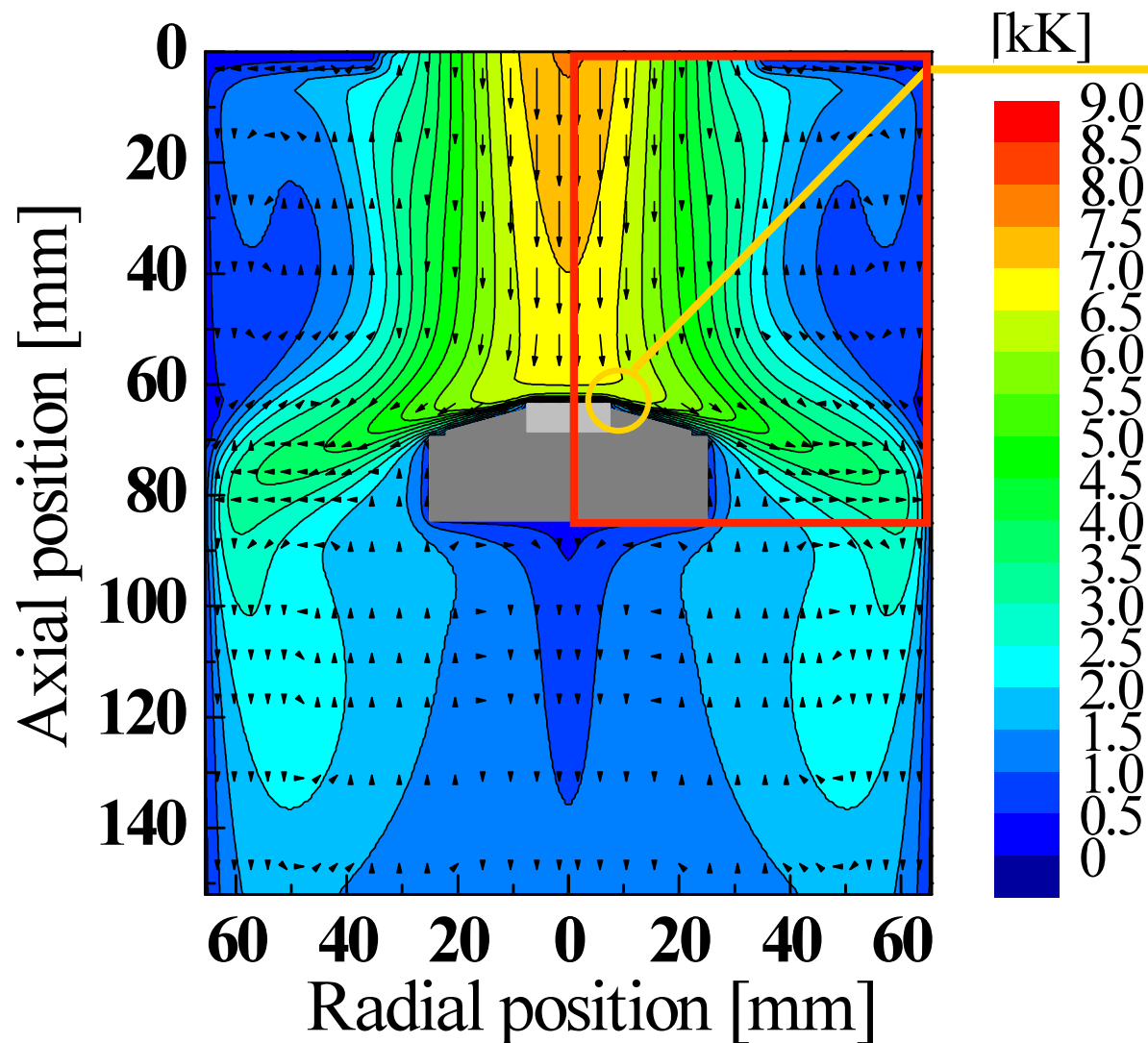
径方向の温度分布

- r : 径方向位置
- v_d : 粒子の速度
- u : プラズマの速度
- r_p : 粒子の半径
- ρ : プラズマの質量密度
- ρ_p : 粒子の質量密度
- C_D : ドラッグ係数
- g : 重力加速度
- T_p : 粒子の温度
- χ_p : 粒子の液化率
- C_{pp} : ポリマーの定圧比熱
- H_m : ポリマーの融点の潜熱
- H_v : ポリマーの沸点の潜熱
- κ_p : ポリマーの熱伝導率
- h_c : 熱伝達係数

⇒ Next

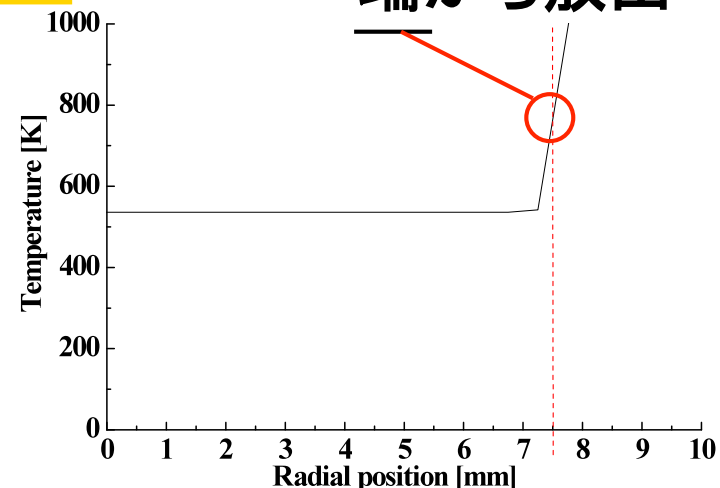
背景プラズマ場の計算手法

計算空間と各計算条件



熱プラズマの温度場と流速ベクトル

ポリマーバルク材の 端から放出



ポリマー表面の径方向温度

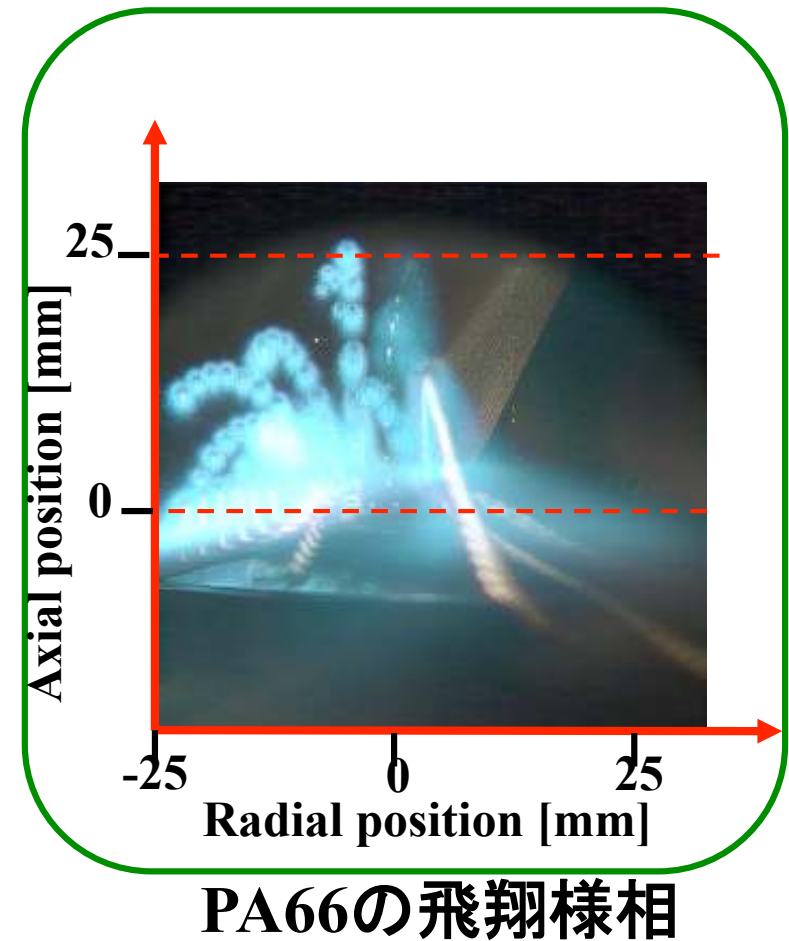
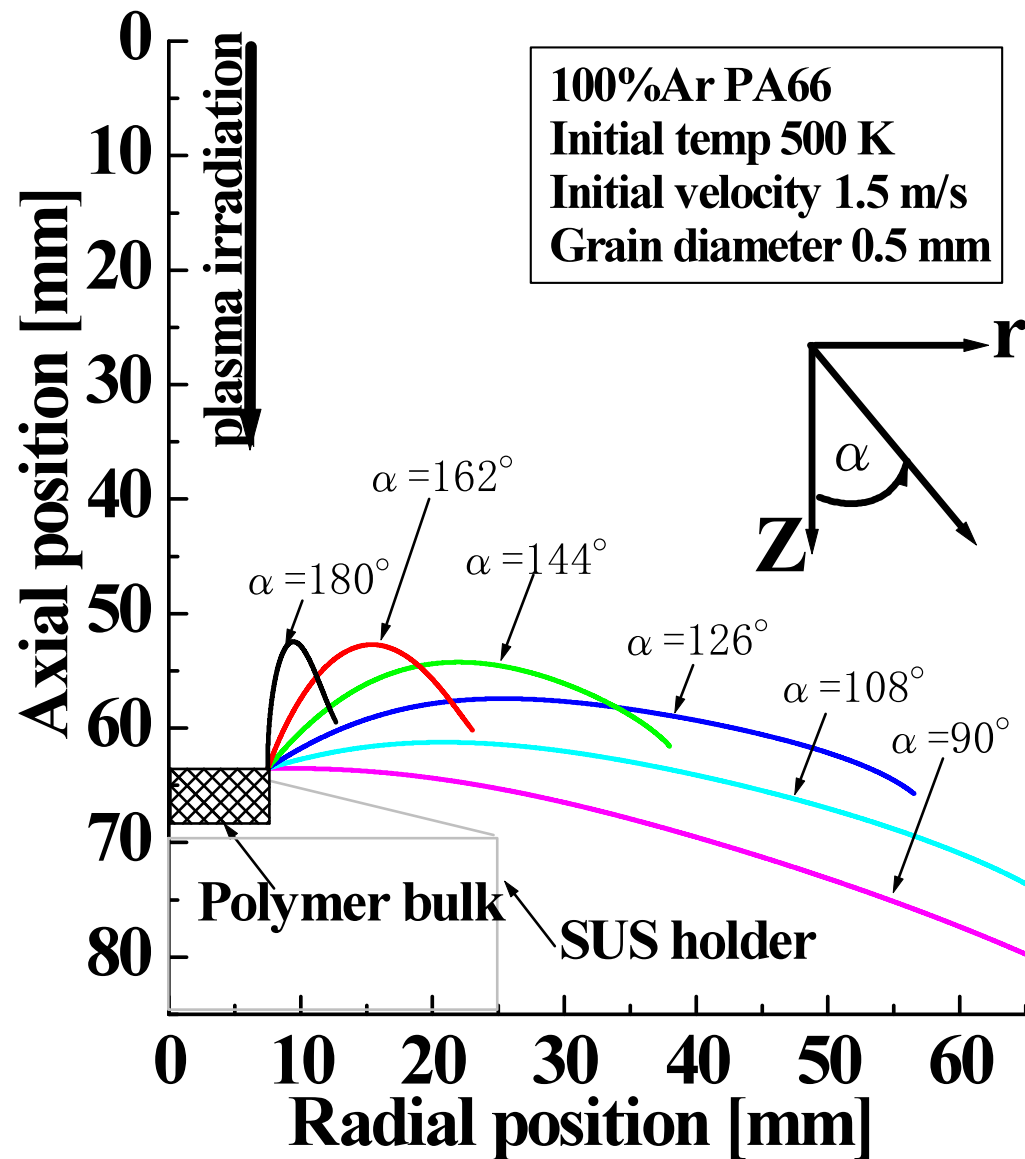
スプレーシオン粒子の初期条件

対象ポリマー材料	PA66
初期温度	500 K
初期直径	0.5 mm
初期速度	1.5 m/s

計算終了条件

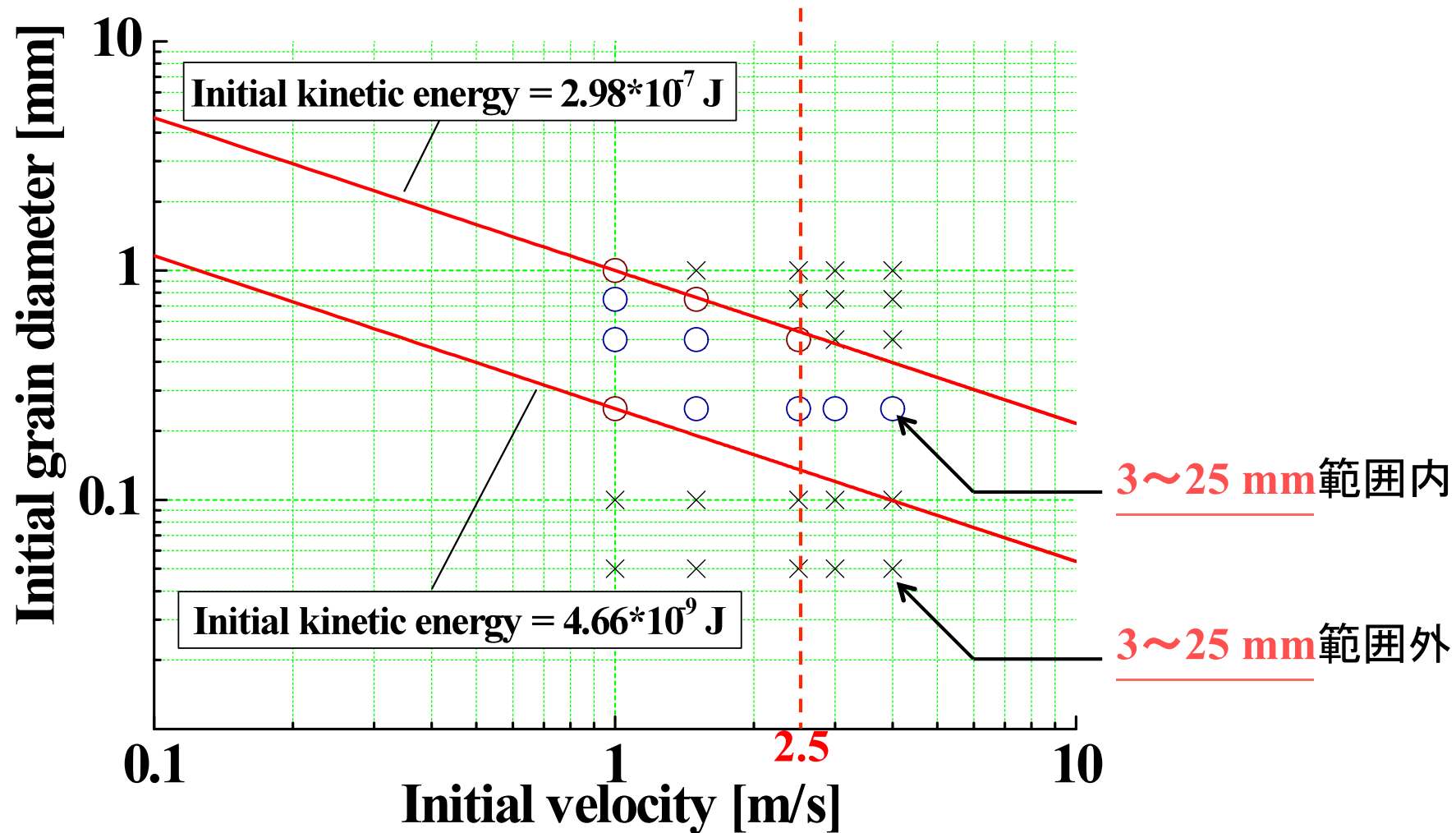
初期直径の1/100以下
⇒ 蒸発して消滅した

スプレーシオン粒子の飛翔軌跡



軸方向に近い方向角
⇒ ほぼ同様な軌跡

飛翔軌跡の撮影結果と計算結果との比較

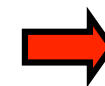


スプレーション粒子が飛翔時に持つ初期エネルギー



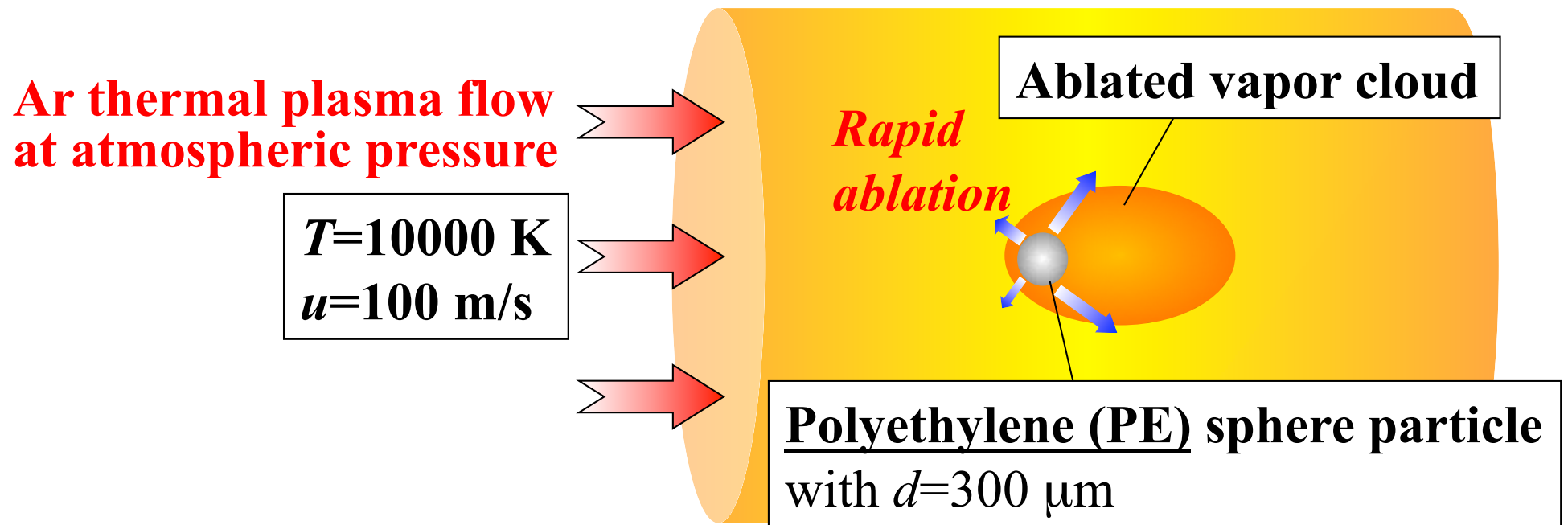
1~100 nJ程度

高速度ビデオカメラ撮影 ⇒ 初期速さ 約2.5 m/s



直径約0.15 mm

The present case



The physics to be considered:

- Heat transfer
- Rapid ablation $\rightarrow$ Rapid pressure rise $\rightarrow$ Strong gas flow
- Rapid ablation $\rightarrow$ Energy loss
- Change in properties of the surrounding plasma
- Transport of ablated vapor
- Shielding due to the ablated vapor from Ar plasmas

Governing Equations

-Mass equation:

$$\frac{D\rho}{Dt} = -\rho(\nabla \cdot \mathbf{u})$$

-Momentum equation:

$$\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho} \nabla p$$

-Energy equation:

$$\frac{DT}{Dt} = -\frac{p_{th}}{\rho C_v} (\nabla \cdot \mathbf{u}) + \frac{1}{\rho C_v} \left[\nabla \cdot (\lambda \nabla T) - P_{rad} - S_{abl} - \varepsilon_{emit} \sigma_{sb} (T^4 - T_a^4) \delta\Omega \right]$$

-Mass fraction of ablated vapor:

$$\frac{DY_{pol}}{Dt} = \frac{1}{\rho_g} \left[\nabla \cdot (\rho_g D_{pol} \nabla Y_{pol}) + S_{Cg} \right]$$

-VOF function:

$$\frac{Df}{Dt} = -S_f$$

-Equation of state (EOS):

$$p = p(\rho, T)$$

These equations are solved by the **CIP-CUP** method developed by Prof. Yabe.

