# 磁場シミュレーション
# 等
# シミュレーションコード開発

砂原　淳

2017年1月10日-11日

H28年度レーザープラズマ科学のための

最先端シミュレーションコードの共同開発・共用に関する研究会

| | | | | | |
|---|---|---|---|---|---|
| | | | | | |
| Star1D | Rad hydro | 1D | | 利用されている | GPI, 広大、九大 |
| Star2D | Rad hydro | 2D | | 利用されている<br>開発中 | EUV |
| SPH | hydro | 1D/2D/3D | | energy式に<br>難あり | |
| DSMC | monte carlo | 3D | | しばらくほったら<br>かし | |
| MD | Molecular dynamics | 3D | Langevin | 計算中<br>開発中 | 阪大 |
| Maxwell | Maxwell Solver | 2D cylinder | | 開発中 | FIREX |
| | | | | | |

introduction

2016年と同じスライド

「レーザープラズマ科学のための最先端シミュレーションコードの開発・共用に関する研究会」

**レーザー核融合**

**EUV光源開発**

**中性子源**

**レーザーアブレーション**

**etc..**

| 流体 | PIC |
|---|---|
| 状態方程式 | Monte-Carlo |
| 熱伝導 | MD |
| 輻射輸送 | DSMC |
| レーザー伝播 | |
| 原子過程 | |
| MHD | |
| Nonlocal | |
| etc.. | |

**1次元, 2次元統合コードを開発する**

# 今年は二次元コードで1μsレベルの計算ができるようにしたい + MHD

2016年と同じスライド

**2016** 今年こそバグとり職人を脱却したい （論文を書くぞ！）

2015 star2d (HLLC-semi-Lagrangian version)

Langevin MD

改良型QEOSテスト

2010

DSMC

SPH

star2d (HLLC version)

2005 star2d (CIP version)

2003 star1d

# 今年は二次元コードで1μsレベルの計算ができるようにしたい + MHD

2017年のスライド

2017

今年こそバグとり職人を脱却したい（論文を書くぞ！）

ALE化　　核反応

改良型QEOSテスト

2016　star2d (Bug fix. Laser raytrace)

Maxwell solver

2015　star2d (HLLC-semi-Lagrangian version)

Langevin MD

2010

DSMC

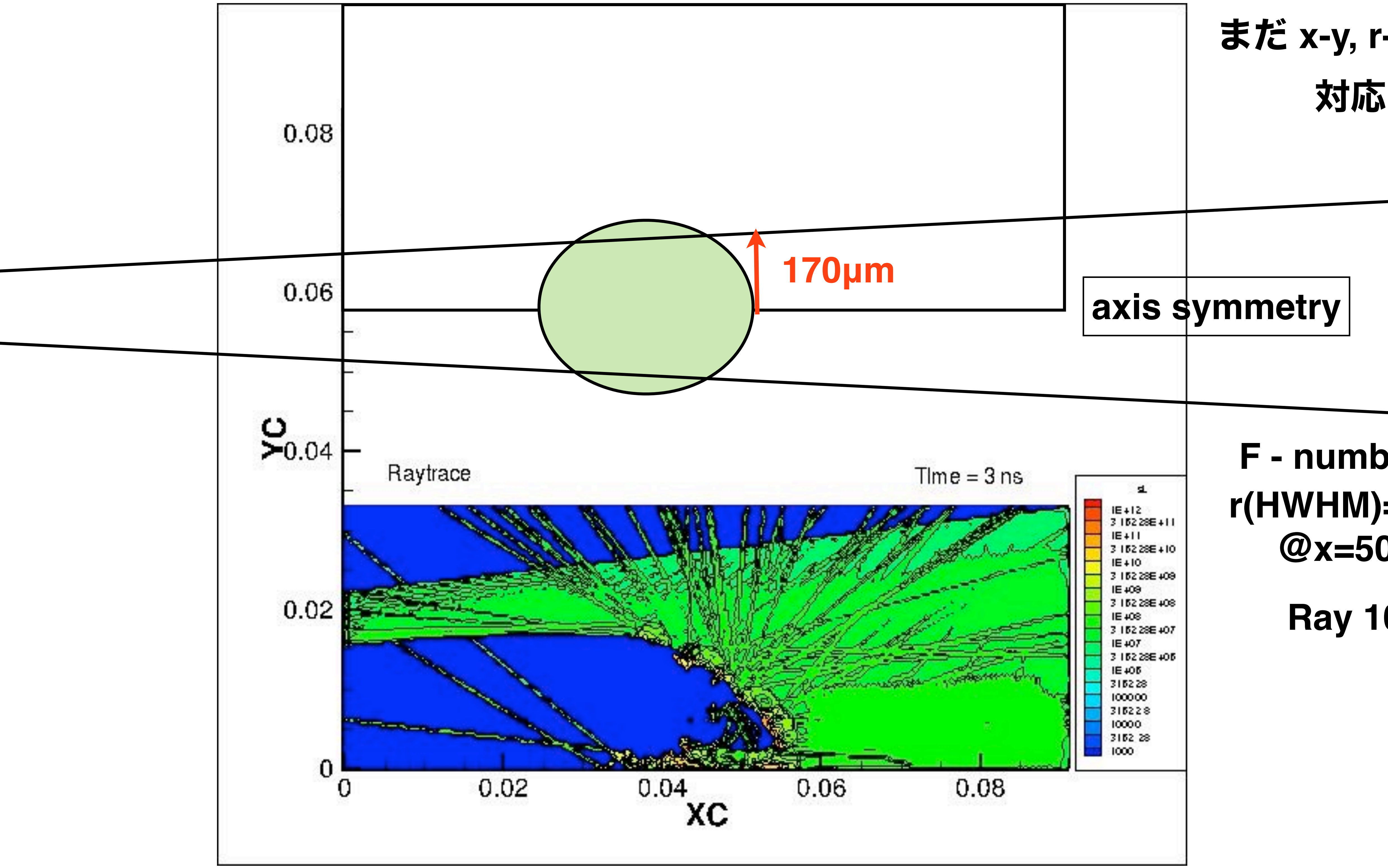
SPH

star2d　(HLLC version)

2005　star2d　(CIP version)