The **CIP-CUP method** is an **unified algorithm** to solve incompressible and compressible flow, and thus it can simulate multiphase flow.

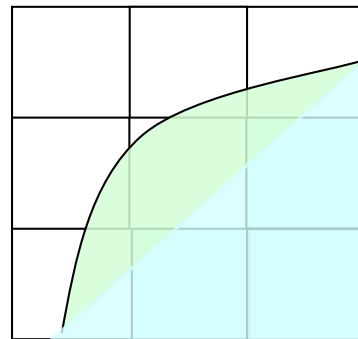
f : the volume of fraction

$$f = \frac{V_{solid}}{V_{CV}}$$

$f=1$: Solid

$0 < f < 1$: containing solid surface

$f=0$: Gas or plasma





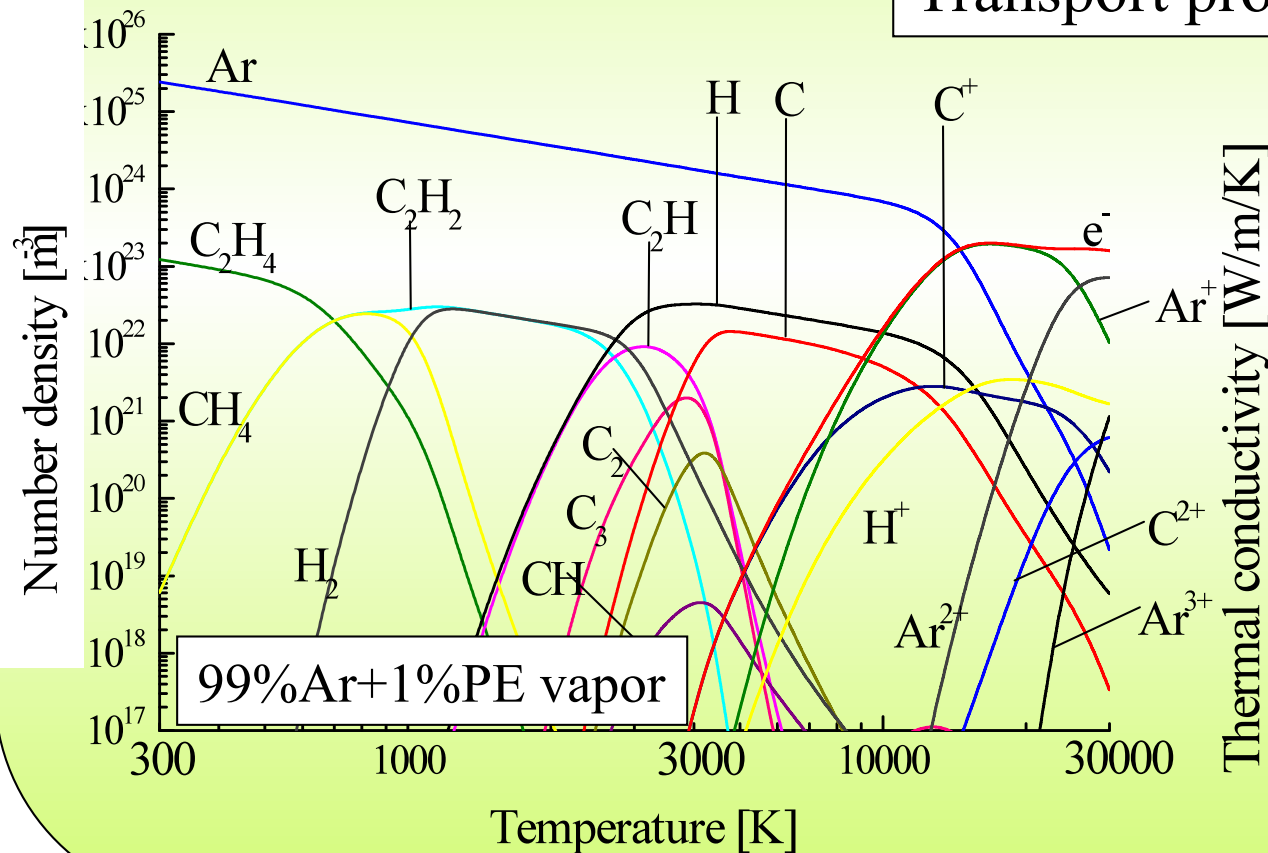
Thermodynamic and transport properties of Ar and ablated vapor

Equilibrium composition of Ar, and ablated vapor

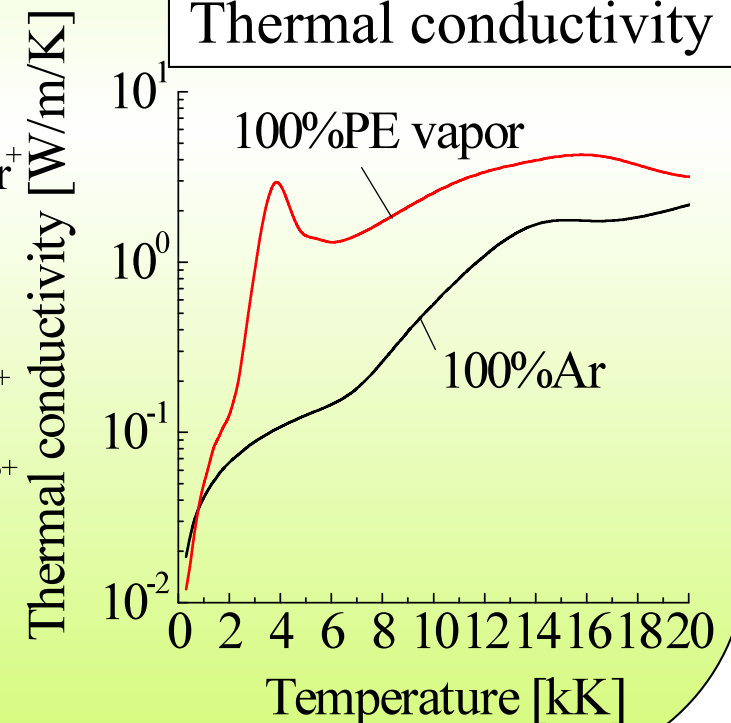
Thermodynamic properties

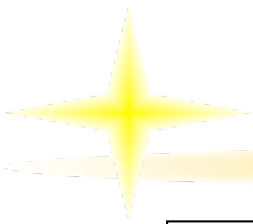
The first order approximation of Chapman-Enskog method

Transport properties

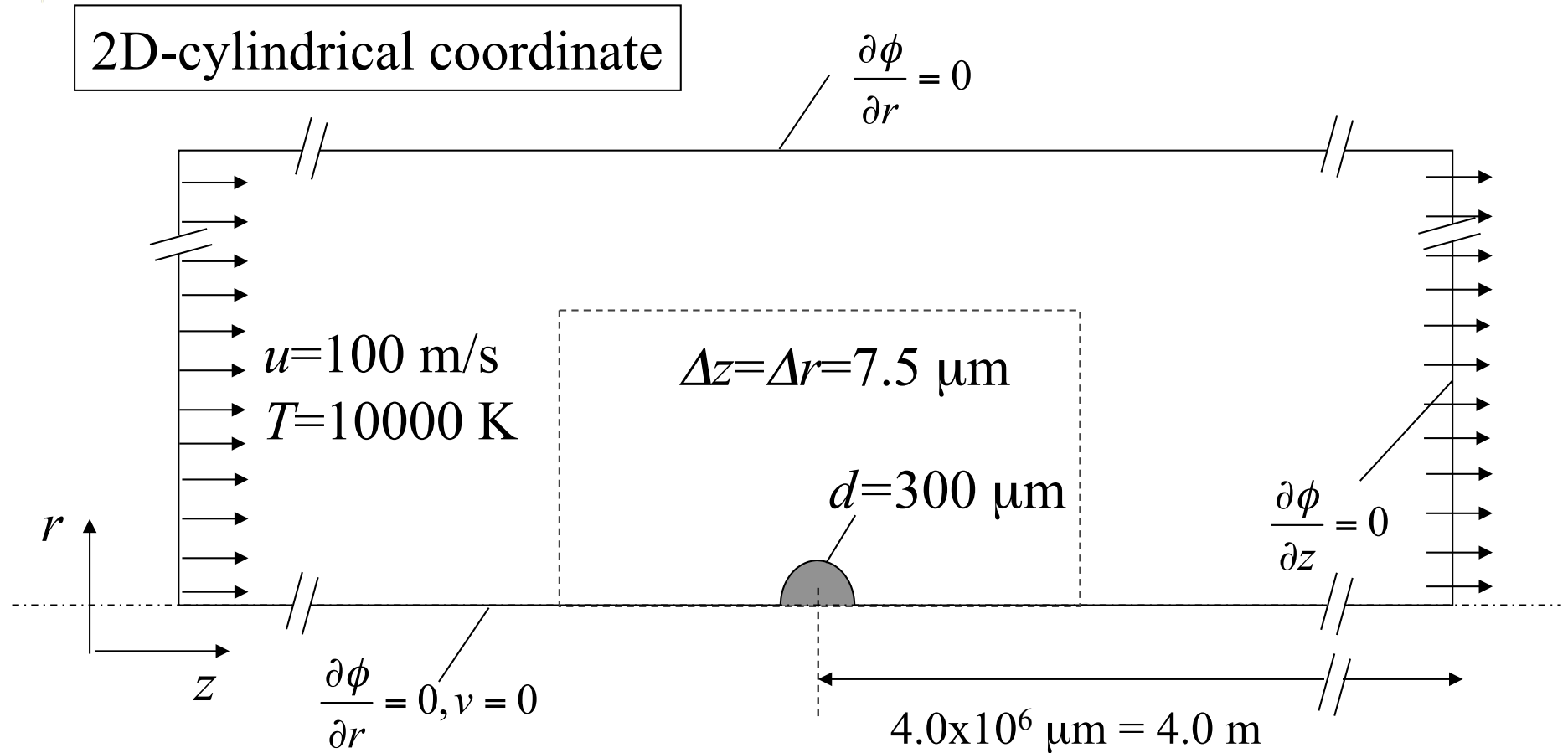


Thermal conductivity





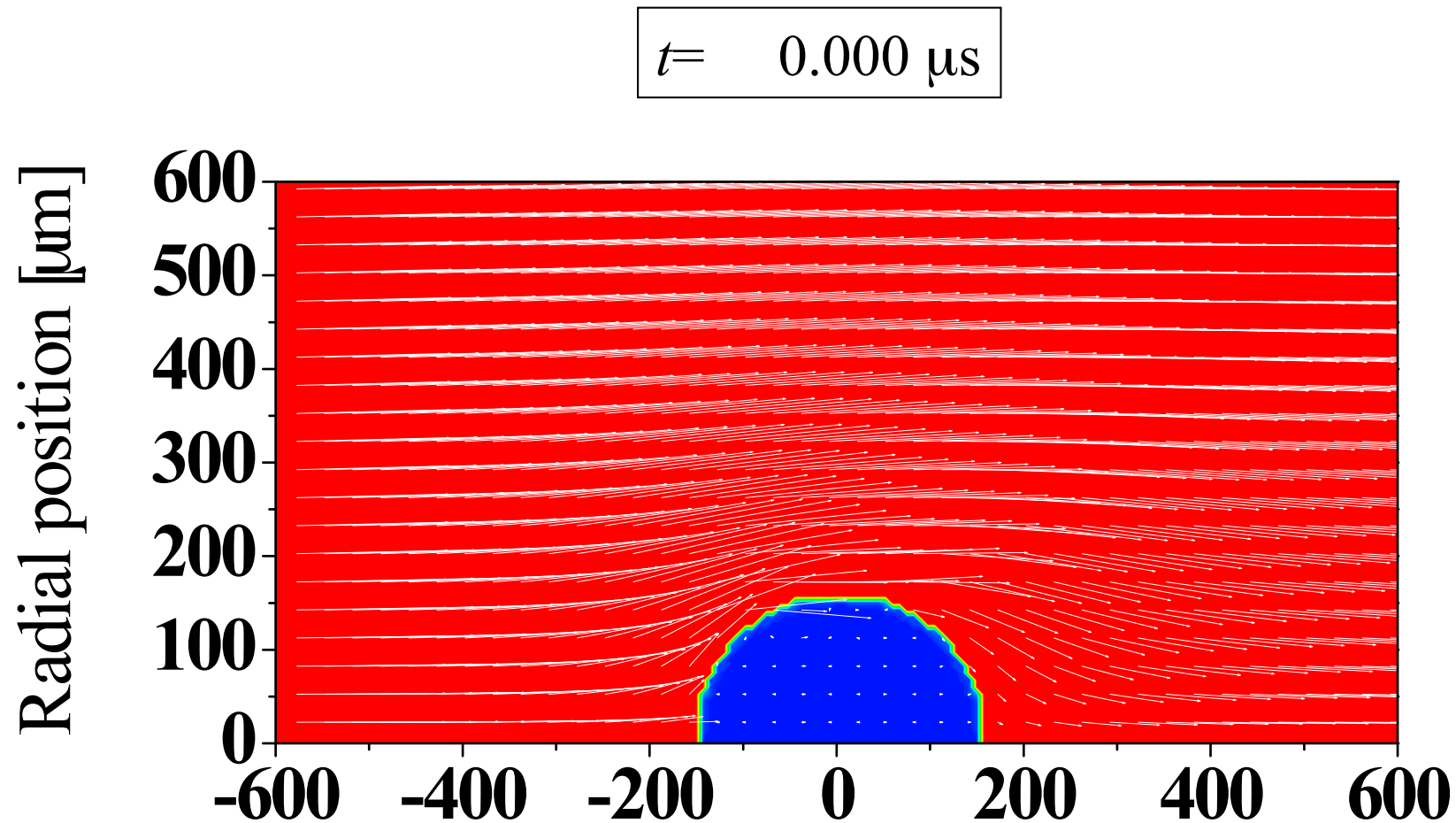
Calculation space



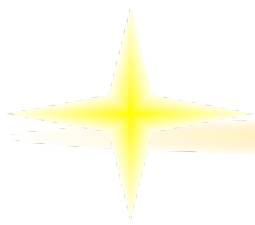
-Kundsen number: $Ku \sim 0.03$

-Reynolds number: $Re \sim 0.65$

Gas flow velocity and temperature fields

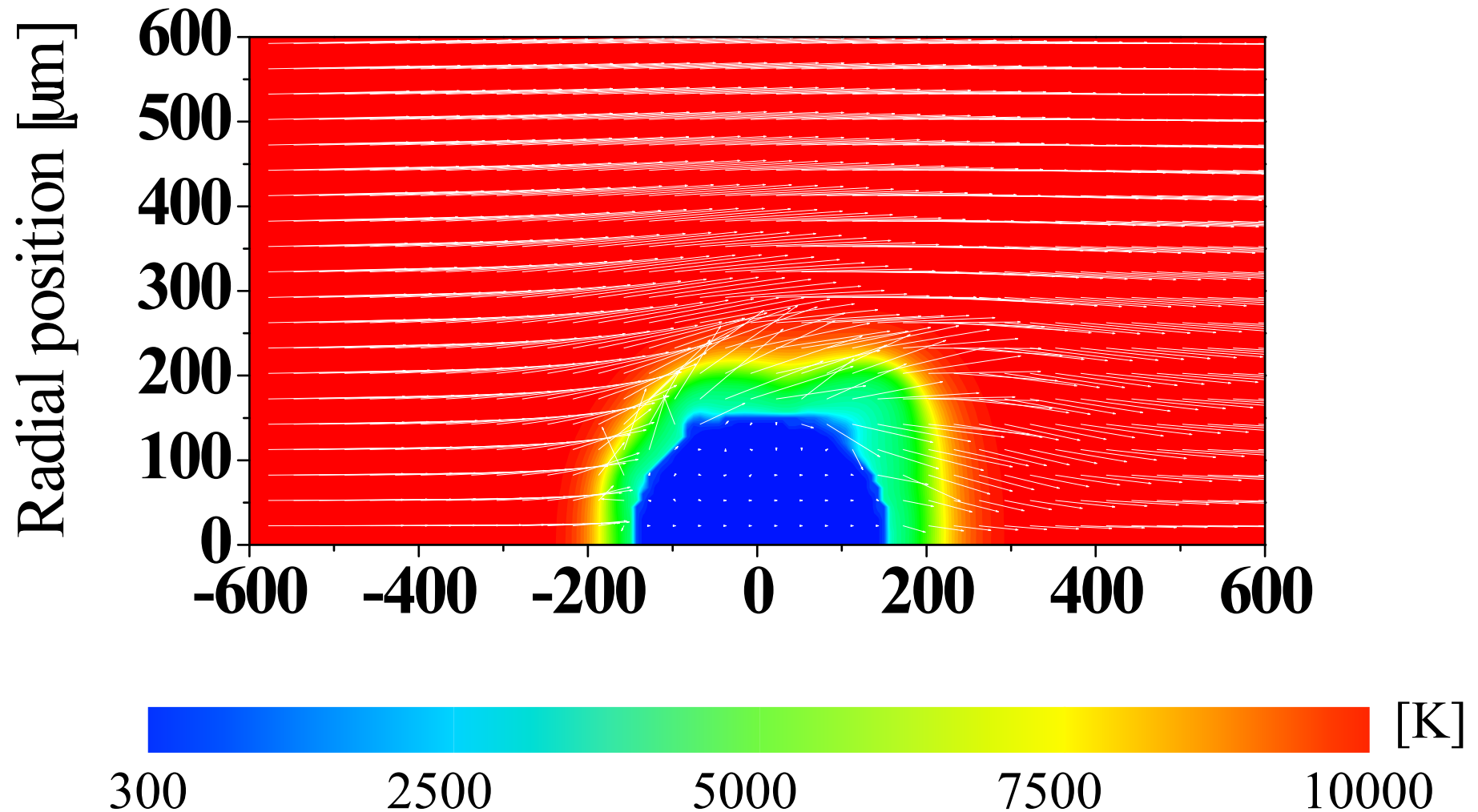


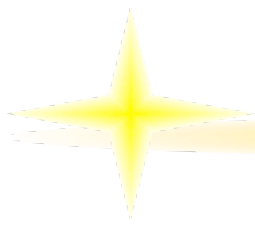
Initial temperature: $T=10000$ K for Ar plasma, $T=300$ K for PE particle
Initial gas flow field was calculated without ablation



Gas flow velocity and temperature fields

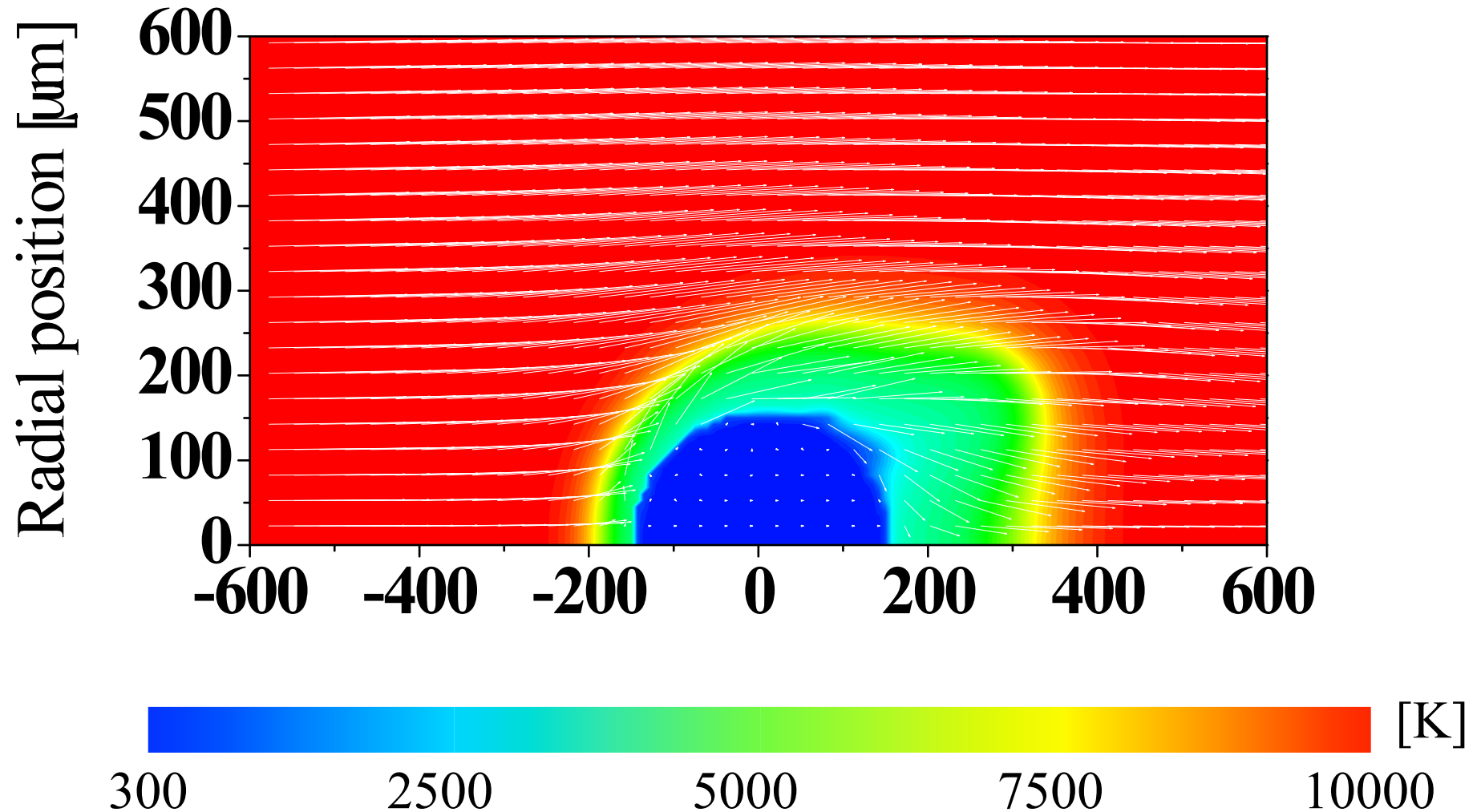
$t = 1.371 \mu\text{s}$

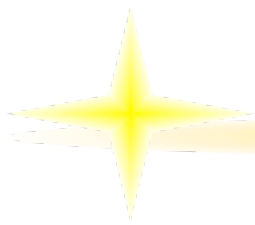




Gas flow velocity and temperature fields

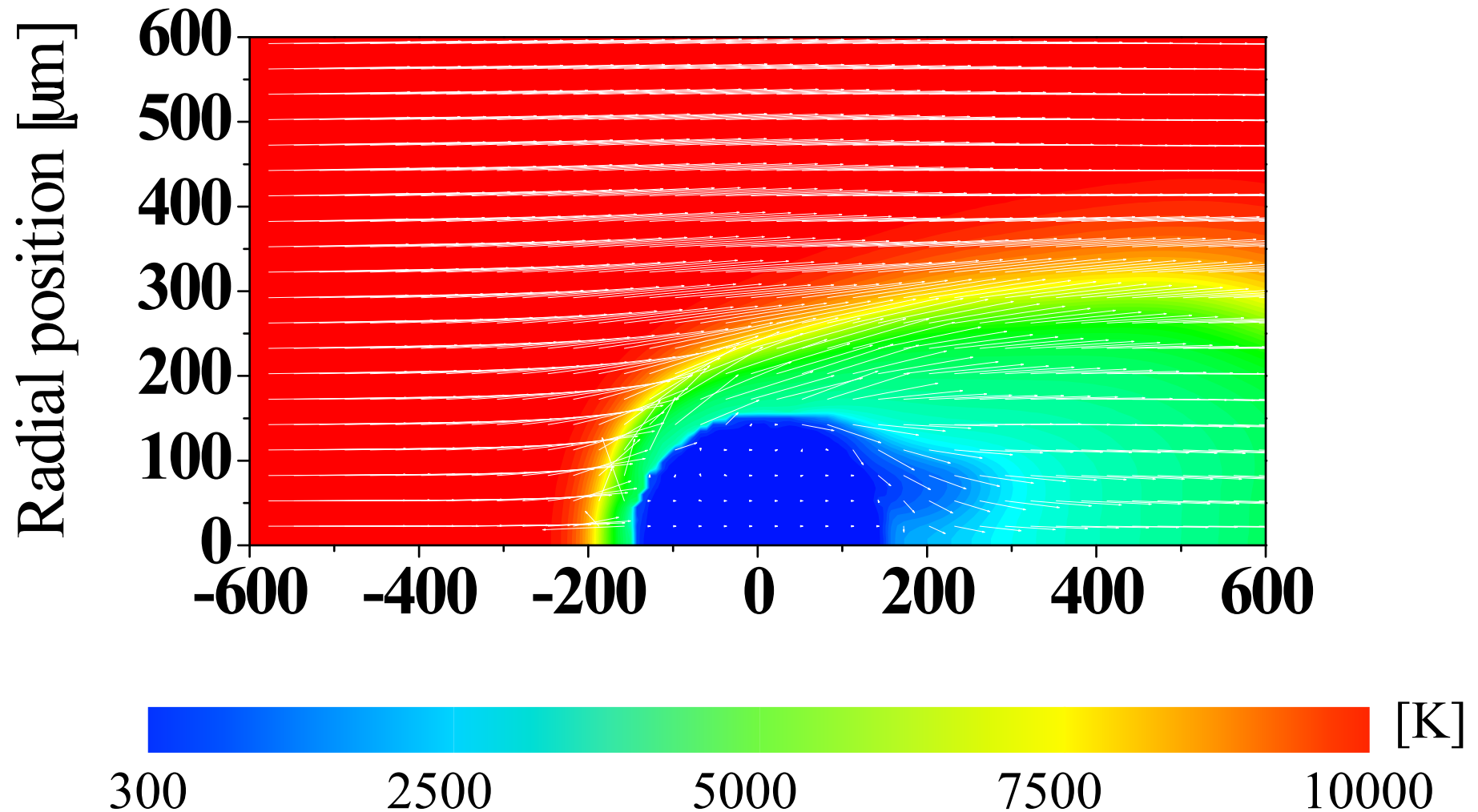
$t = 3.185 \mu\text{s}$

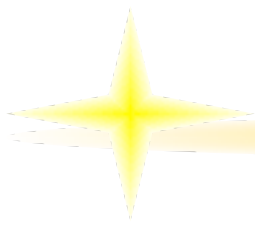




Gas flow velocity and temperature fields

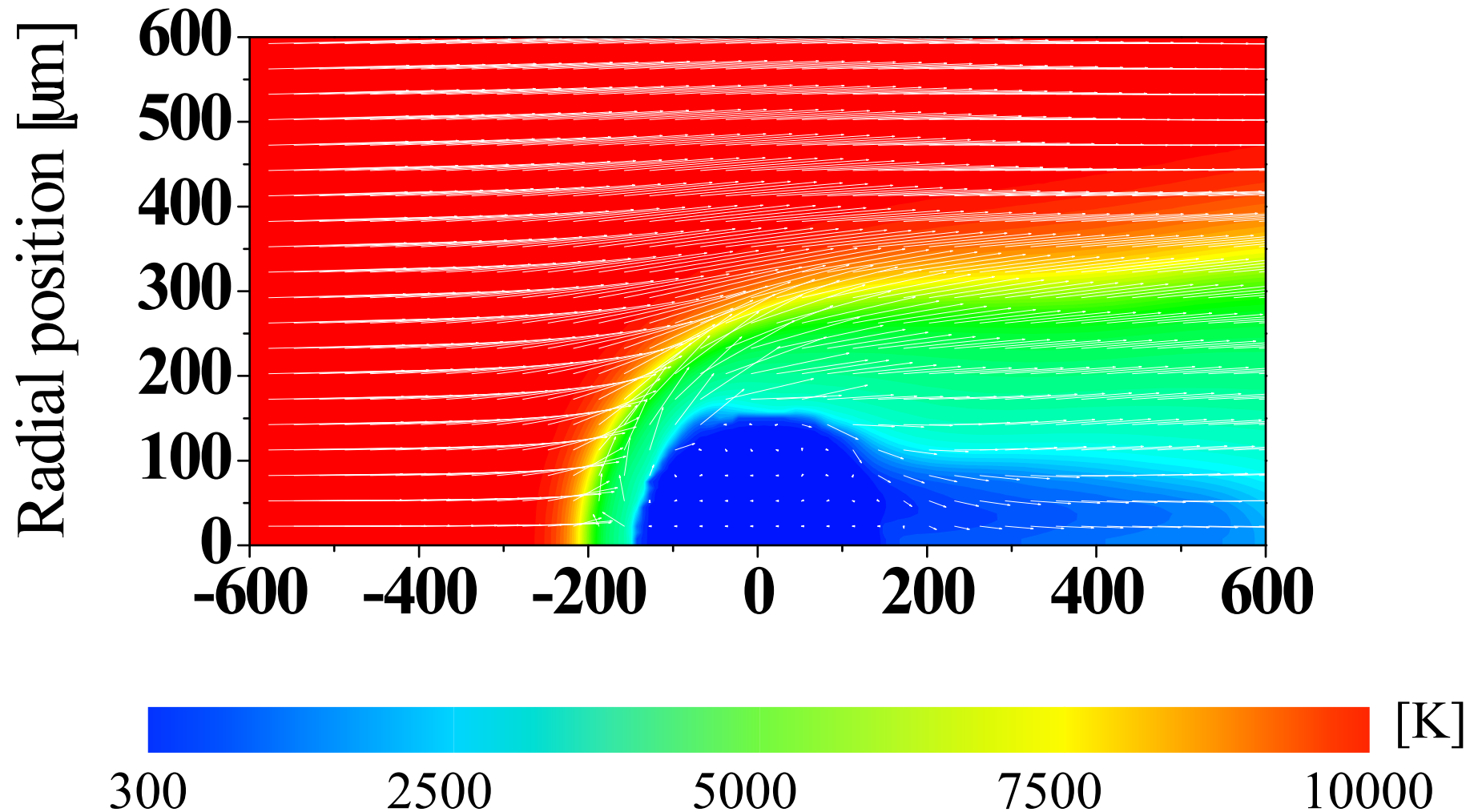
$t = 8.736 \mu\text{s}$

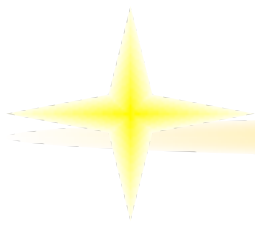




Gas flow velocity and temperature fields

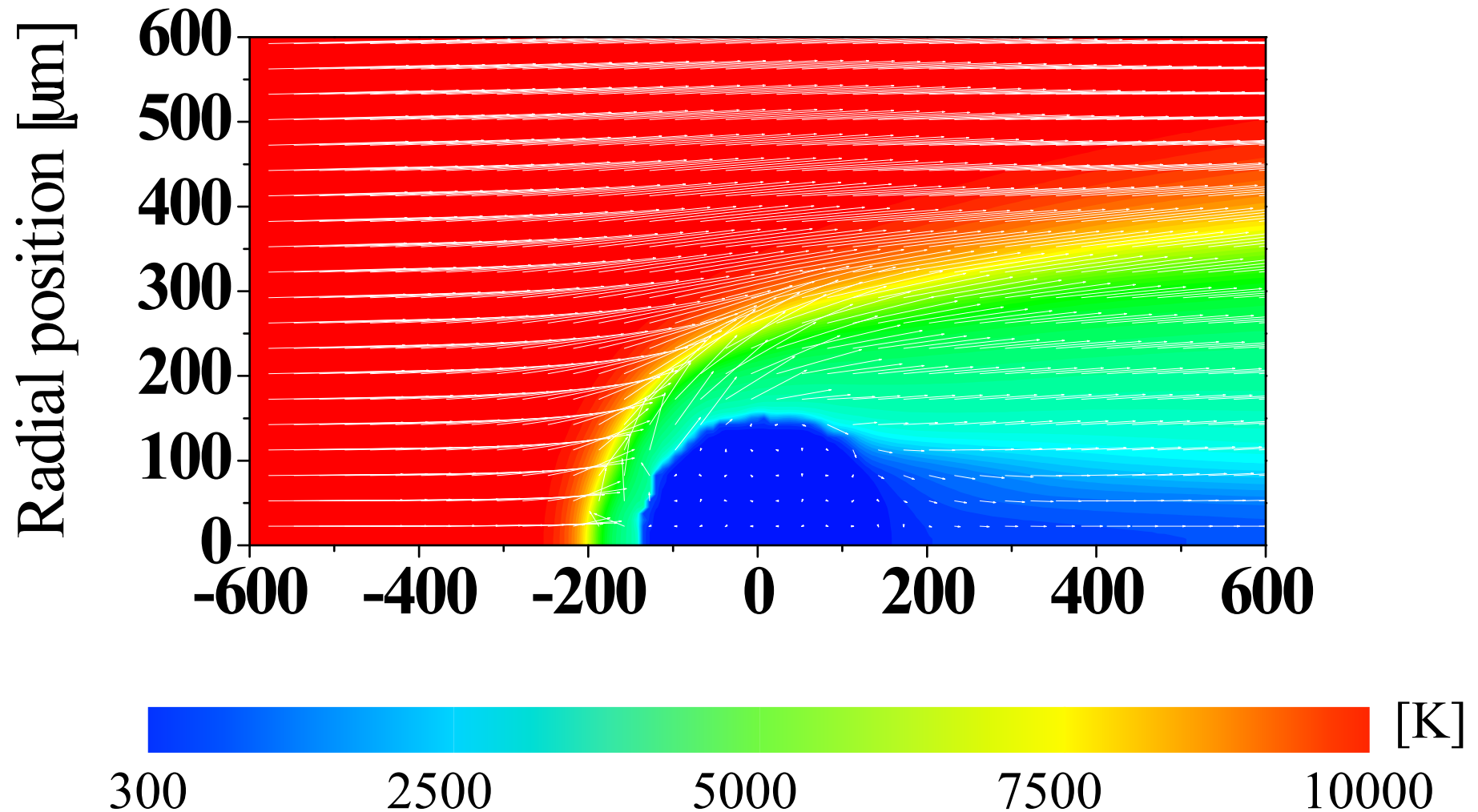
$t = 17.56 \mu\text{s}$

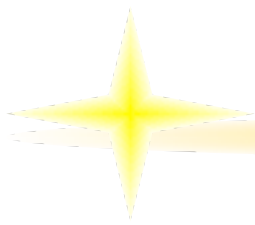




Gas flow velocity and temperature fields

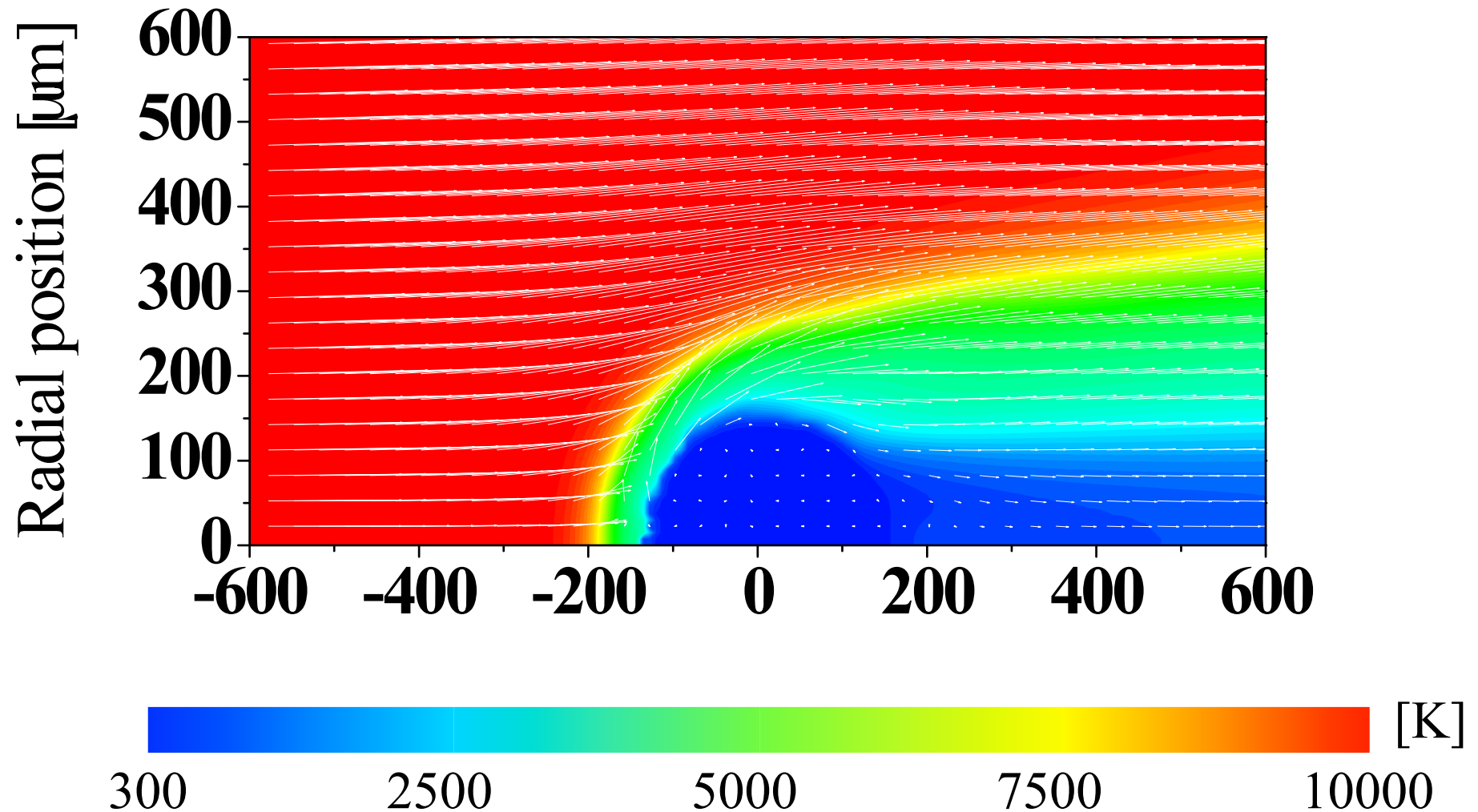
$t = 35.71 \mu\text{s}$

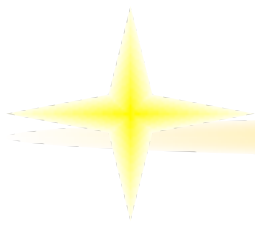




Gas flow velocity and temperature fields

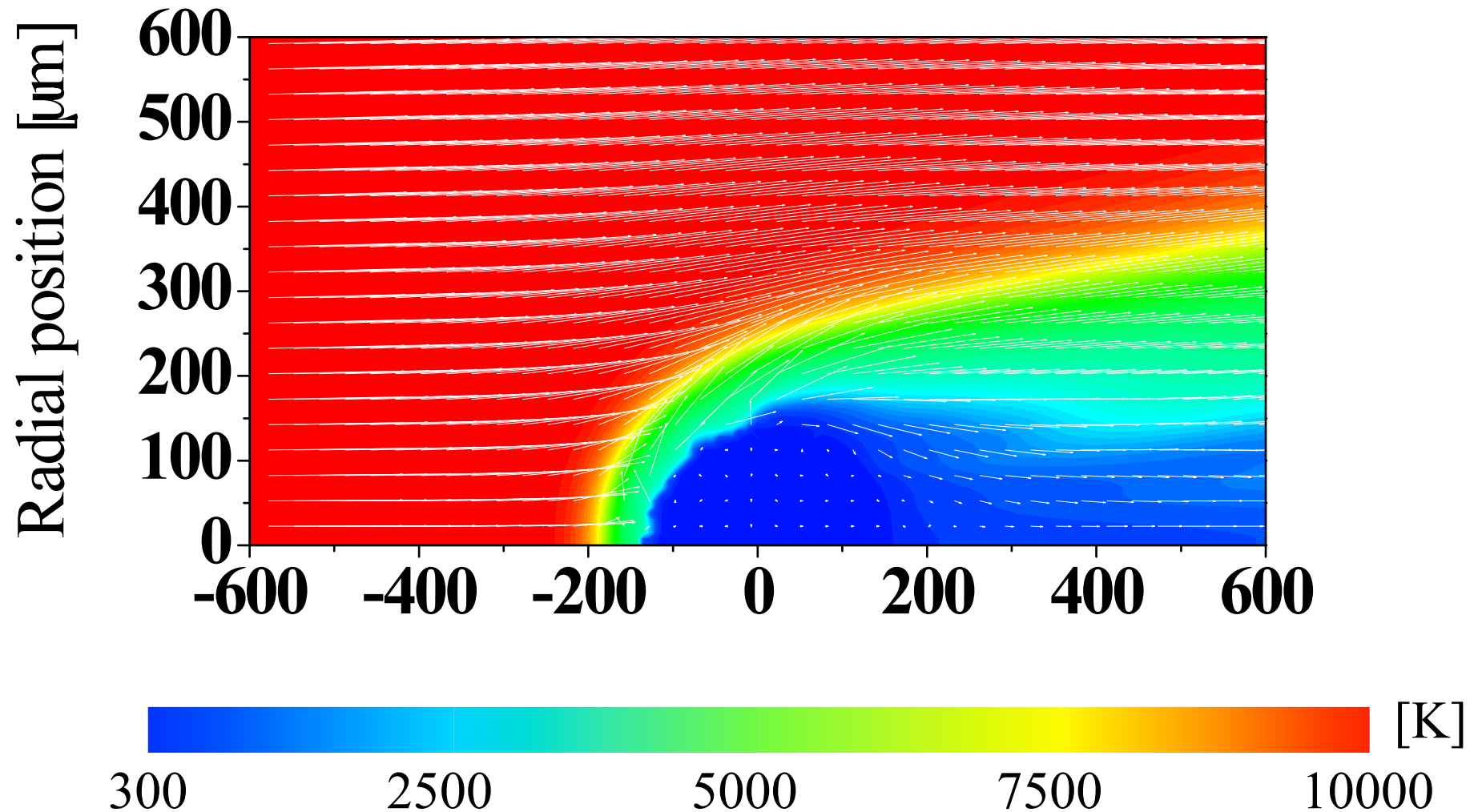
$t = 91.25 \mu\text{s}$





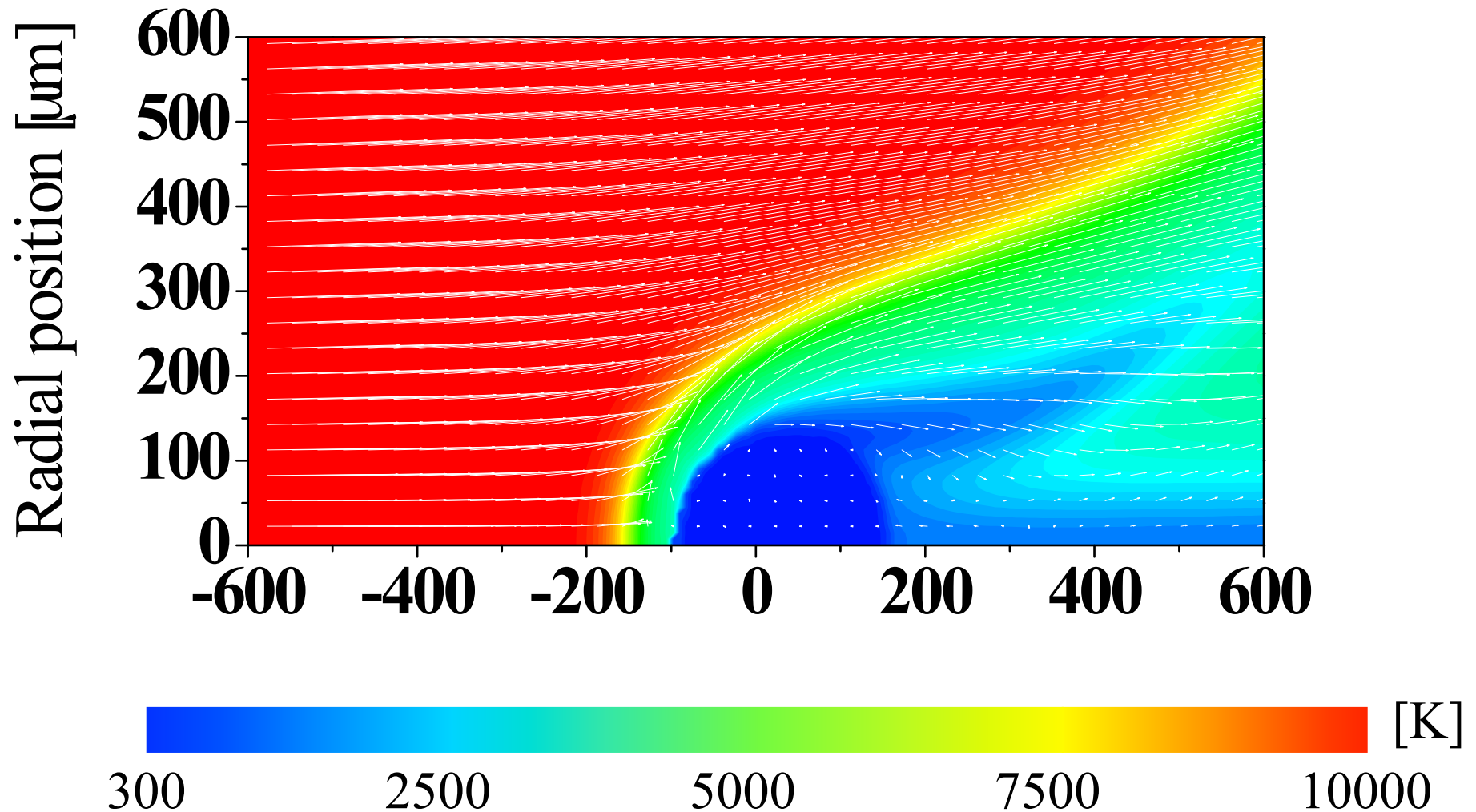
Gas flow velocity and temperature fields

$t = 183.0 \mu\text{s}$



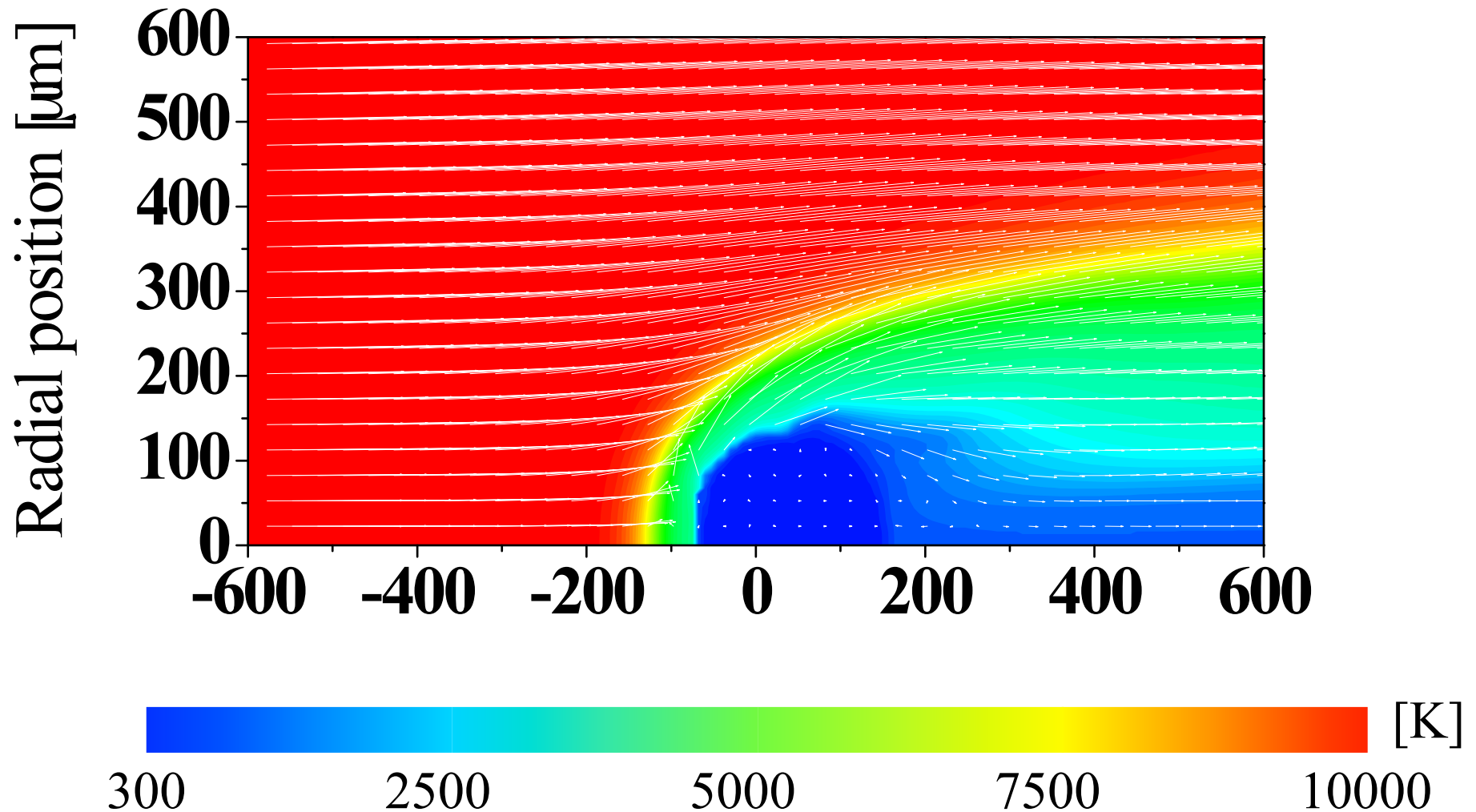
Gas flow velocity and temperature fields