2003　star1d

# Star2Dへのレーザー光線追跡ルーチンの導入

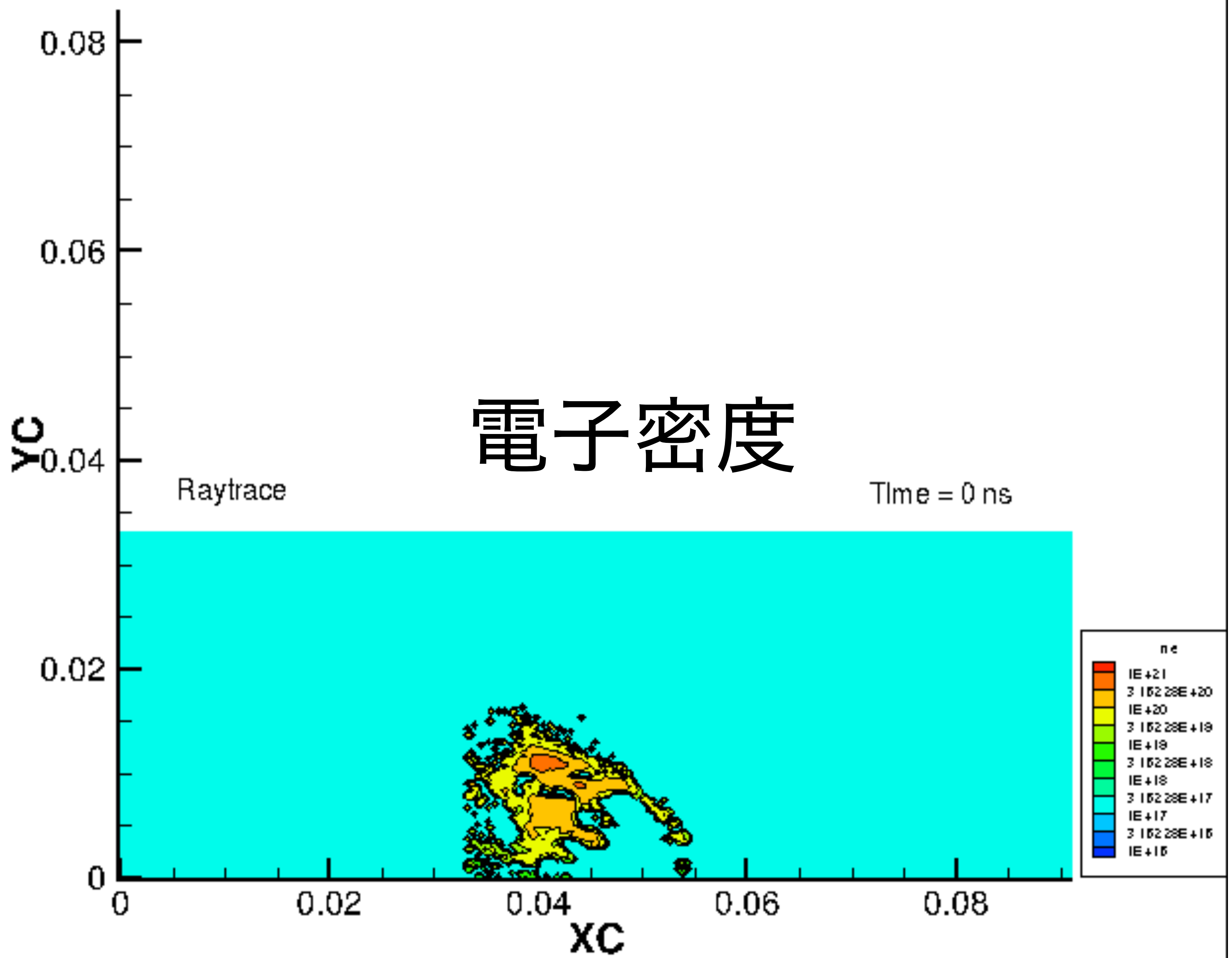



まだ x-y, r-zのみ
対応

F - number = 10
r(HWHM)=170μm
@x=500μm

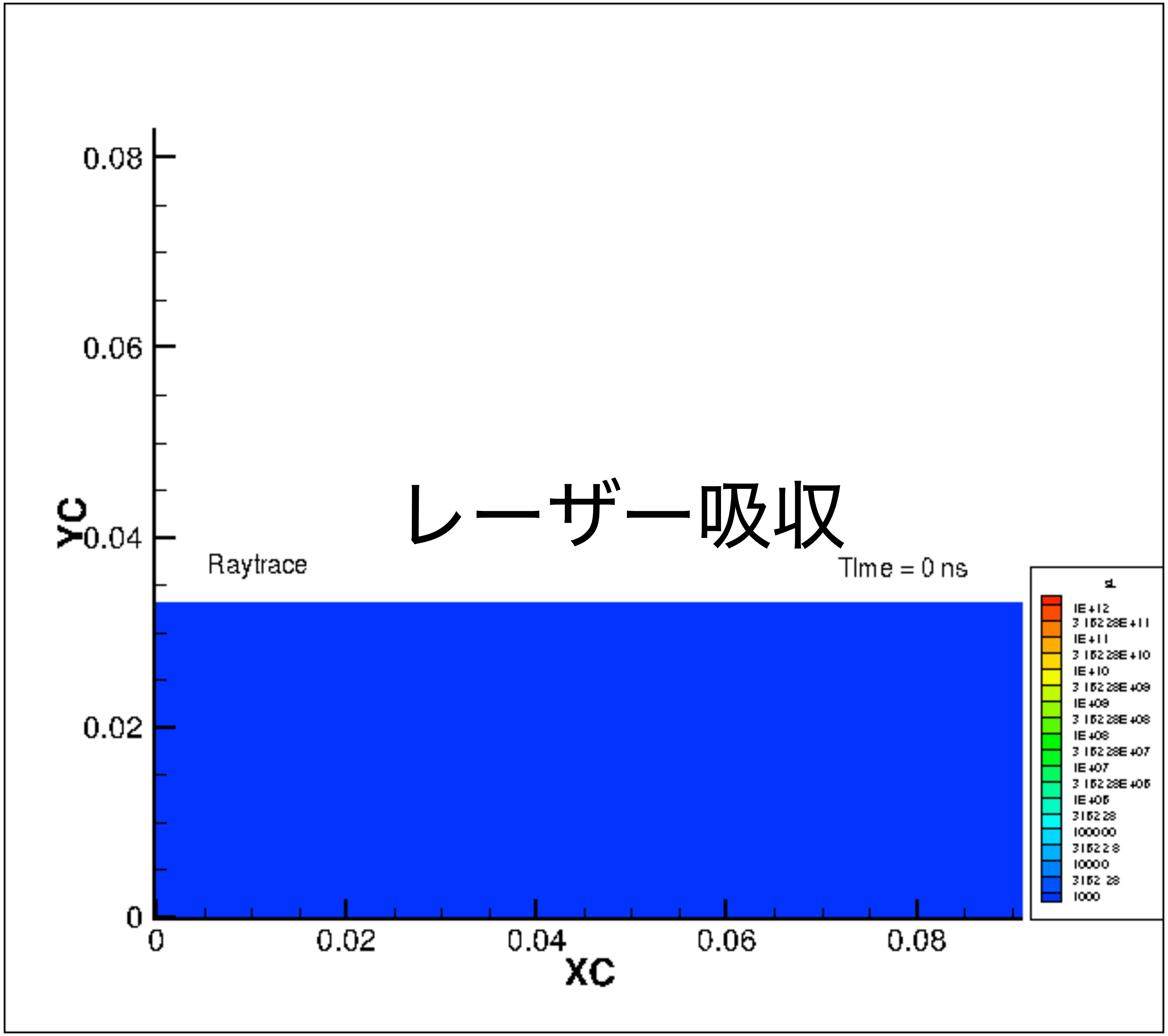
Ray 100本

# 電子密度

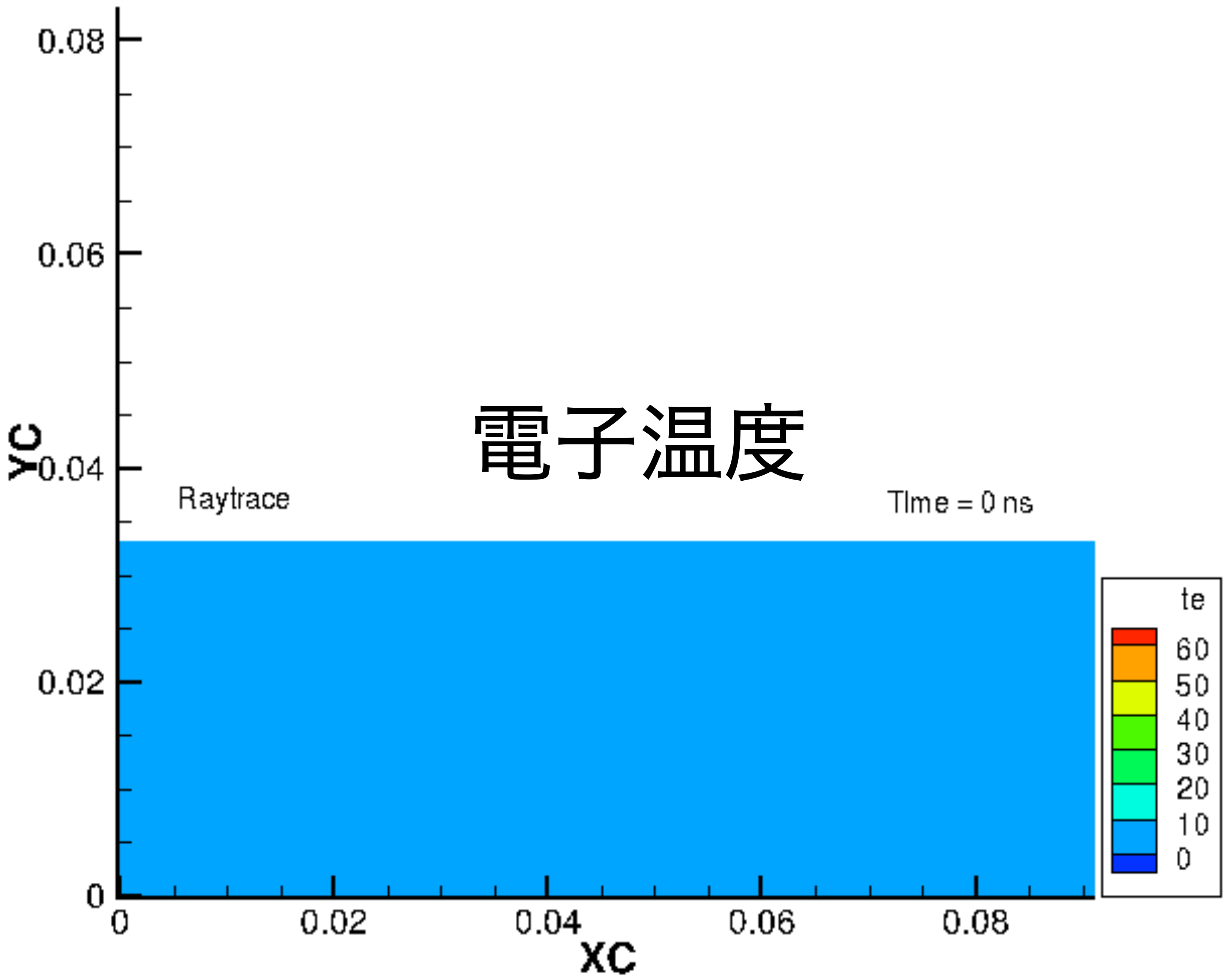


YC
0.08
0.06
0.04
0.02
0
Raytrace
Time = 0 ns
XC
0
0.02
0.04
0.06
0.08
ne
1E+21
3.16228E+20
1E+20
3.16228E+19
1E+19
3.16228E+18
1E+18
3.16228E+17
1E+17
3.16228E+16
1E+16