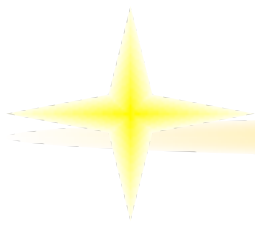
$t = 344.7 \mu\text{s}$



Gas flow velocity and temperature fields

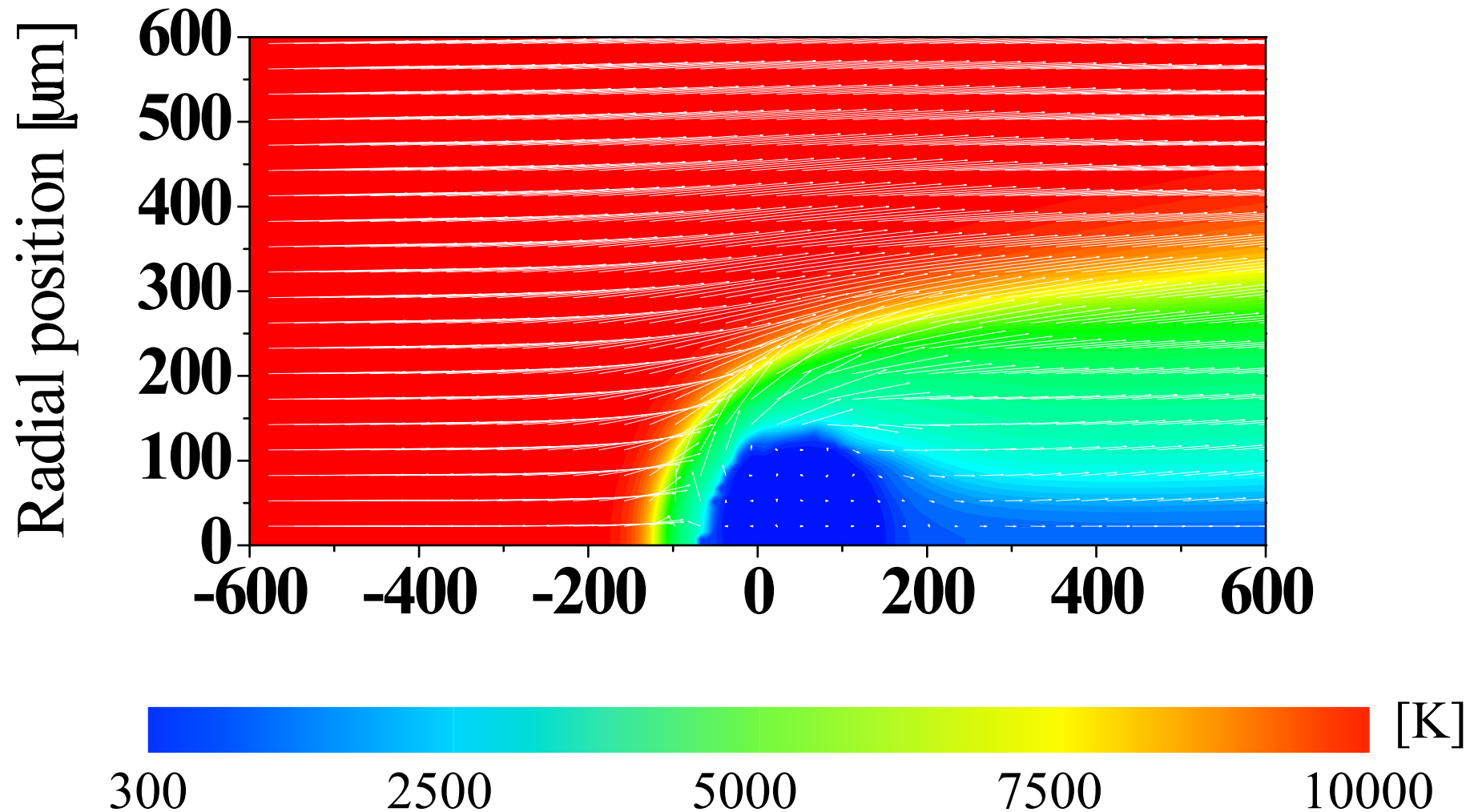
$t = 430.7 \mu\text{s}$

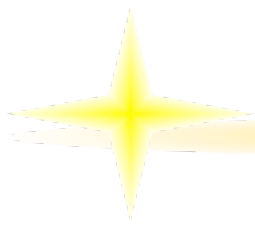




Gas flow velocity and temperature fields

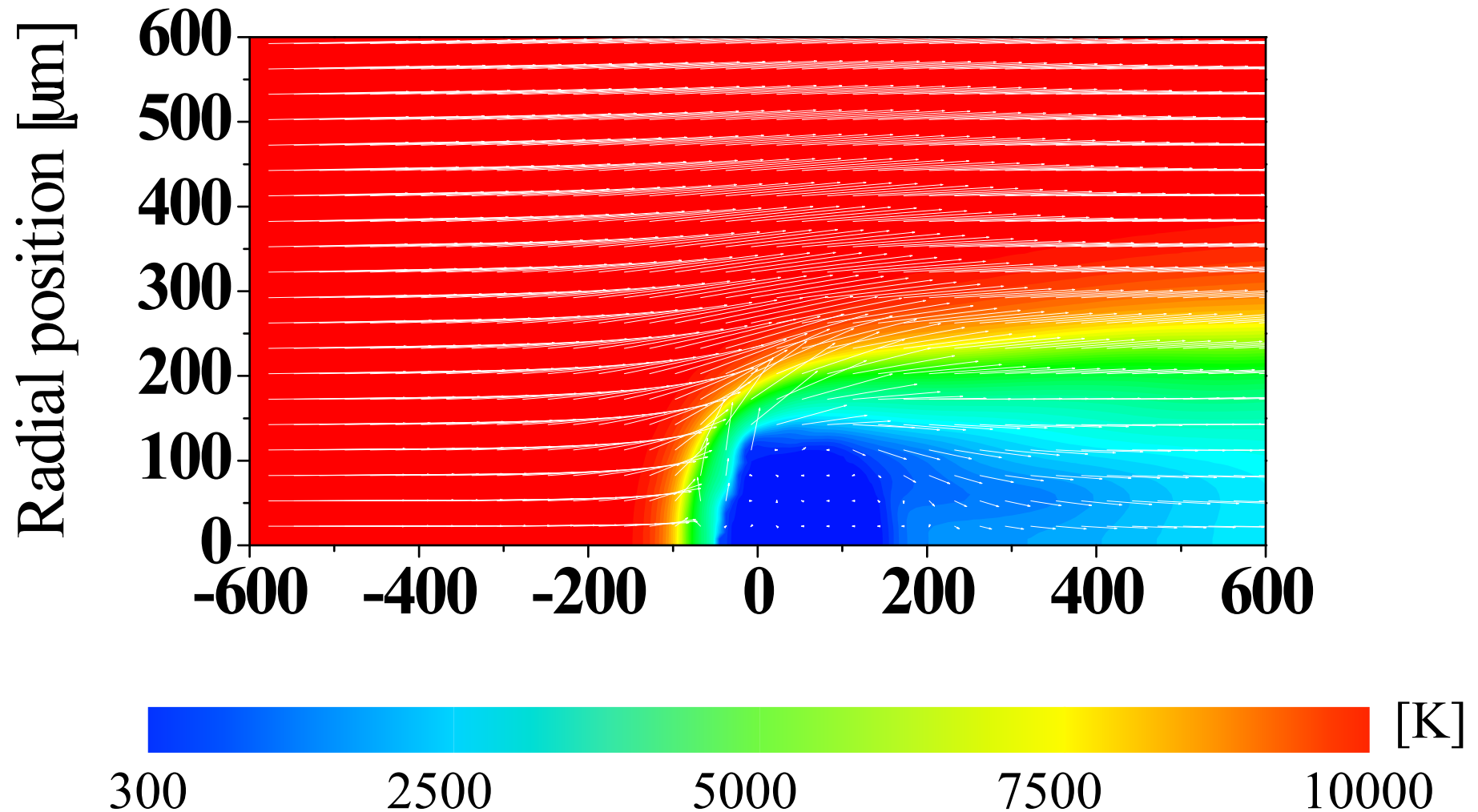
$t = 523.4 \mu\text{s}$

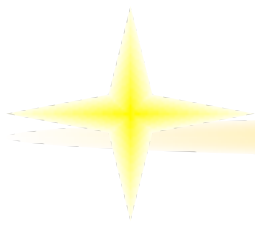




Gas flow velocity and temperature fields

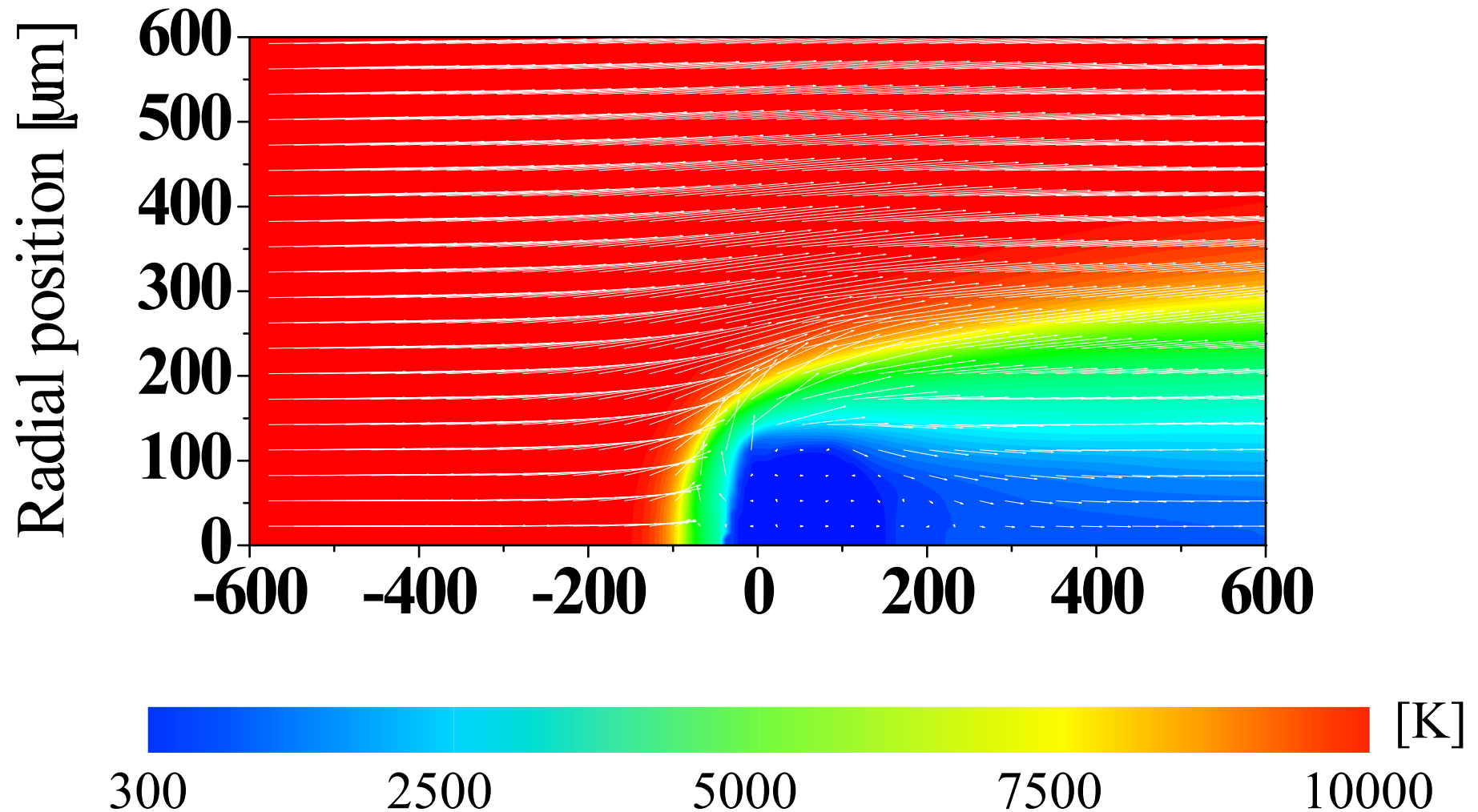
$t = 616.51 \mu\text{s}$





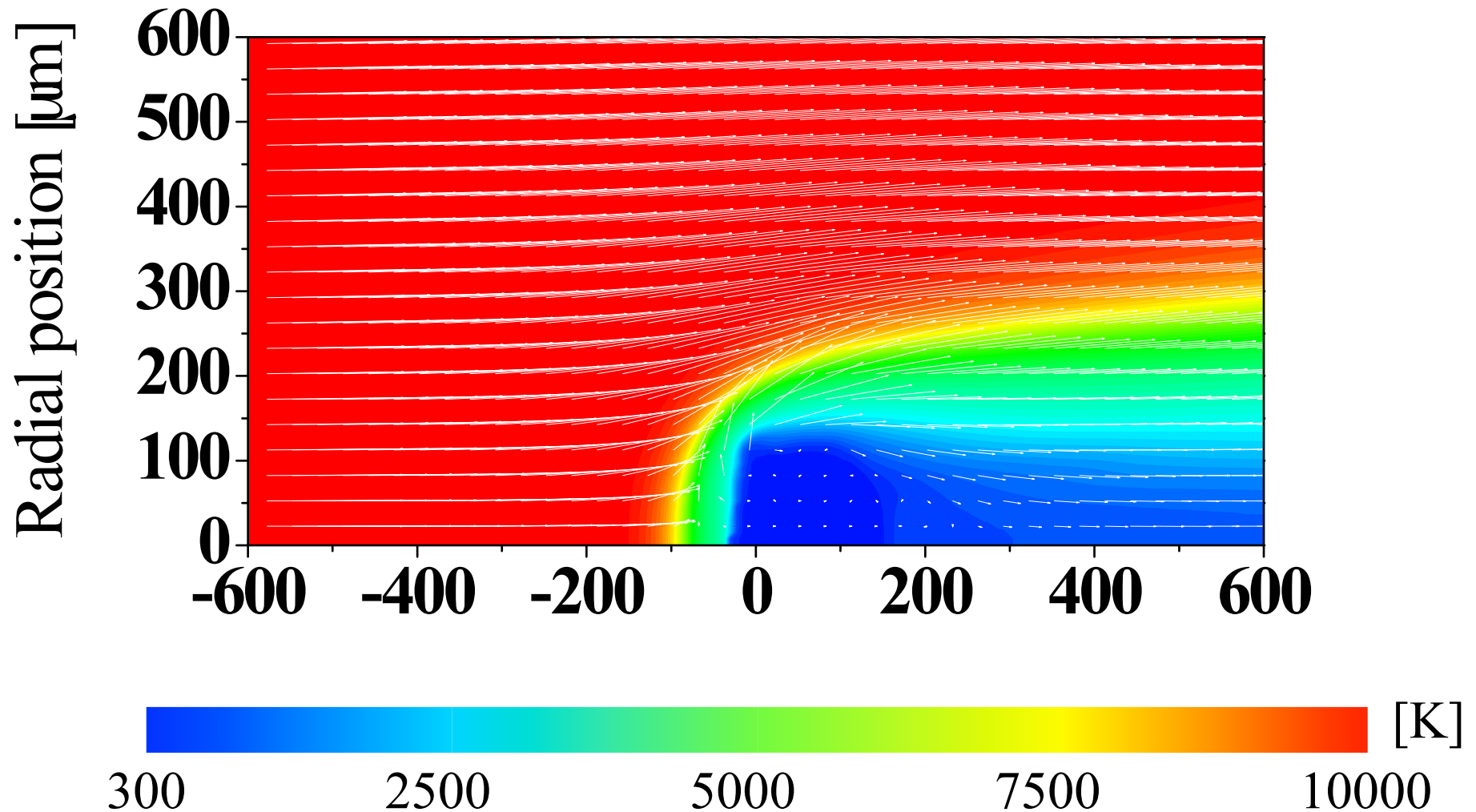
Gas flow velocity and temperature fields

$t = 709.89 \mu\text{s}$



Gas flow velocity and temperature fields

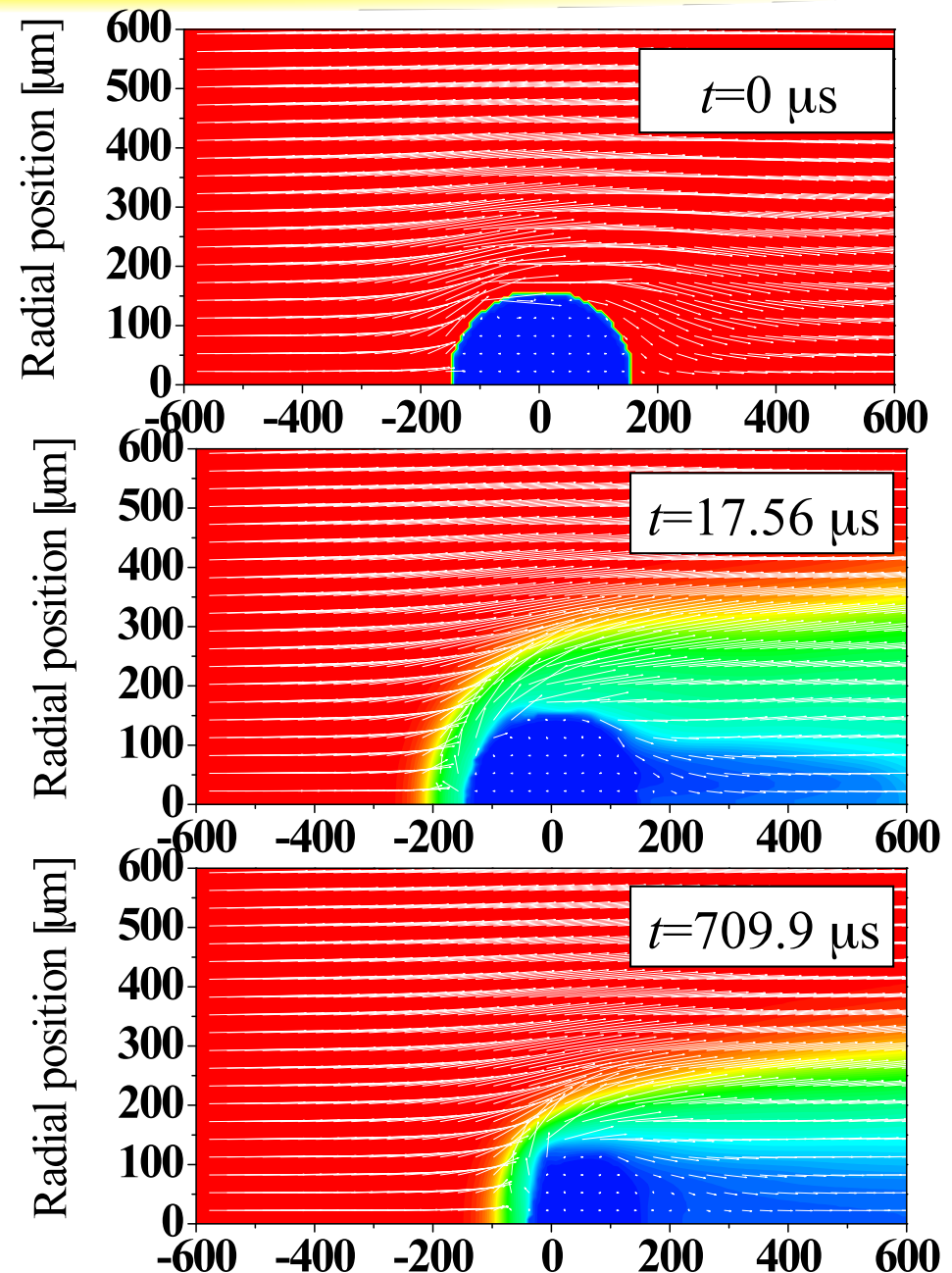
$t = 803.33 \mu\text{s}$



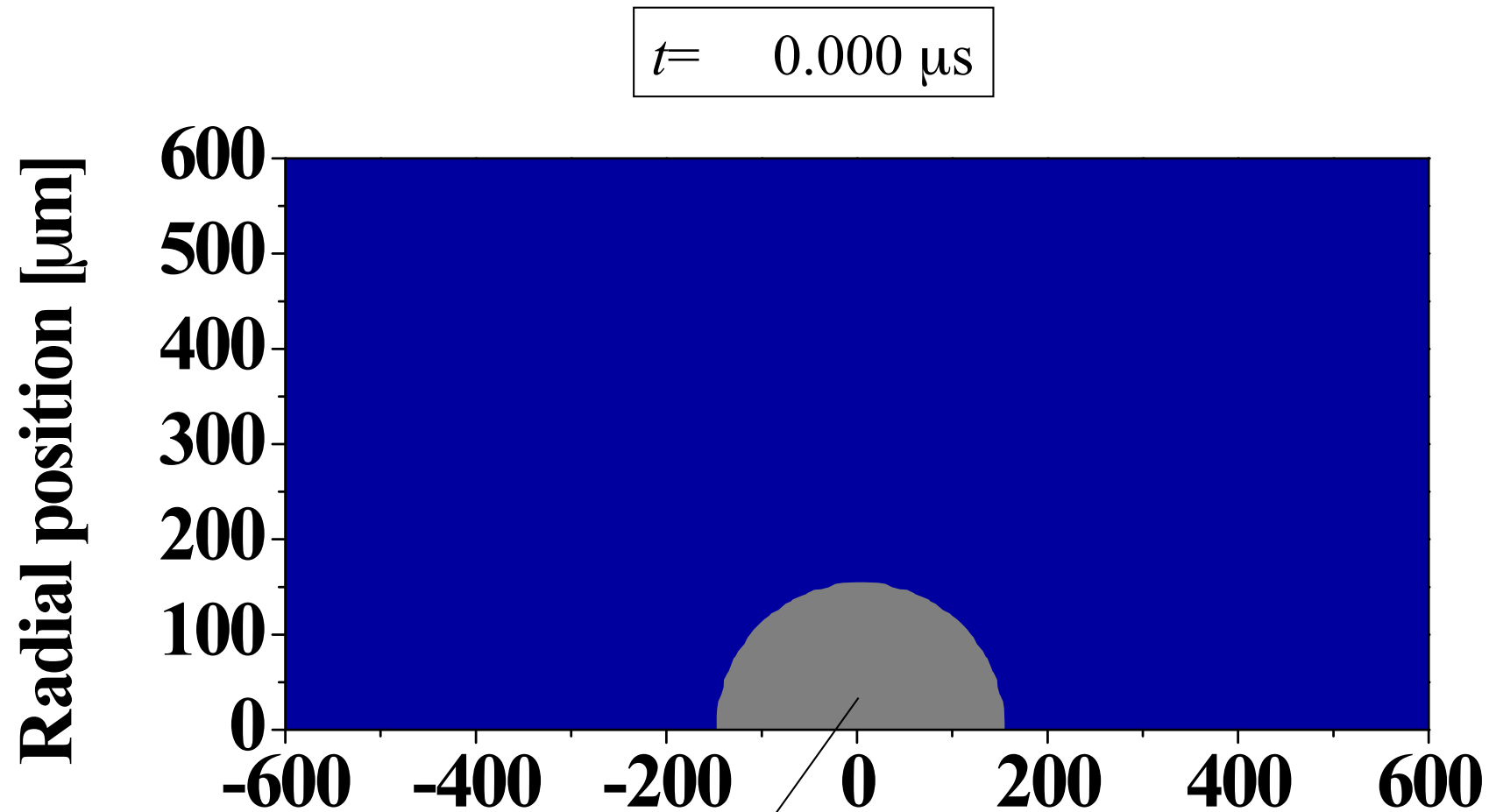


Time evolution in gas flow and temperature fields

- Rapid ablation occurs especially at upstream surface of the solid particle, which produces gas flow.
- Temperature around the particle is decreased because of thermal conduction and convection by low temperature ablated vapor.
- The ablated vapor shields the solid particle from direct interaction with the Ar plasma.



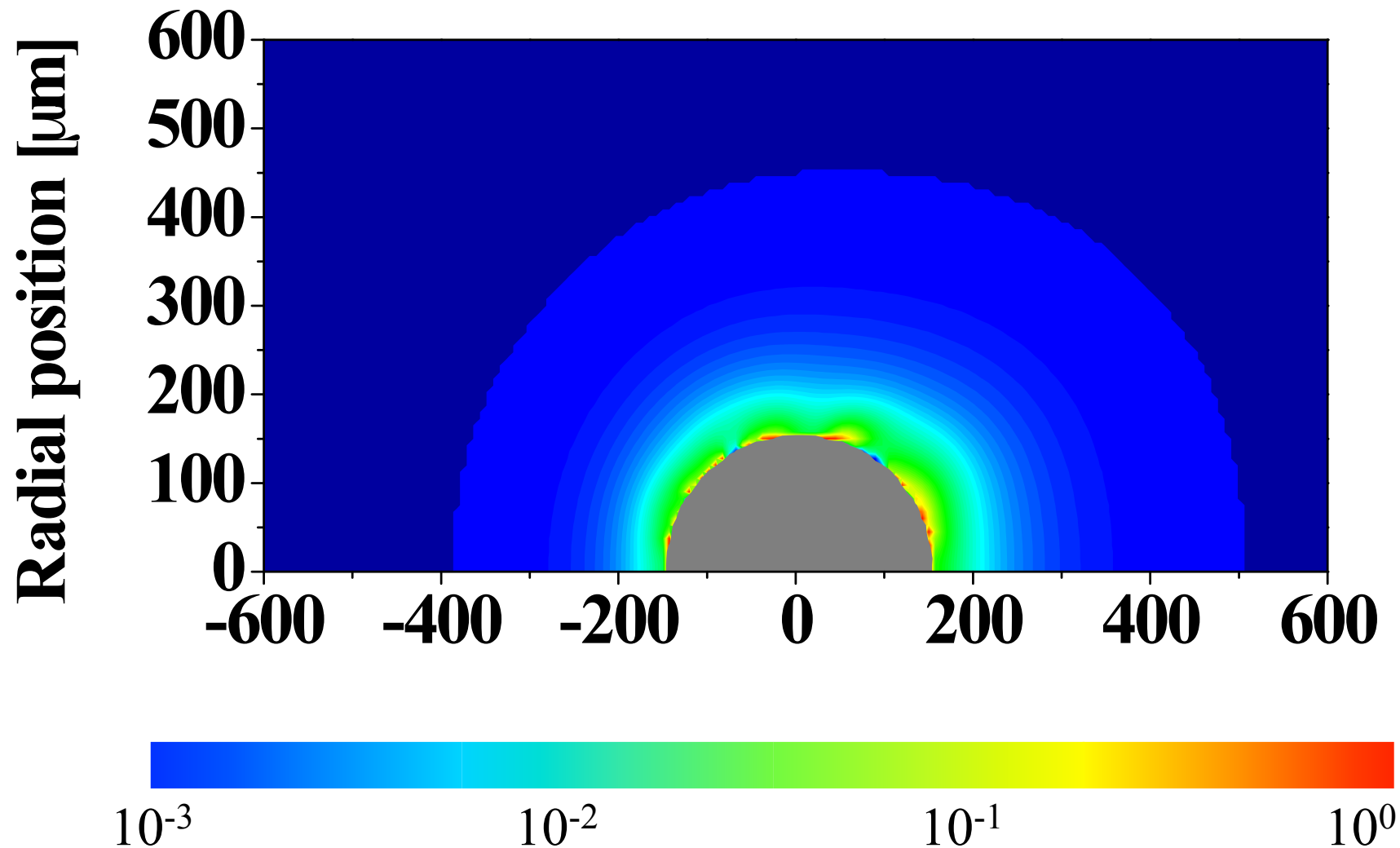
Mass fraction of ablated vapor and VOF function