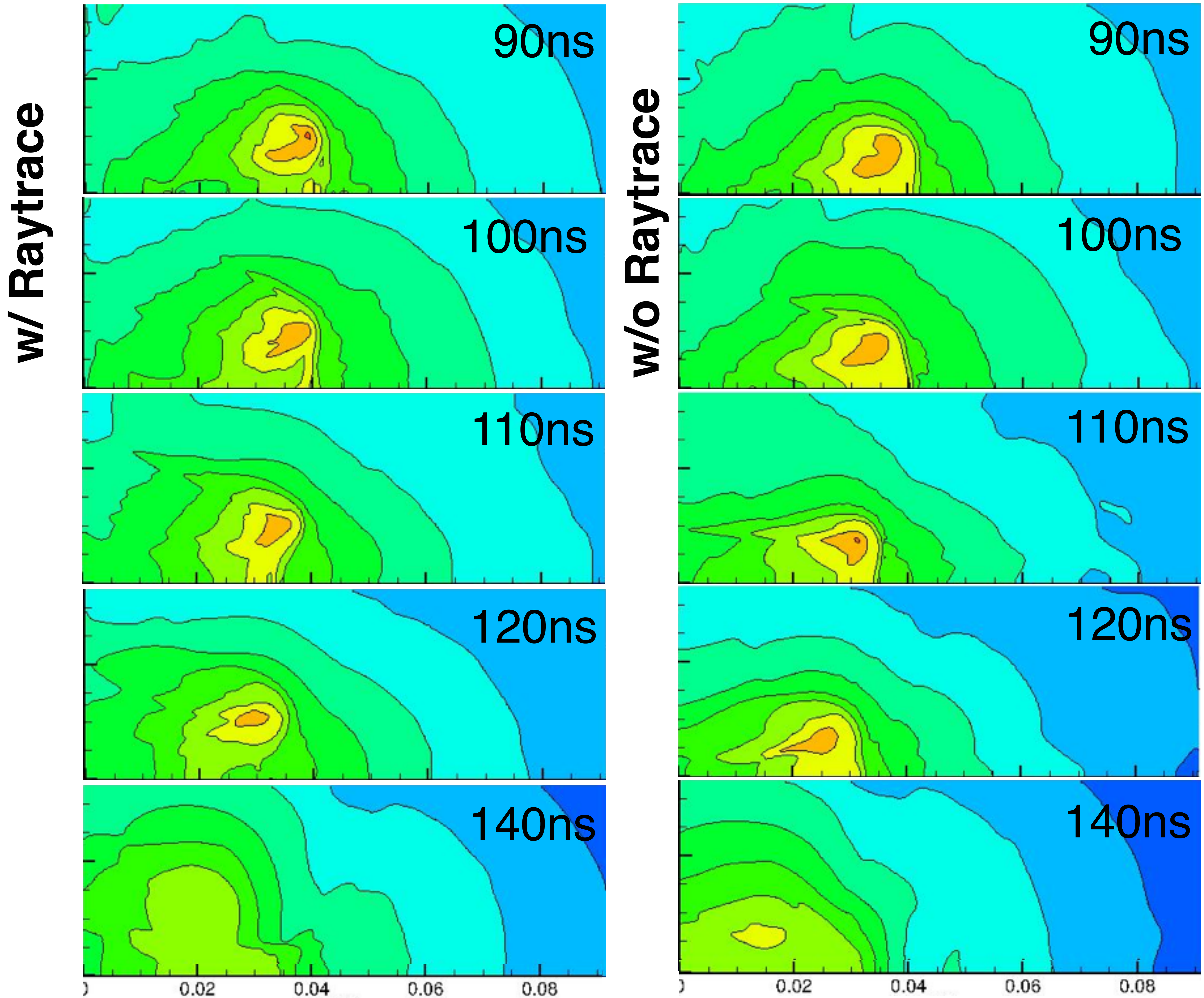
# レーザー吸収

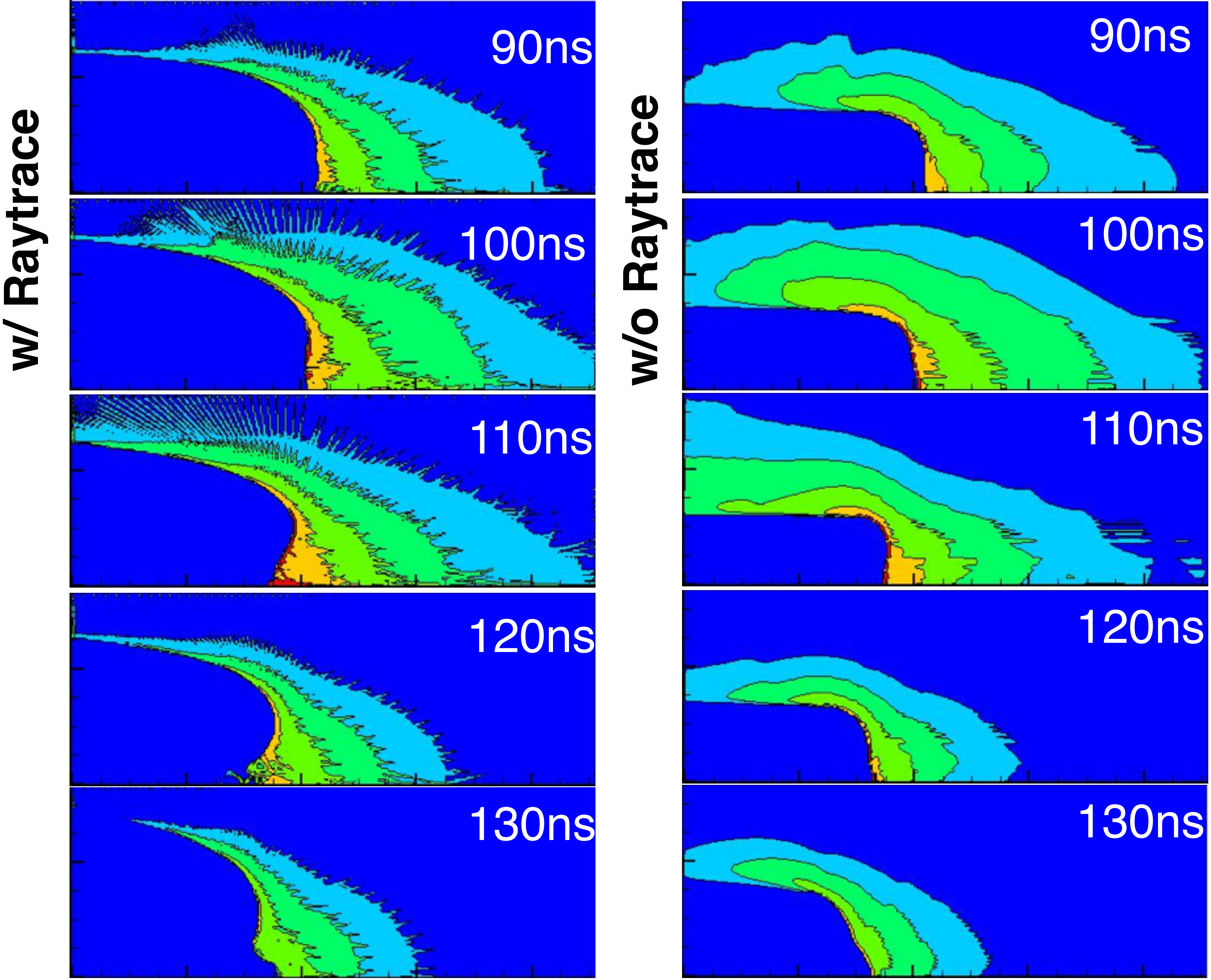


# 電子温度



Raytrace
Time = 0 ns
YC
0.08
0.06
0.04
0.02
0
XC
0
0.02
0.04
0.06
0.08
te
60
50
40
30
20
10
0


w/ Raytrace
w/o Raytrace
90ns
100ns
110ns
120ns
140ns
90ns
100ns
110ns
120ns
140ns
0.02
0.04
0.06
0.08
0.02
0.04
0.06
0.08



w/ Raytrace
90ns
100ns
110ns
120ns
130ns
w/o Raytrace
90ns
100ns
110ns
120ns
130ns

## まとめ

- Star2Dにlaser raytraceルーチンを導入した
  x-y, r-z（円柱座標）のみ
- r-θ (球座標)についても近日完成予定
- 斜め入射部分については　straight line近似と
  raytraceでは計算結果が大きく異なる
- Star1Dに続き、Star2Dについても本格的に
  使って頂きたく候
- ALE, MHD

# Diffusion of external magnetic fields into the cone-in-shell target in the fast ignition

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Hiroshi Azechi
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FIREX-team

## Acknowledgements

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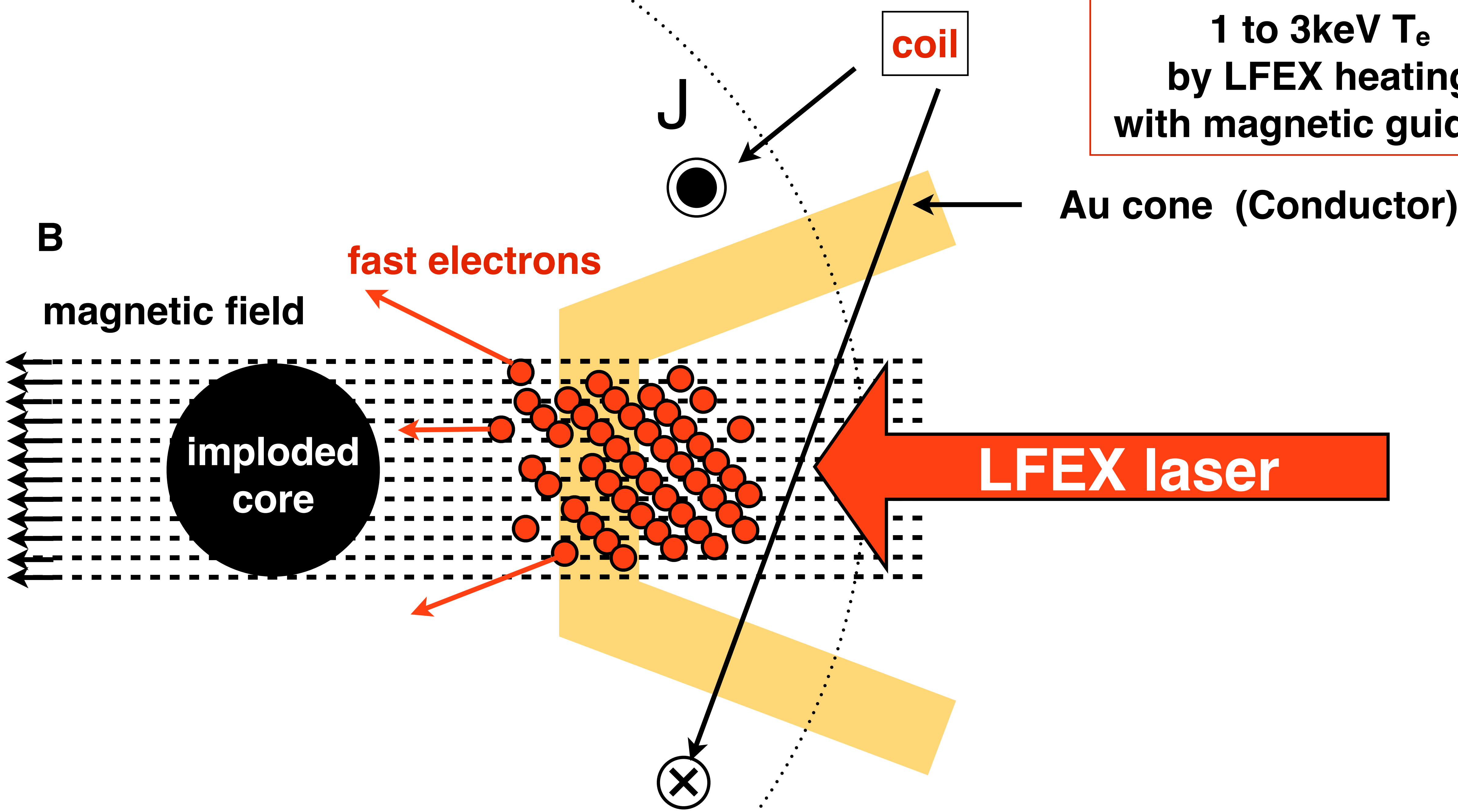
# Motivation

We observed
1 to 3keV $T_e$
by LFEX heating
with magnetic guiding




Magnetic guiding of fast electrons is very important in our fast ignition scheme.

We will simulate the diffusion of externally applied magnetic field into the interior of the cone target.

## Summary

In order to simulate the temporal evolution of magnetic field, we developed Maxwell solver in the cylindrical coordinates.

We have simulated the diffusion of externally applied magnetic field into the interior of the cone target with $10^6$ S/m.

The surface of the cone can be heated by the eddy current. However the bulk of the gold wall remains at the temperature lower than 0.4 eV.

Magnetic diffusion time is 0.5ns / 40μm thick gold of $10^6$ S/m, which is short enough for the fast ignition exp. However, the intensity of magnetic field inside cone is reduced by the eddy current.

With $10^4$ S/m conductivity, the magnetic field can diffuse so faster and the intensity of magnetic field inside the cone is comparable to that outside the cone wall.

We calculated the electrical conductivity of gold in the range from 0.4 to 5 eV.

# We have developed 2D cylinder Maxwell solver.

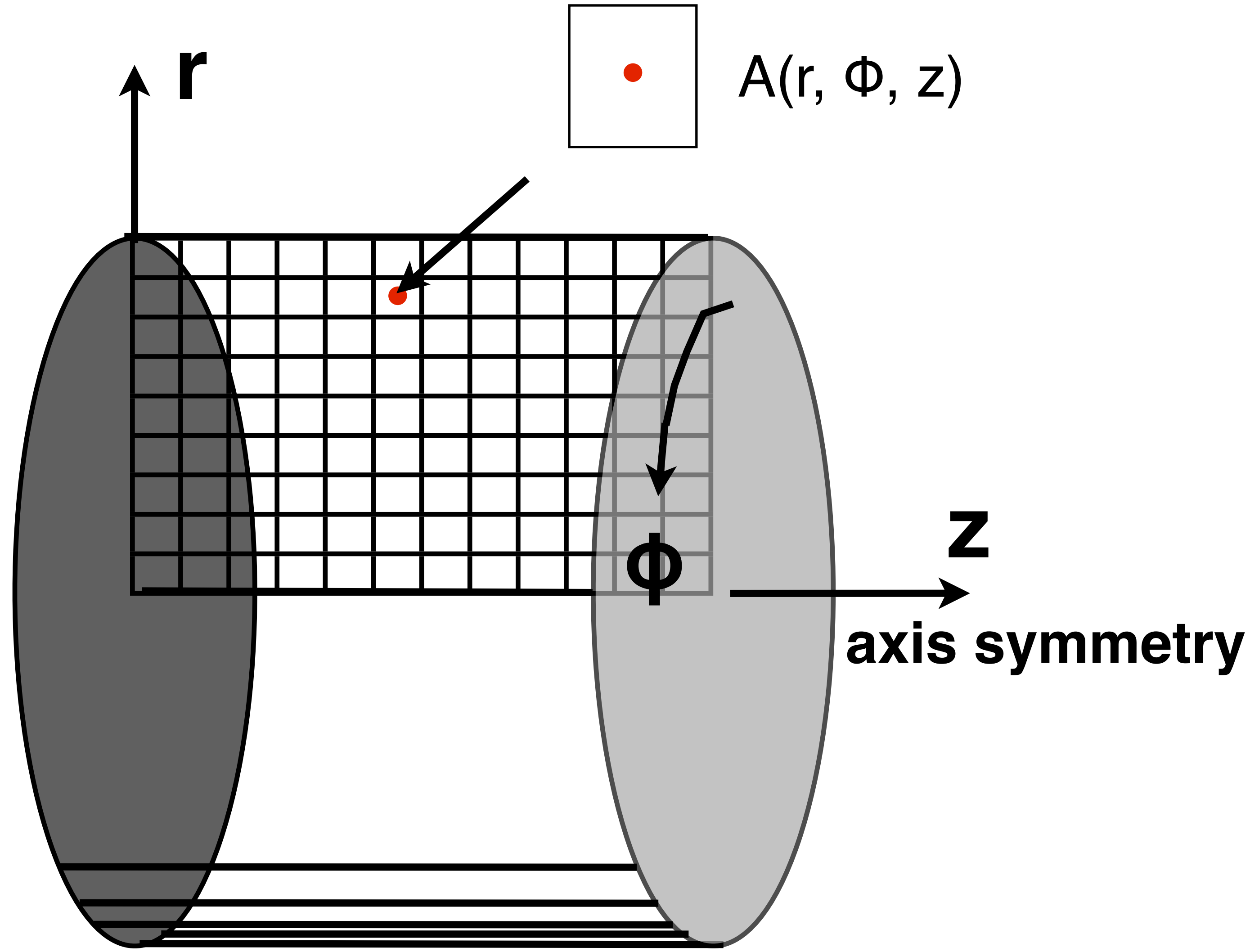
**Maxwell equation**

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$
$$\mathbf{D} = \epsilon \mathbf{E}$$
$$\mathbf{B} = \mu \mathbf{H}$$

**Ohm's law**

$$\mathbf{J} = \sigma \mathbf{E} + \mathbf{J}'$$

$$\frac{\partial}{\partial \phi} \equiv 0$$

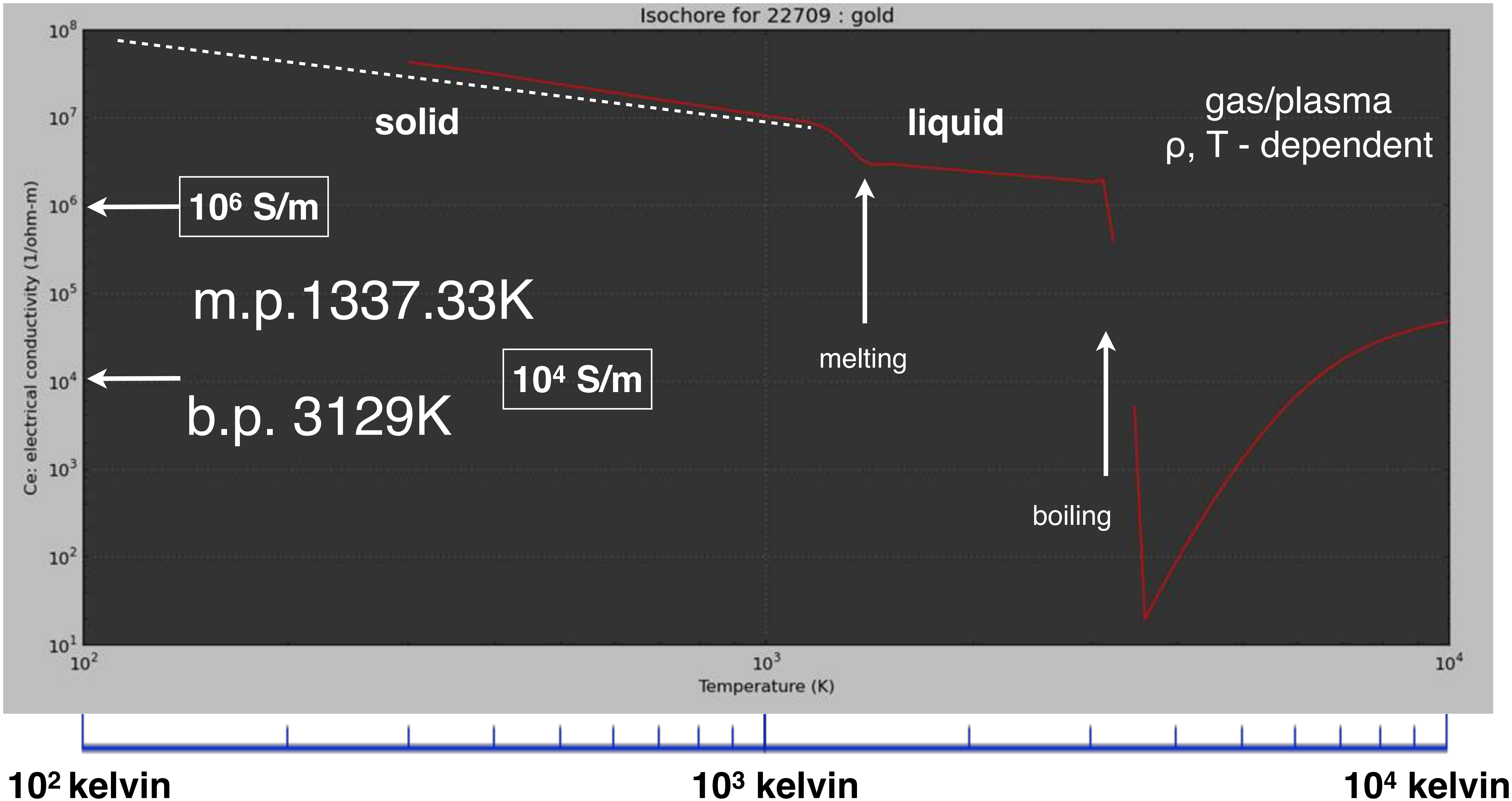



**Maxwell equation in cylindrical coordinate is solved by the directional split method**

$$\frac{\partial}{\partial t}\begin{bmatrix} \mu H_r \\ \mu H_\phi \\ \mu r H_z \end{bmatrix} + \frac{\partial}{\partial z}\begin{bmatrix} -E_\phi \\ E_r \\ 0 \end{bmatrix} + \frac{\partial}{\partial r}\begin{bmatrix} 0 \\ -E_z \\ rE_\phi \end{bmatrix} = 0$$

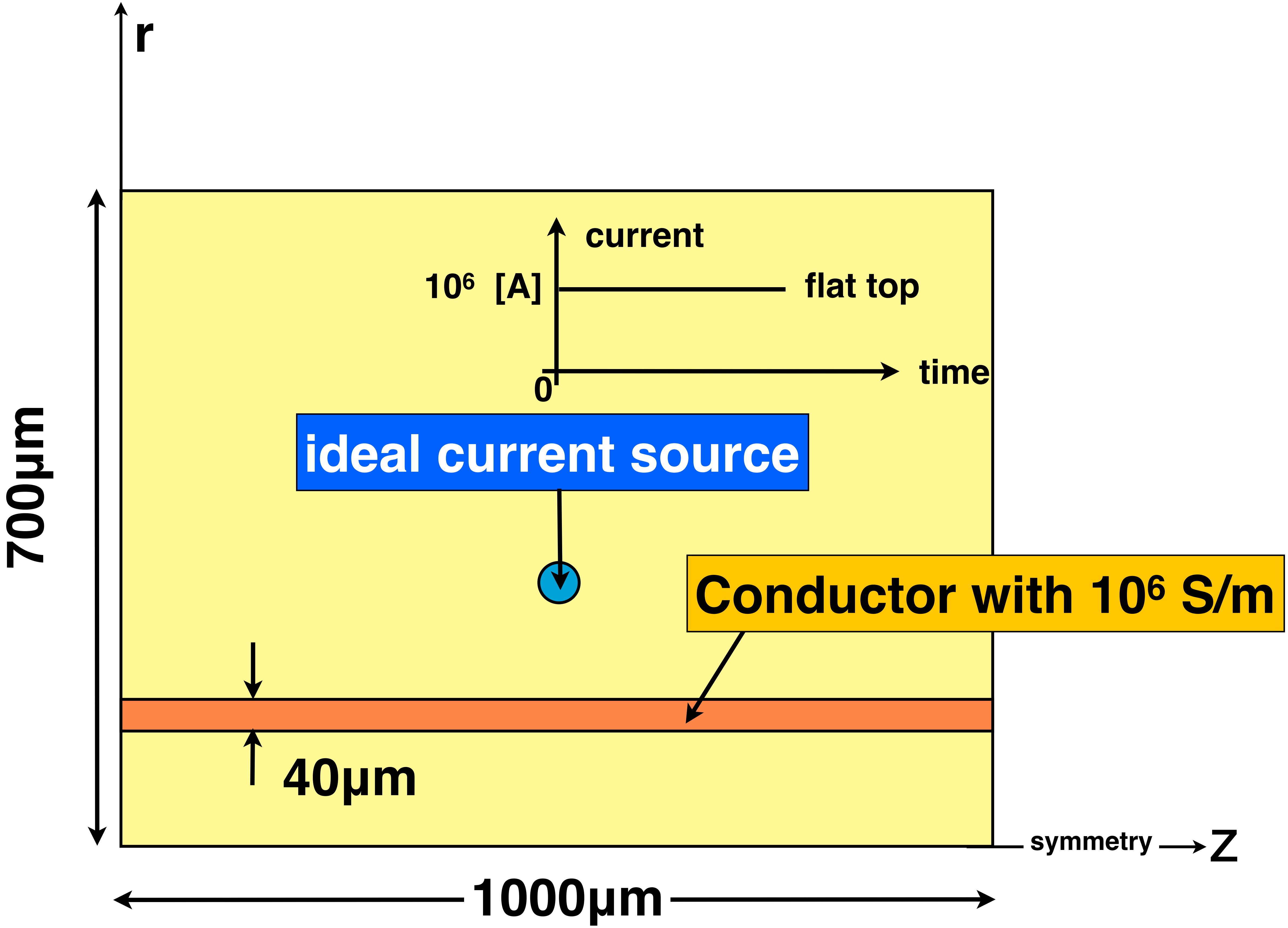
$$\frac{\partial}{\partial t}\begin{bmatrix} \epsilon E_r \\ \epsilon E_\phi \\ r\epsilon E_z \end{bmatrix} + \frac{\partial}{\partial z}\begin{bmatrix} H_\phi \\ -H_r \\ 0 \end{bmatrix} + \frac{\partial}{\partial r}\begin{bmatrix} 0 \\ H_z \\ -rH_\phi \end{bmatrix} = \begin{bmatrix} -\sigma E_r - j'_r \\ -\sigma E_\phi - j'_\phi \\ -r\sigma E_z - rj'_z \end{bmatrix}$$