The VOF function. If $f > 0.5$, the color is gray

Mass fraction of ablated vapor

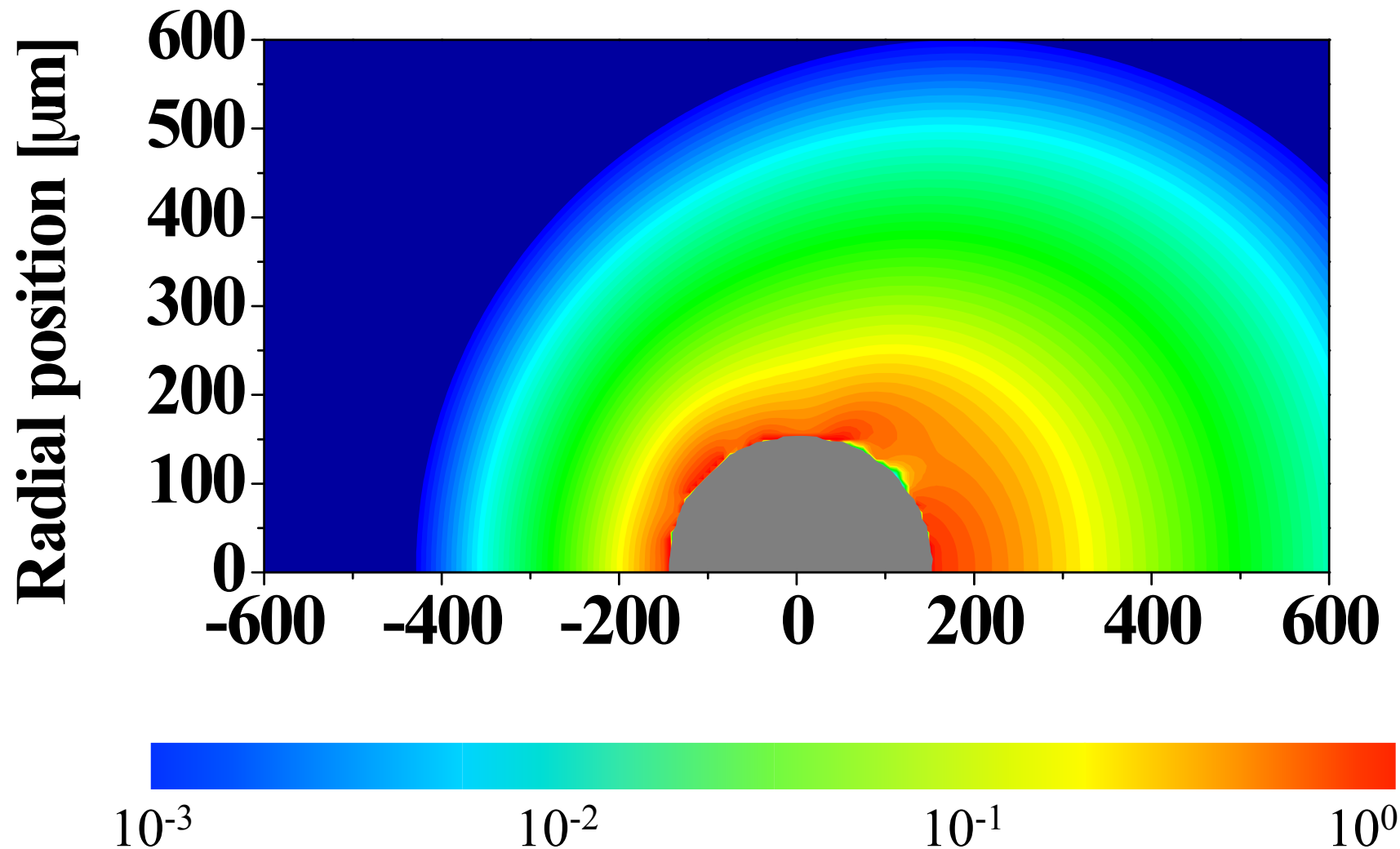
$t = 1.371 \mu\text{s}$



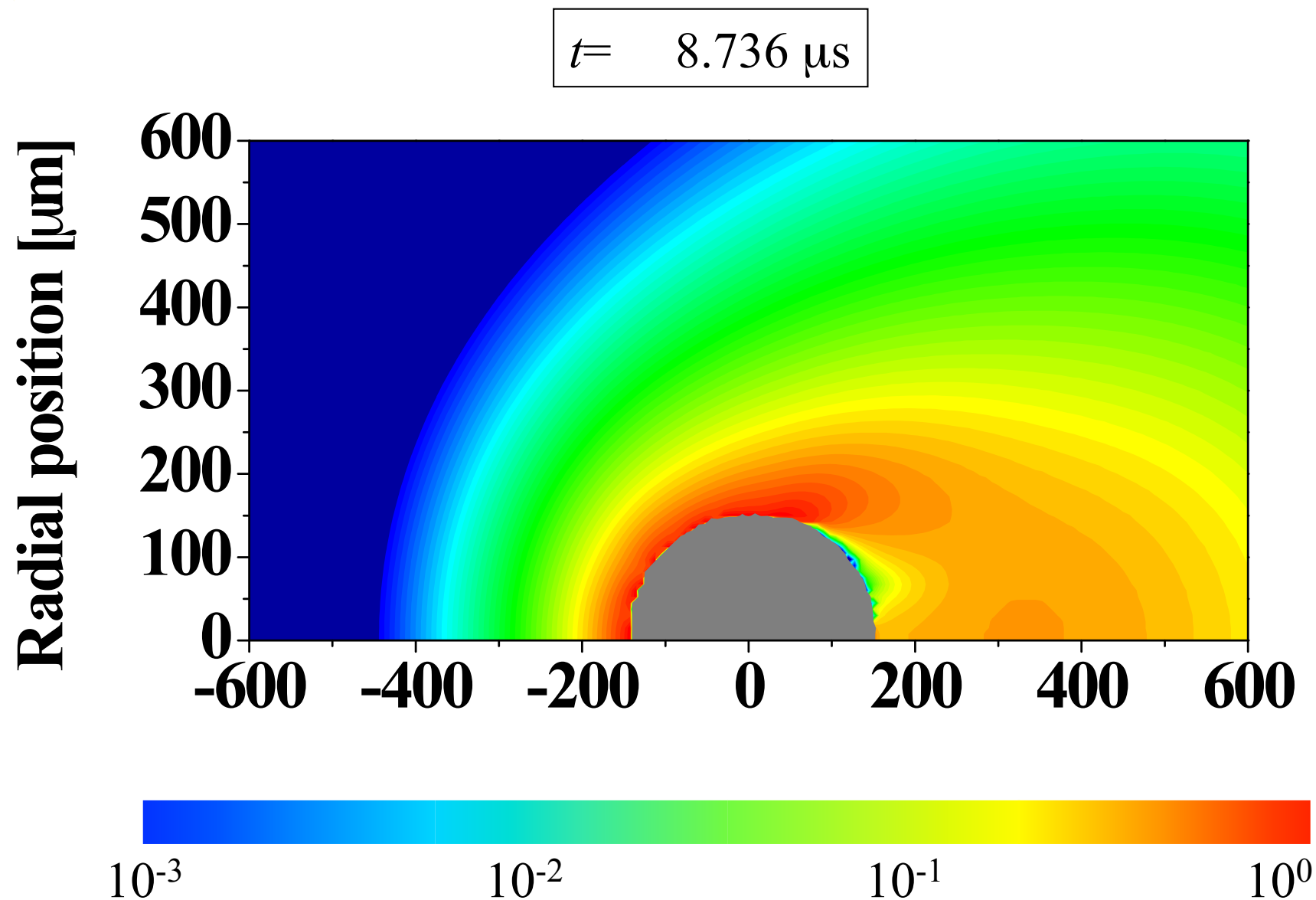


Mass fraction of ablated vapor

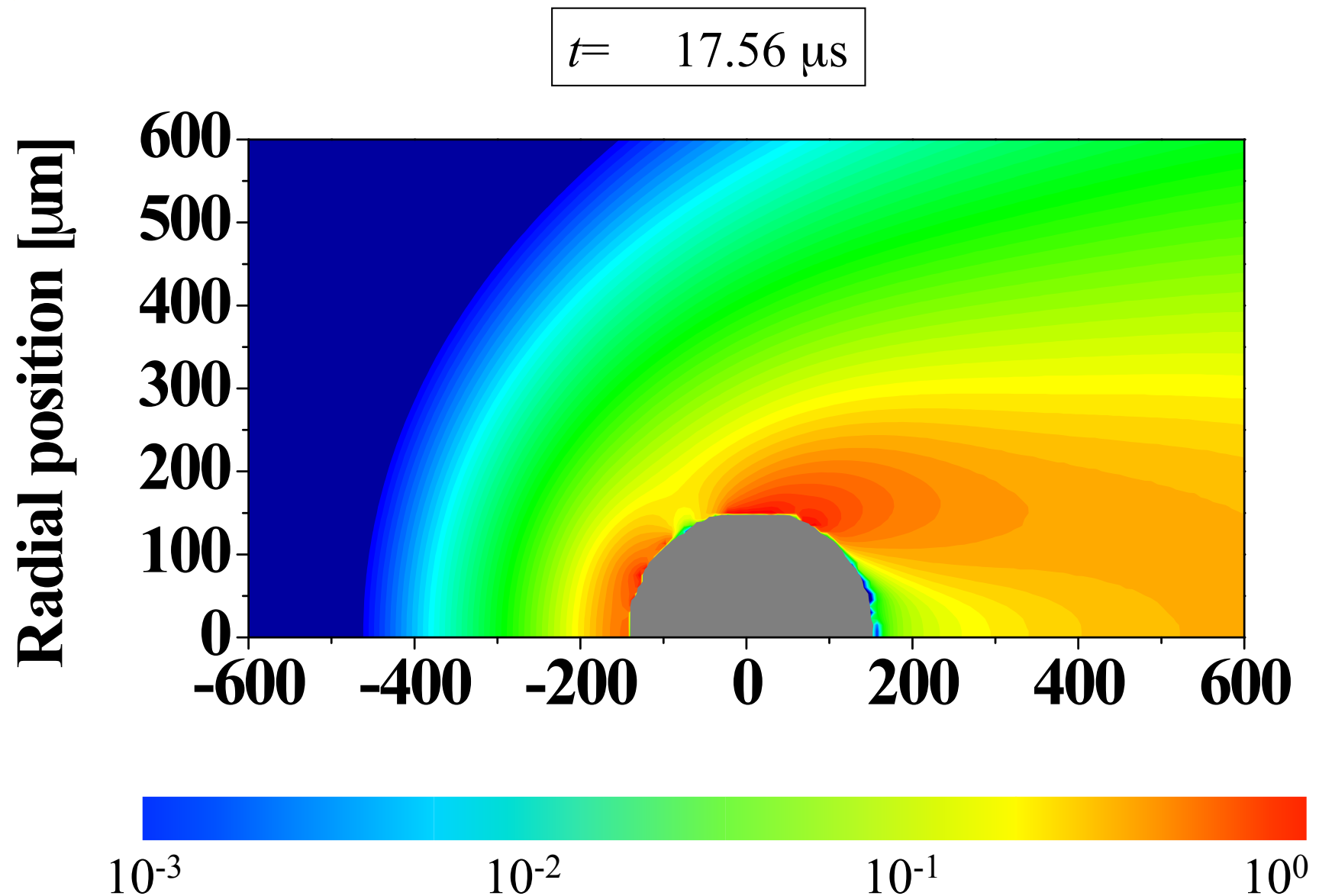
$t = 3.185 \mu\text{s}$



Mass fraction of ablated vapor

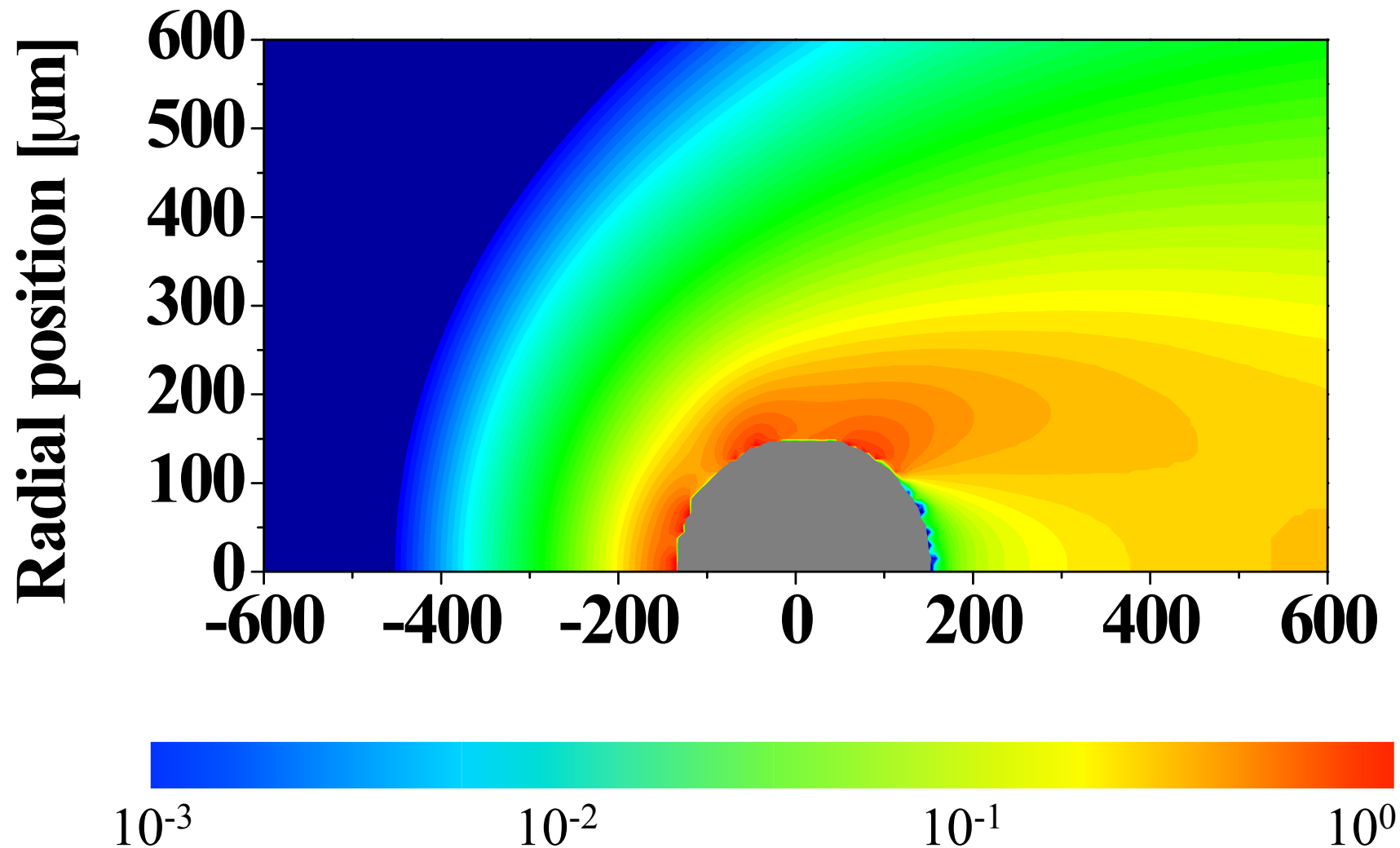


Mass fraction of ablated vapor

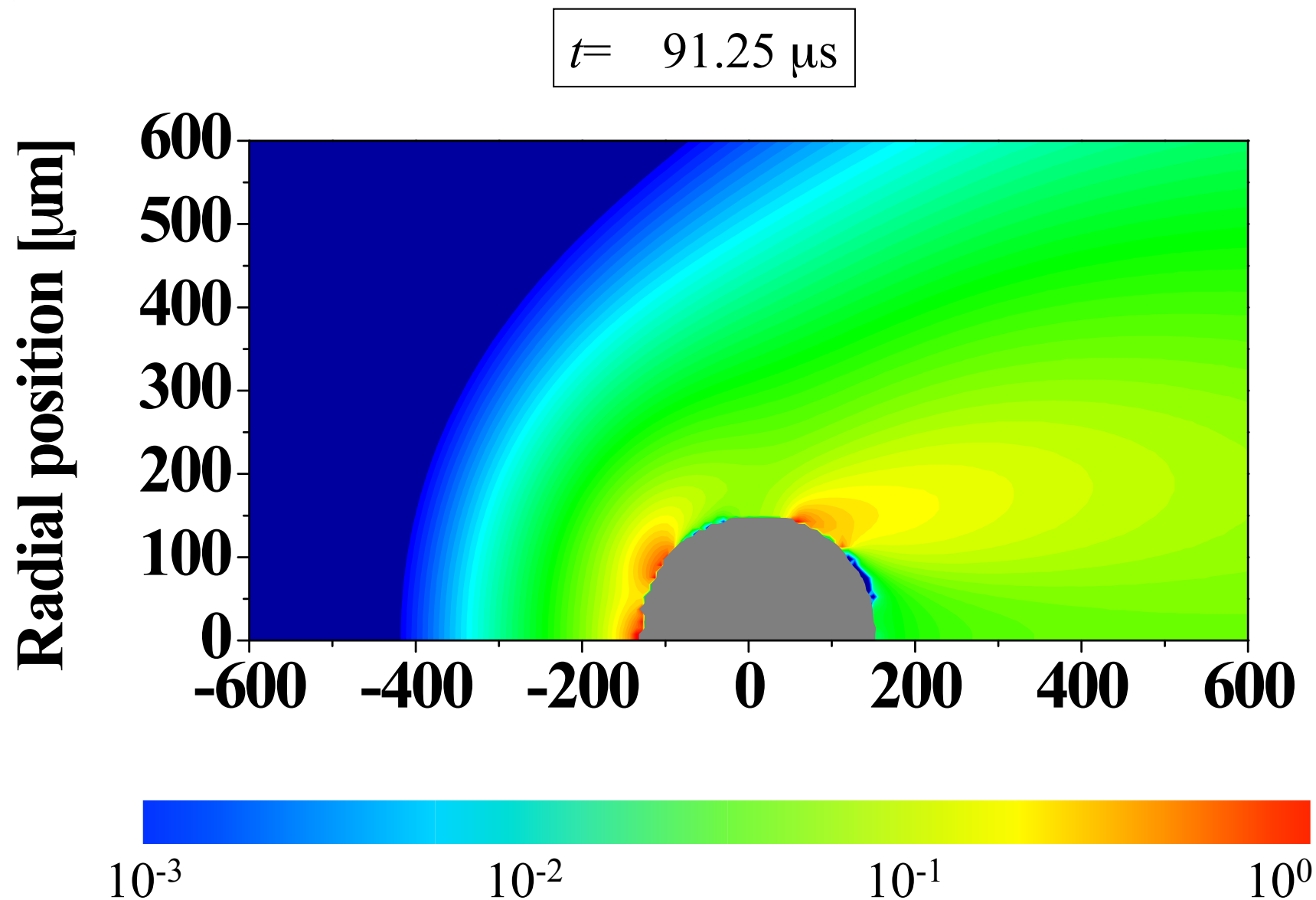


Mass fraction of ablated vapor

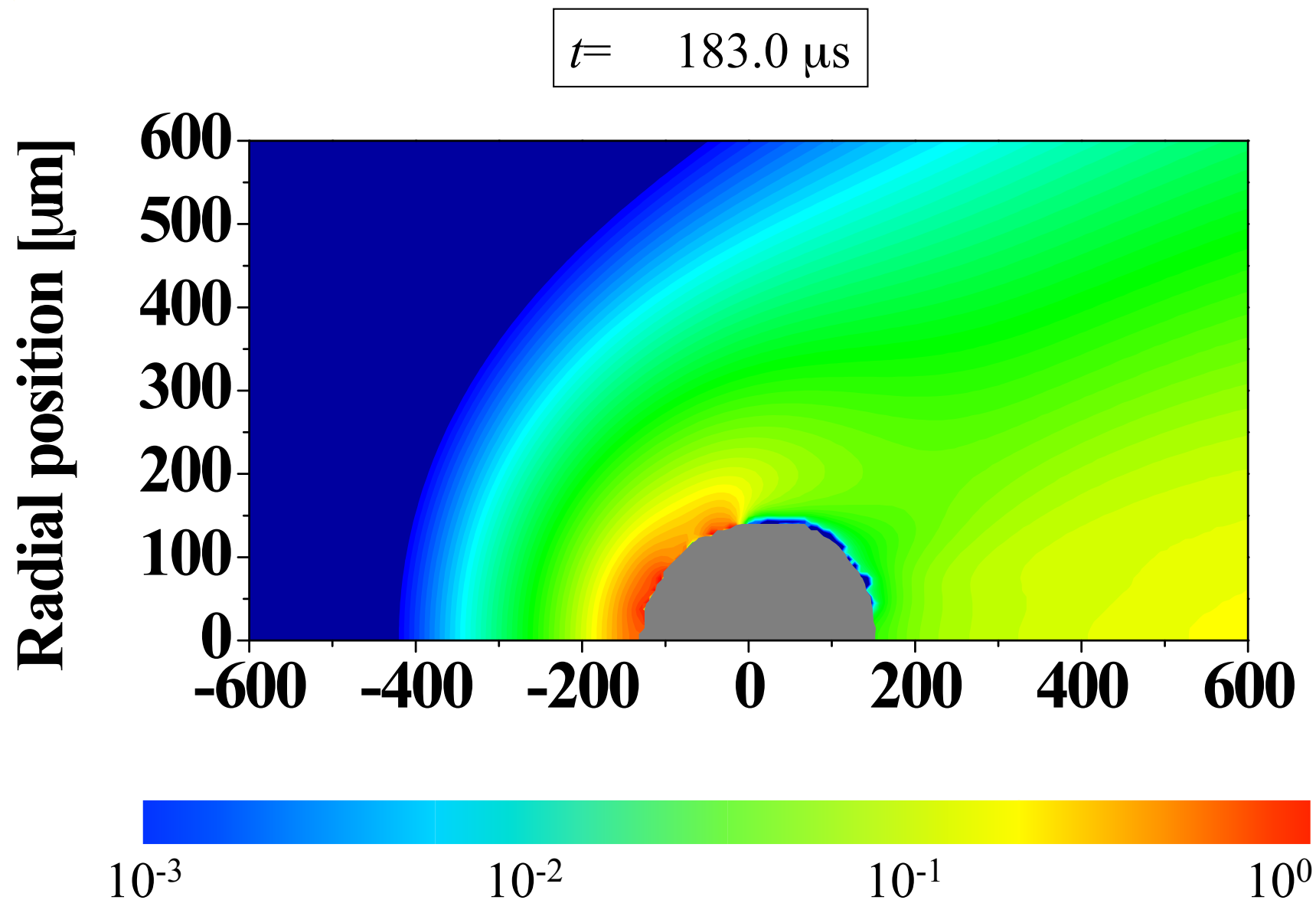
$t = 35.71 \mu\text{s}$



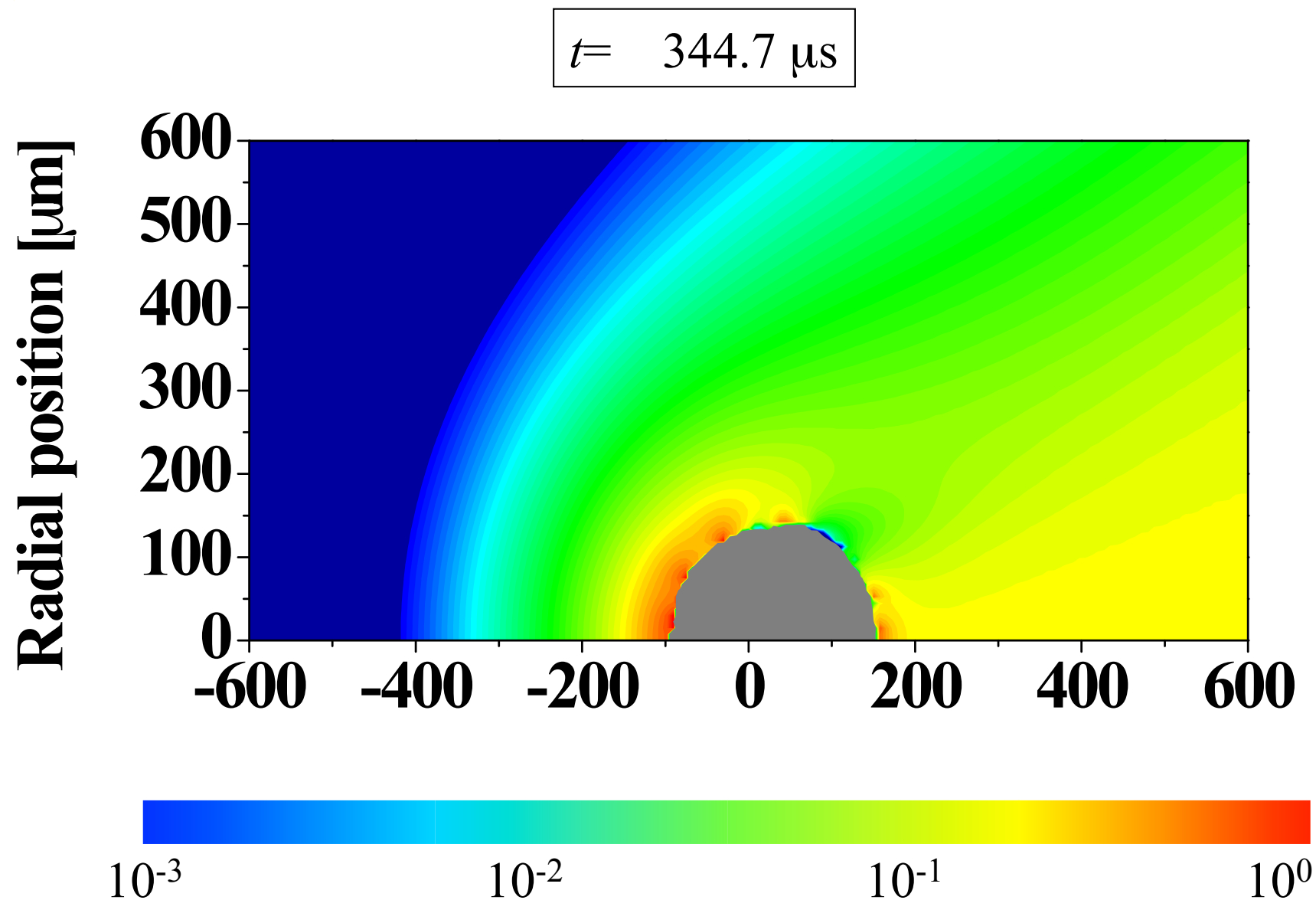
Mass fraction of ablated vapor



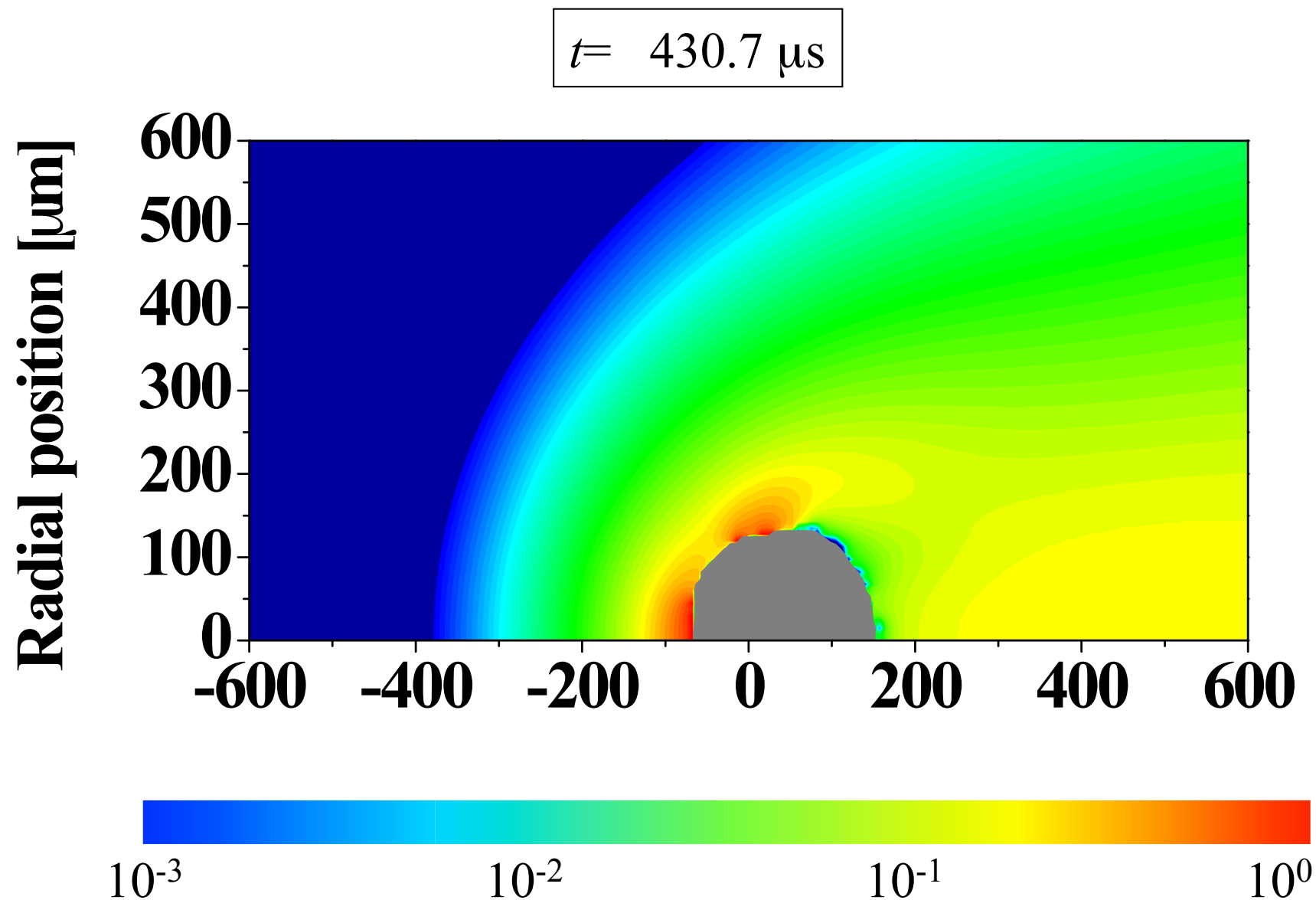
Mass fraction of ablated vapor



Mass fraction of ablated vapor