# Conductivity of gold

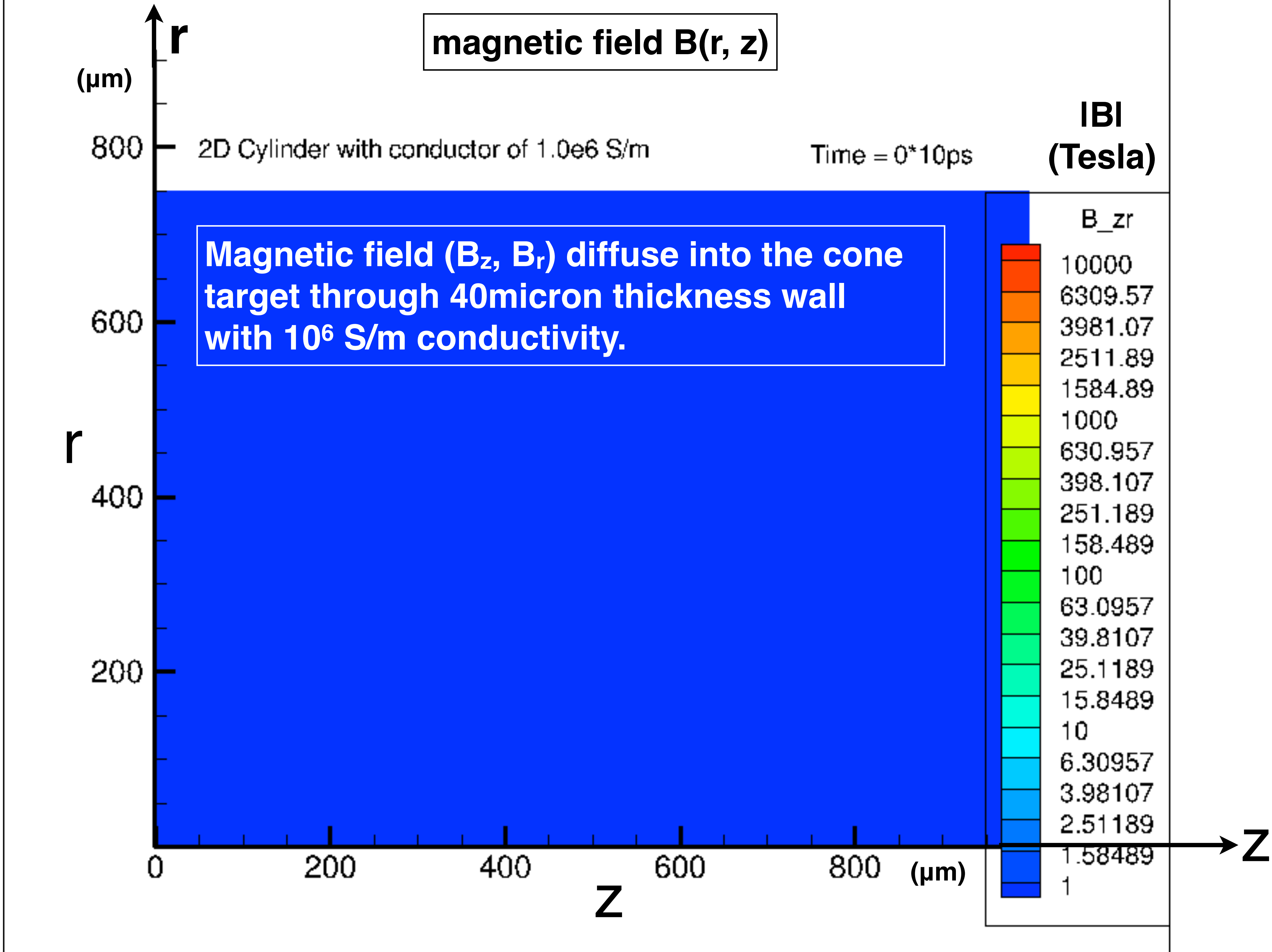



**The conductivity of gold abruptly decreases after the boiling is reached. This helps the magnetic diffusion.**

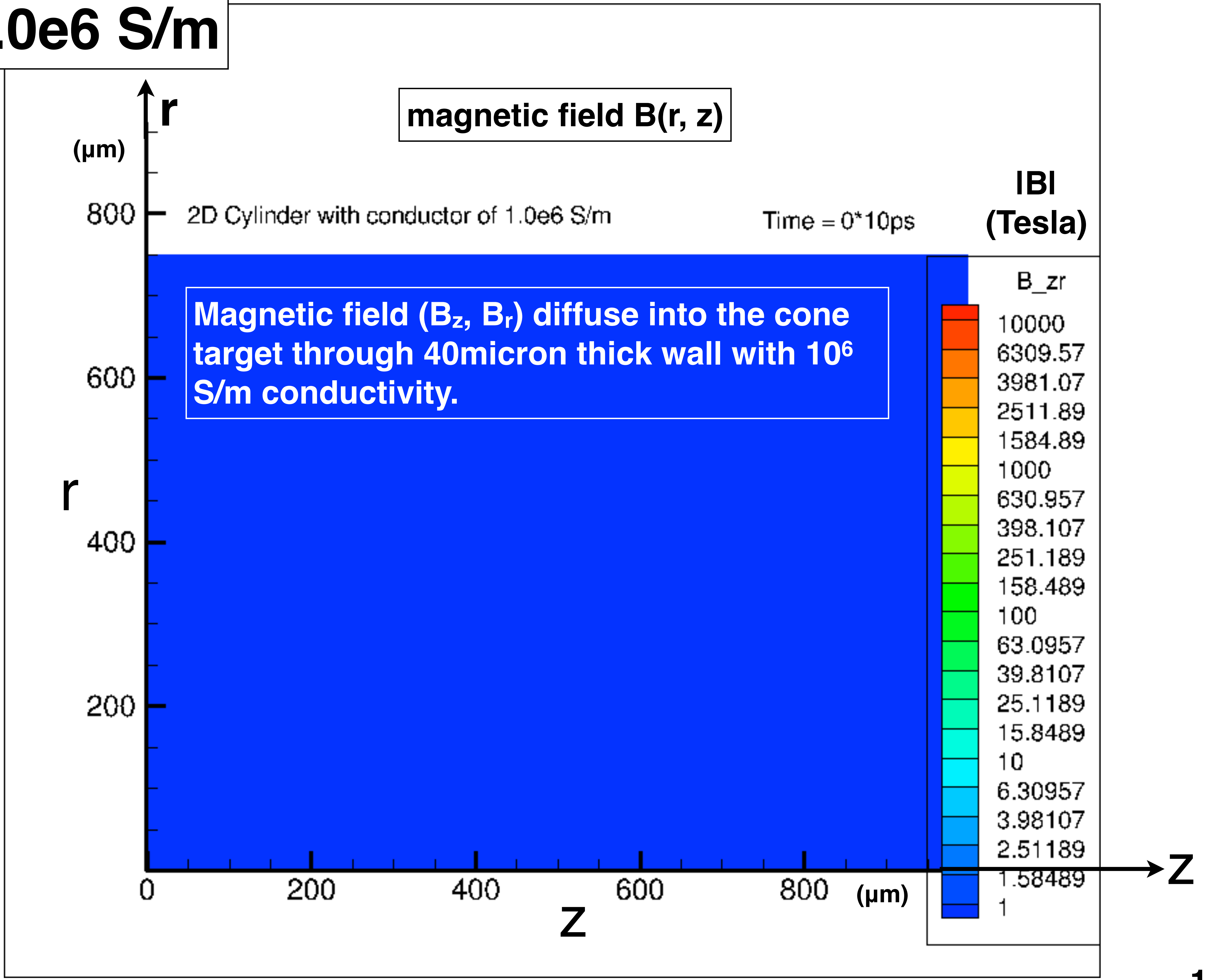
σ=1.0e6 S/m


r
current
10⁶ [A]
flat top
0
time
ideal current source
Conductor with 10⁶ S/m
700μm
40μm
1000μm
symmetry
Z

# σ=1.0e6 S/m

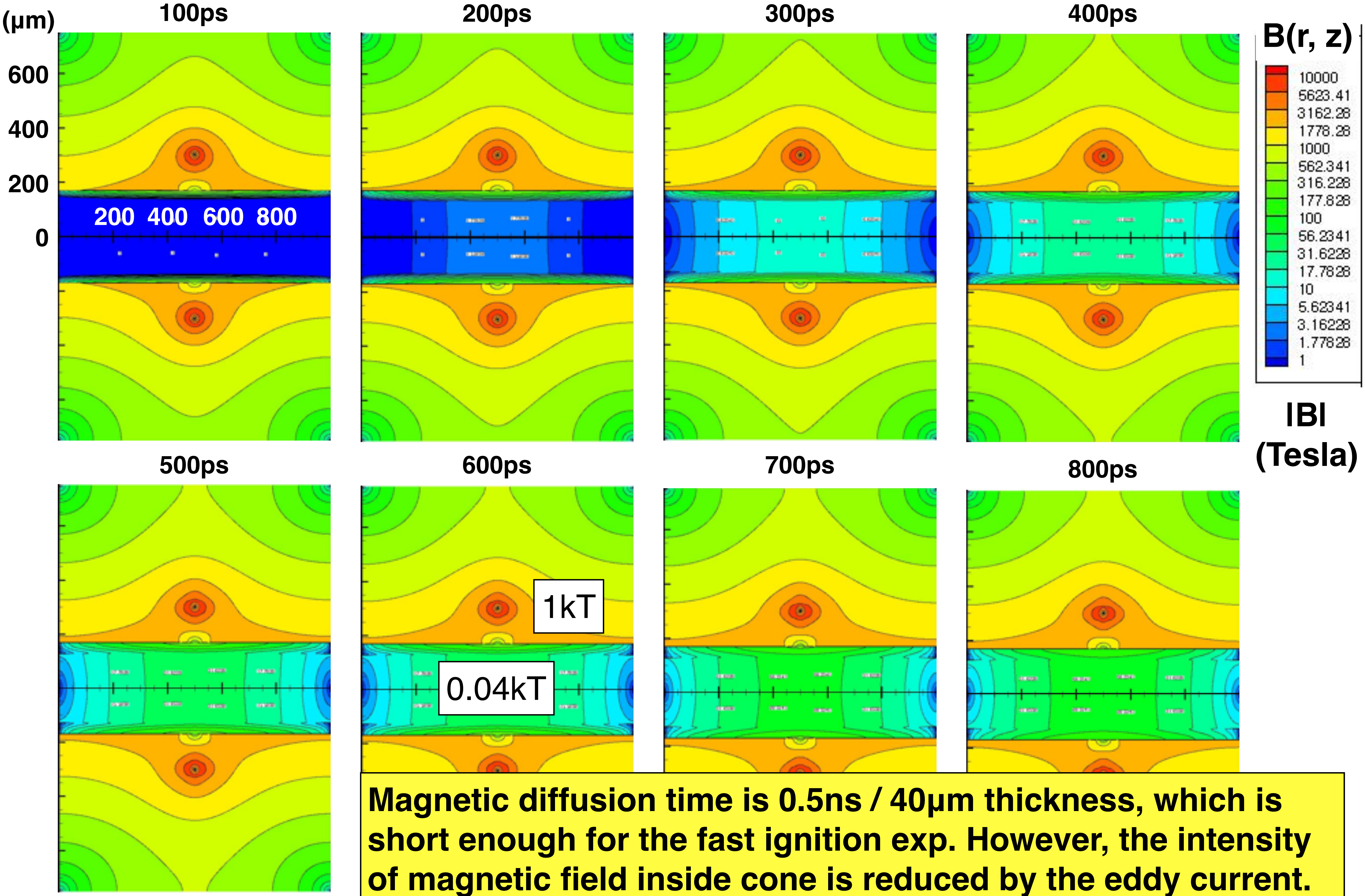

magnetic field B(r, z)
r
(μm)
2D Cylinder with conductor of 1.0e6 S/m
Time = 0*10ps
IBI
(Tesla)
B_zr
10000
6309.57
3981.07
2511.89
1584.89
1000
630.957
398.107
251.189
158.489
100
63.0957
39.8107
25.1189
15.8489
10
6.30957
3.98107
2.51189
1.58489
1
Magnetic field ($B_z$, $B_r$) diffuse into the cone target through 40micron thickness wall with $10^6$ S/m conductivity.
800
600
400
200
0
200
400
600
800
(μm)
Z
Z
r

# σ=1.0e6 S/m


magnetic field B(r, z)
r
(μm)
800
600
400
200
2D Cylinder with conductor of 1.0e6 S/m
Time = 0*10ps
Magnetic field ($B_z$, $B_r$) diffuse into the cone target through 40micron thick wall with $10^6$ S/m conductivity.
0
200
400
600
800
(μm)
Z
IBI
(Tesla)
B_zr
10000
6309.57
3981.07
2511.89
1584.89
1000
630.957
398.107
251.189
158.489
100
63.0957
39.8107
25.1189
15.8489
10
6.30957
3.98107
2.51189
1.58489
1

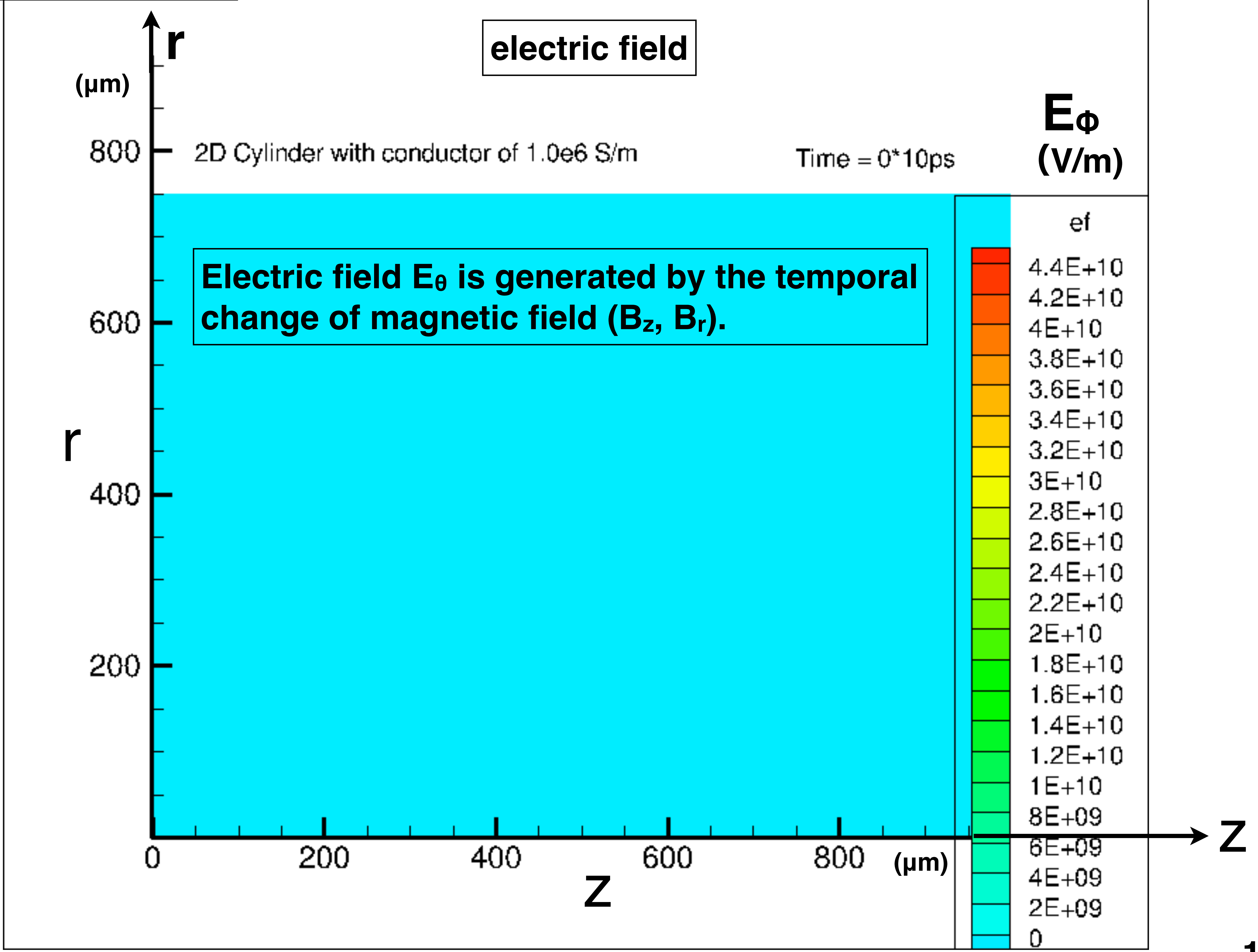
**magnetic field**

**diffusion ~500ps**

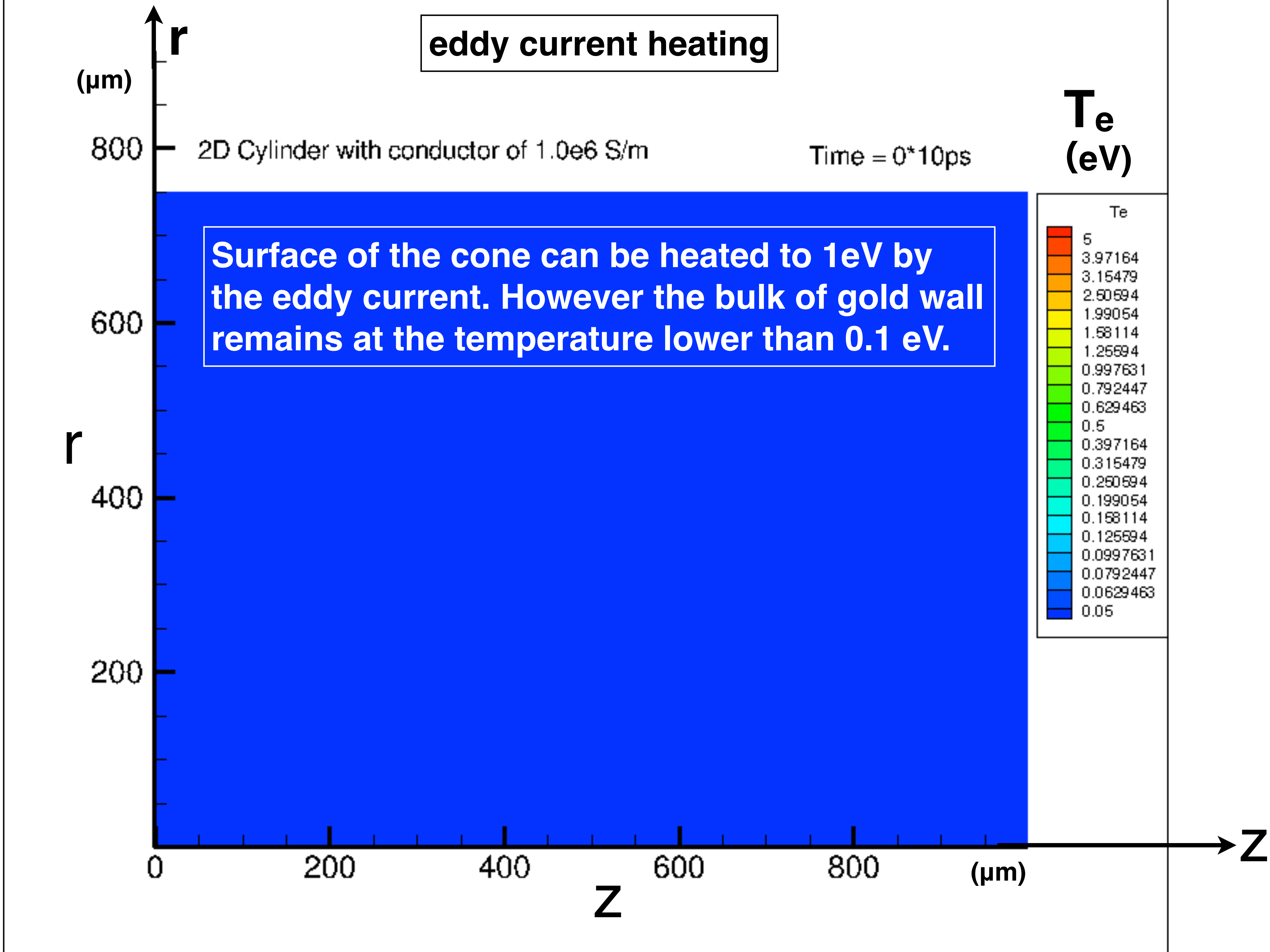



**Magnetic diffusion time is 0.5ns / 40μm thickness, which is short enough for the fast ignition exp. However, the intensity of magnetic field inside cone is reduced by the eddy current.**