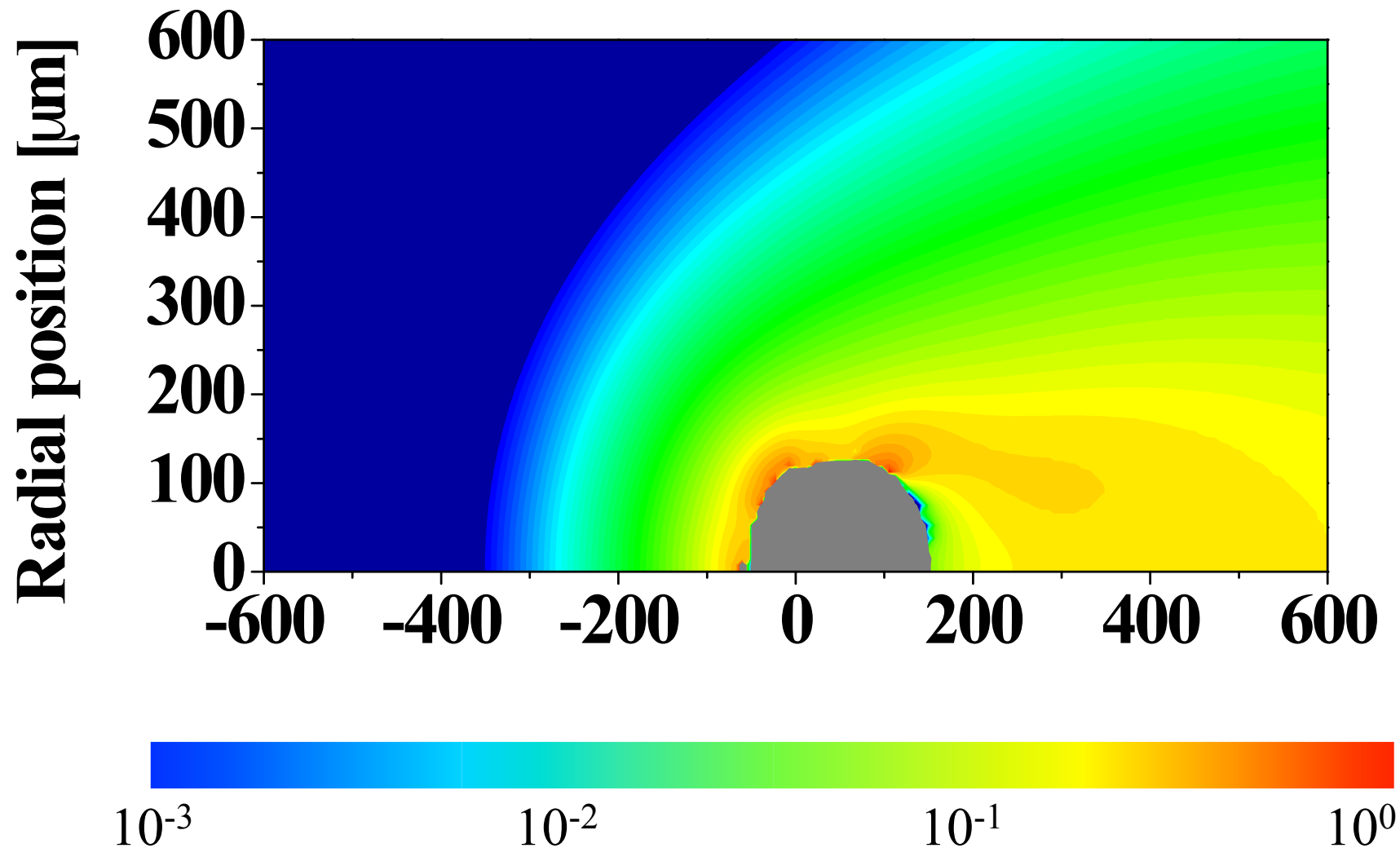


Mass fraction of ablated vapor



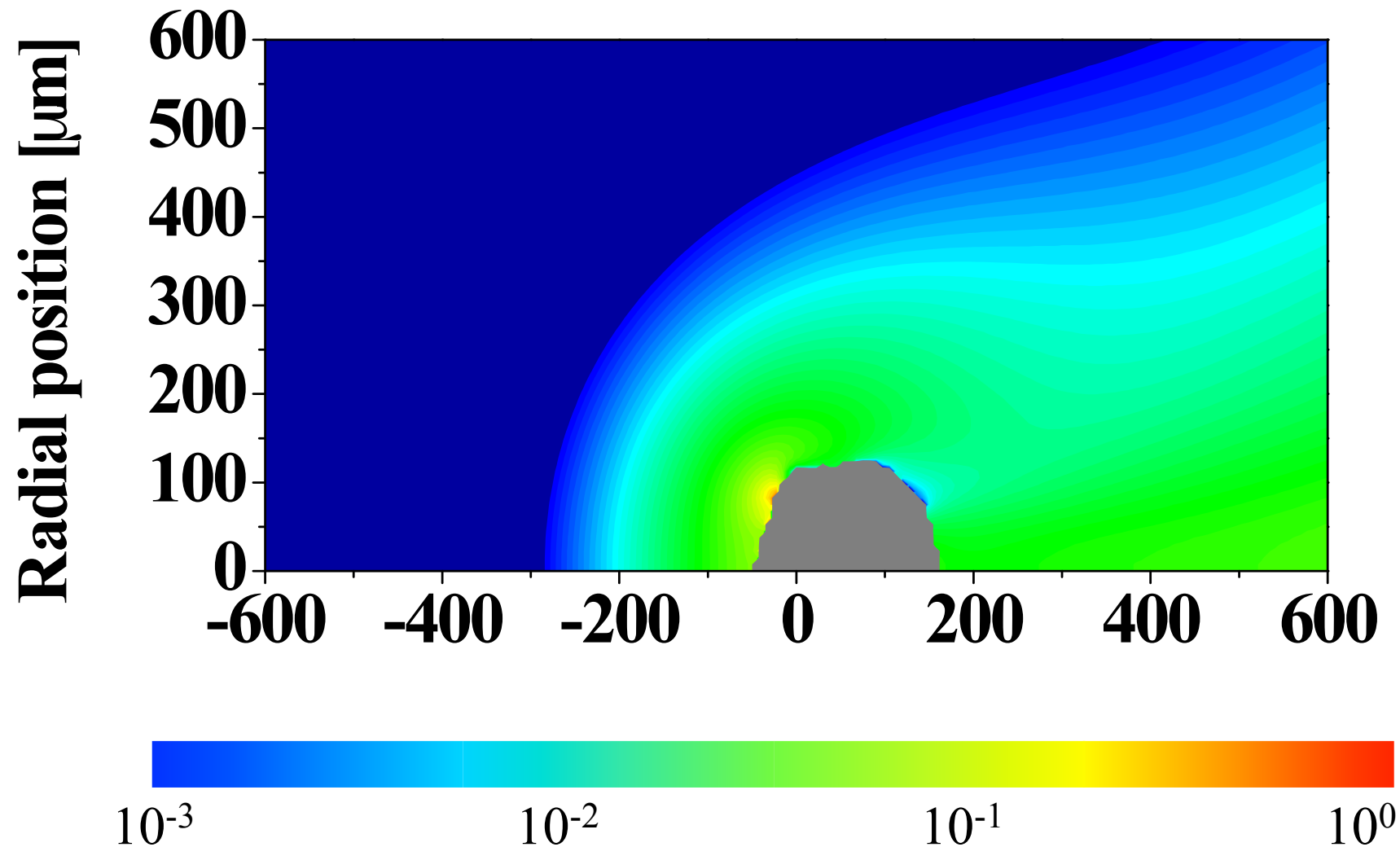
Mass fraction of ablated vapor

$t = 523.4 \mu\text{s}$



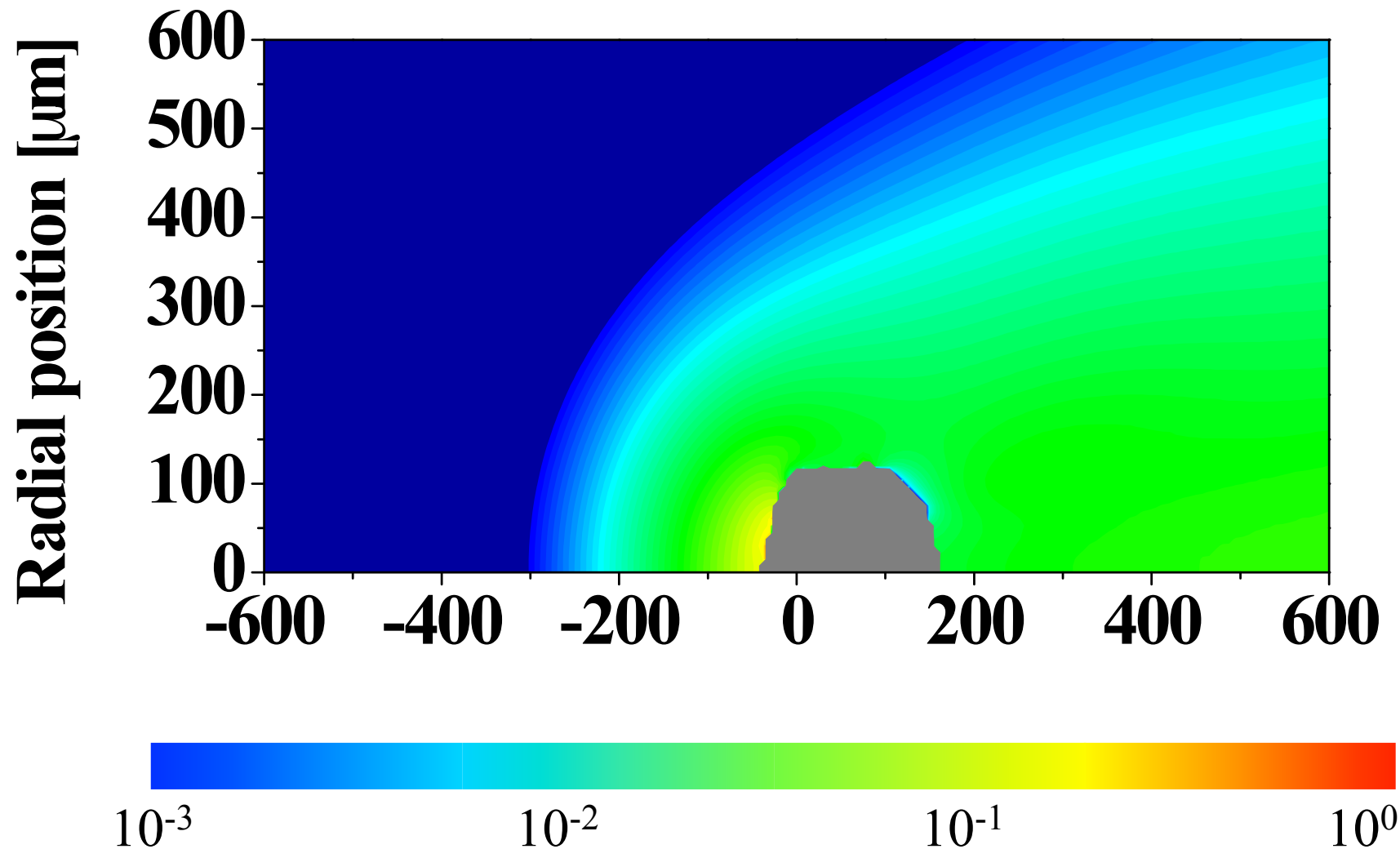
Mass fraction of ablated vapor

$t = 616.51 \mu\text{s}$



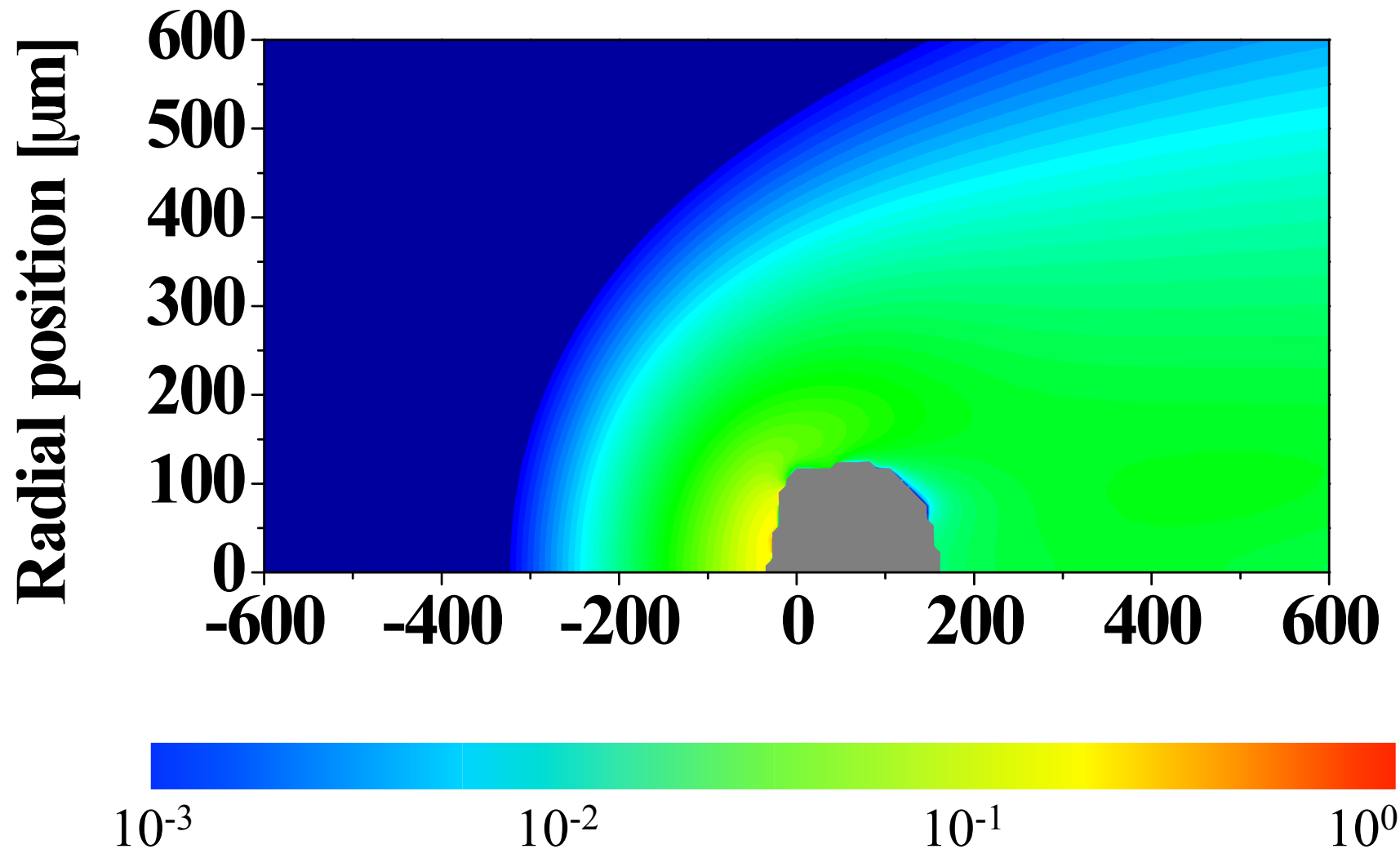
Mass fraction of ablated vapor

$t = 709.89 \mu\text{s}$



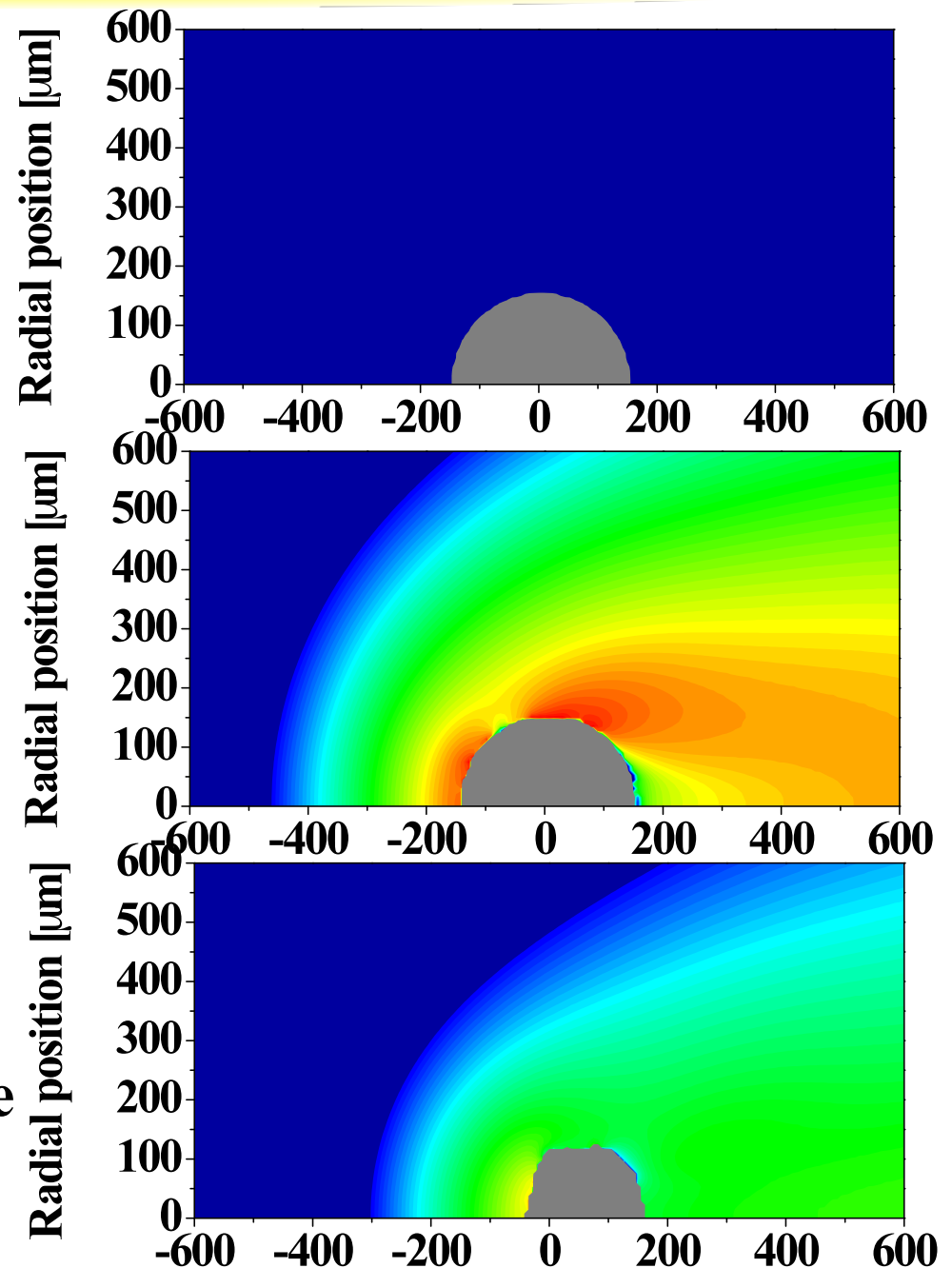
Mass fraction of ablated vapor

$t = 803.31 \mu\text{s}$



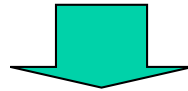
Transport of ablated vapor and shape change of the particle

- Ablated vapor is transported by diffusion, and by also convection due to the external Ar gas flow and the gas flow produced by the ablation.
- Rapid ablation especially around upstream of the particle decreases the upstream radius of the particle.
- Lifetime of dust particle was estimated to be 6 times longer than the conventional method without considering temperature decrease around the particle.**



Conclusions

- The DUSTT code was adopted to a dust particle in plasma of JT-60U configuration.
- Behaviors of carbon dust particles with radii of 1-100 μm from different walls were calculated by solving mass, motion and energy equations.



- Behavior of dust particle is dominated by ion drag force.
- Dust radius is reduced mainly by thermal sublimation.

Future work

- Comparison with experimental data
- Statistical analysis of dust particles with other radii