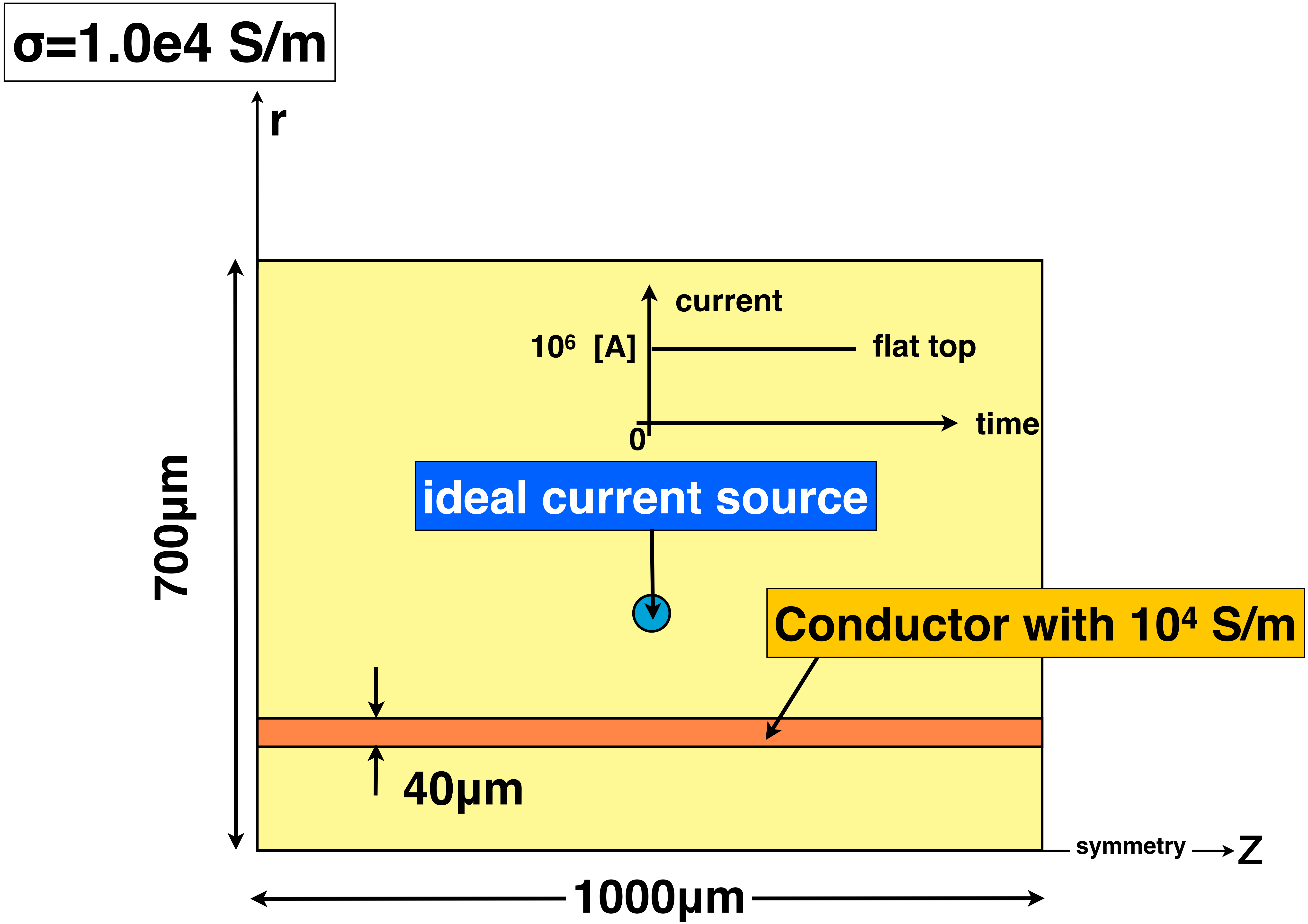
σ=1.0e6 S/m


electric field
2D Cylinder with conductor of 1.0e6 S/m
Time = 0*10ps
Electric field Eθ is generated by the temporal change of magnetic field (Bz, Br).
Eϕ
(V/m)
ef
4.4E+10
4.2E+10
4E+10
3.8E+10
3.6E+10
3.4E+10
3.2E+10
3E+10
2.8E+10
2.6E+10
2.4E+10
2.2E+10
2E+10
1.8E+10
1.6E+10
1.4E+10
1.2E+10
1E+10
8E+09
6E+09
4E+09
2E+09
0
r
(μm)
800
600
400
200
0
200
400
600
800
(μm)
Z

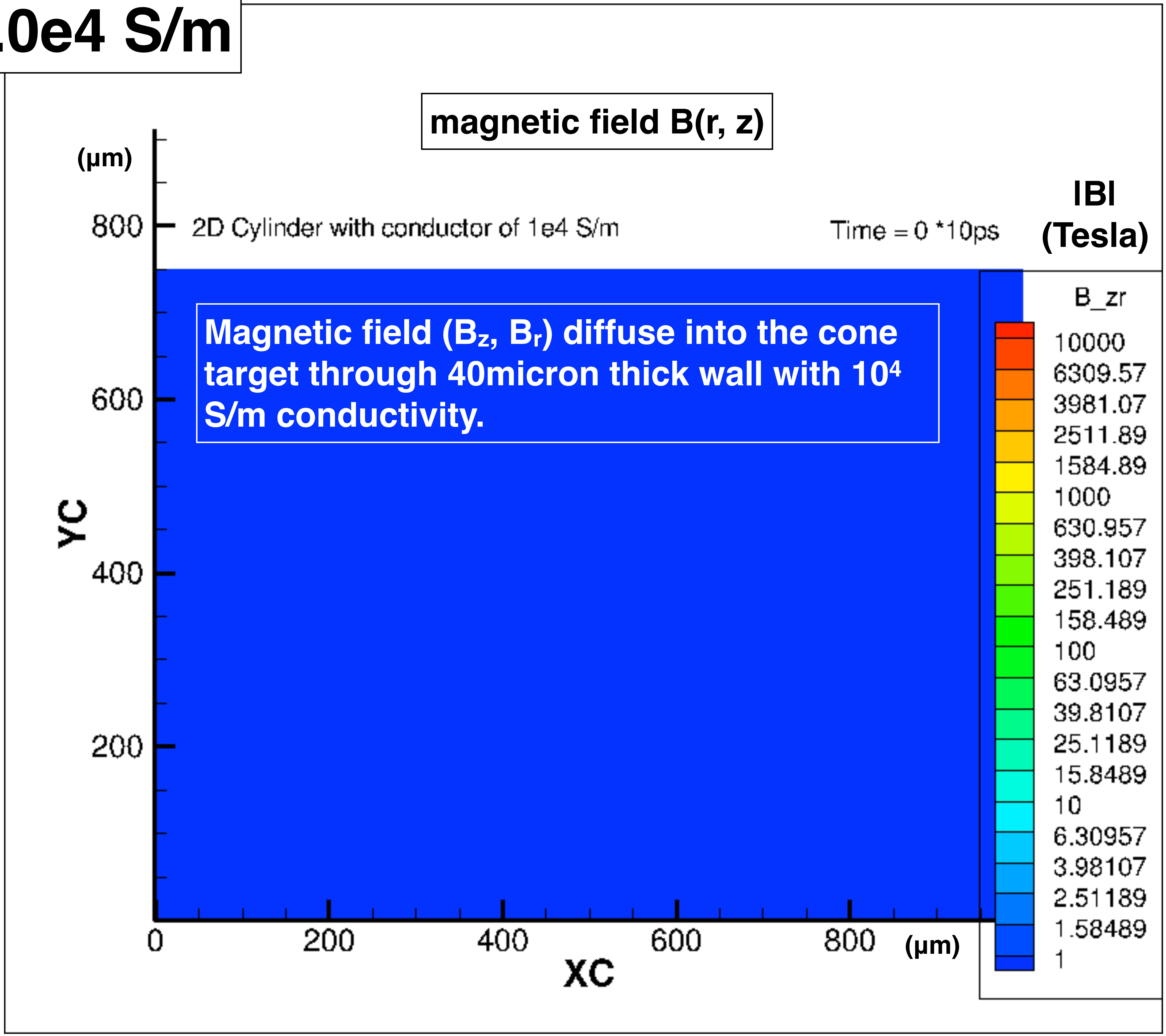
# σ=1.0e6 S/m



eddy current heating
r
(μm)
800
600
400
200
0
2D Cylinder with conductor of 1.0e6 S/m
Time = 0*10ps
Te
(eV)
Te
5
3.97164
3.15479
2.50594
1.99054
1.58114
1.25594
0.997631
0.792447
0.629463
0.5
0.397164
0.315479
0.250594
0.199054
0.158114
0.125594
0.0997631
0.0792447
0.0629463
0.05
Surface of the cone can be heated to 1eV by the eddy current. However the bulk of gold wall remains at the temperature lower than 0.1 eV.
r
0
200
400
600
800
(μm)
Z
Z

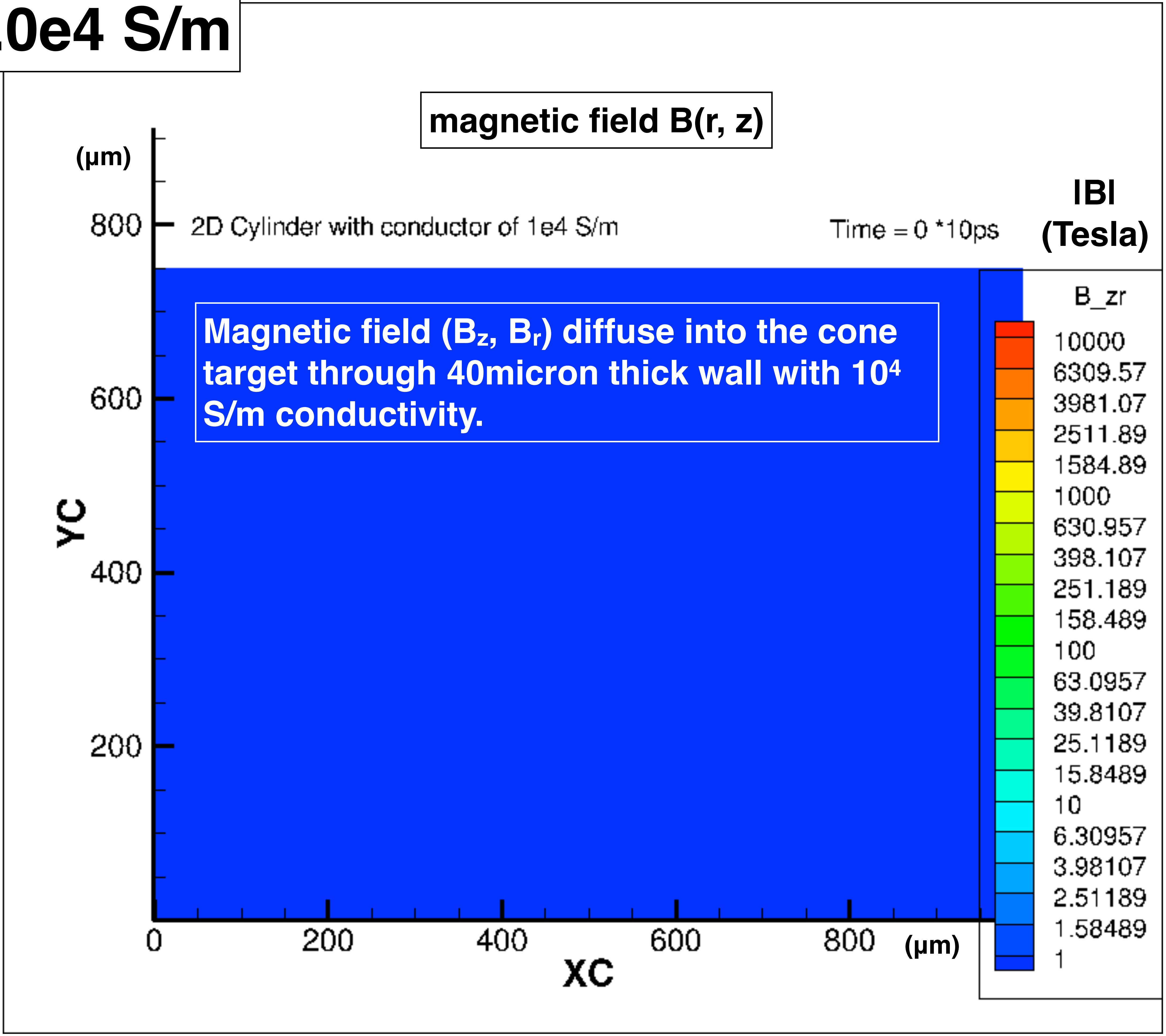

σ=1.0e4 S/m
r
current
10⁶ [A]
flat top
0
time
ideal current source
Conductor with 10⁴ S/m
700µm
40µm
symmetry
Z
1000µm

# σ=1.0e4 S/m



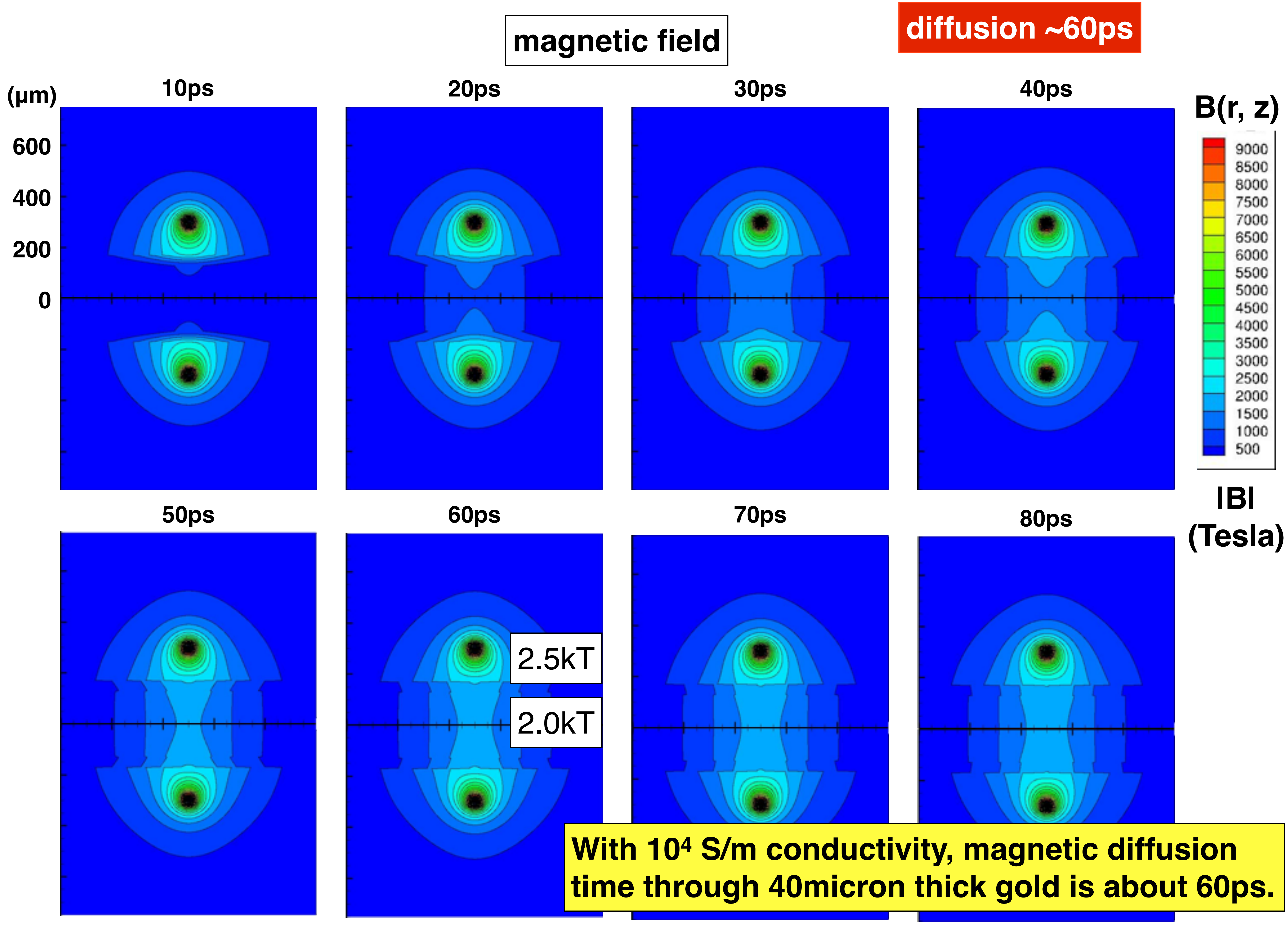
magnetic field B(r, z)
(μm)
800
600
400
200
YC
2D Cylinder with conductor of 1e4 S/m
Time = 0 *10ps
IBI
(Tesla)
B_zr
10000
6309.57
3981.07
2511.89
1584.89
1000
630.957
398.107
251.189
158.489
100
63.0957
39.8107
25.1189
15.8489
10
6.30957
3.98107
2.51189
1.58489
1
Magnetic field (Bz, Br) diffuse into the cone target through 40micron thick wall with 10^4 S/m conductivity.
0
200
400
600
800
(μm)
XC

# σ=1.0e4 S/m



magnetic field B(r, z)
(μm)
800
600
400
200
YC
2D Cylinder with conductor of 1e4 S/m
Time = 0 *10ps
|B|
(Tesla)
B_zr
10000
6309.57
3981.07
2511.89
1584.89
1000
630.957
398.107
251.189
158.489
100
63.0957
39.8107
25.1189
15.8489
10
6.30957
3.98107
2.51189
1.58489
1
Magnetic field ($B_z$, $B_r$) diffuse into the cone target through 40micron thick wall with $10^4$ S/m conductivity.
0
200
400
600
800
(μm)
XC

diffusion ~60ps




With $10^4$ S/m conductivity, magnetic diffusion time through 40micron thick gold is about 60ps.

**diffusion term**

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \boxed{\frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}}$$

**electrical conductivity**

⬅ **displacement current is omitted.**

Speed of light : $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$ = $2.9979 \times 10^8$ m/s

Permeability: $\mu_0 = 4\pi \times 10^{-7}$ H/m

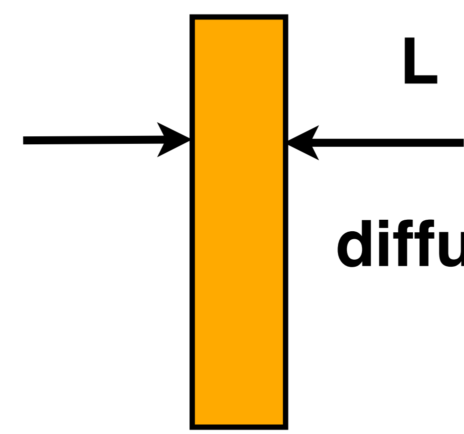
Permittivity: $\epsilon_0 = 8.8542 \times 10^{-12}$ F/m

**traveling time**

$$\frac{1}{\sqrt{\mu(\epsilon + \sigma \Delta t)}} \Delta t$$

**vacuum** → $\sigma = 0$: $c\,\Delta t$

**metal** → $\sigma = 10^6$ S/m, $\epsilon \ll \sigma \Delta t$: $\frac{\Delta t}{\sqrt{\mu_0 \sigma \Delta t}}$




**diffusion time scale**

**$\Delta t = \mu_0 \sigma L^2$**

| | estimated | simulated |
|---|---|---|
| **L = 40 micron, $\sigma = 10^6$ S/m ----->** | **2ns** | **600ps** |
| **L = 40 micron, $\sigma = 10^4$ S/m ----->** | **20ps** | **60ps** |

**Actually, the conductivity is not constant.**
**It is function of density and temperature.**

# Saha equation

$$\frac{n_i n_e}{n_{i-1}} = 2\frac{U_i}{U_{i-1}}\left[\frac{2\pi m_e k_B T}{h^2}\right]^{3/2} \exp\left(-\frac{I_i^{\text{eff}}}{k_B T}\right), \quad (i = 1, \ldots, Z)$$

$n_e$ electron number density

$n_i$ i-fold ionized ion number density

$U_i$ partition function = integral of $g_n \exp(-E_n/k_b T)$
from ground state to excited one with $I_p$-ΔI

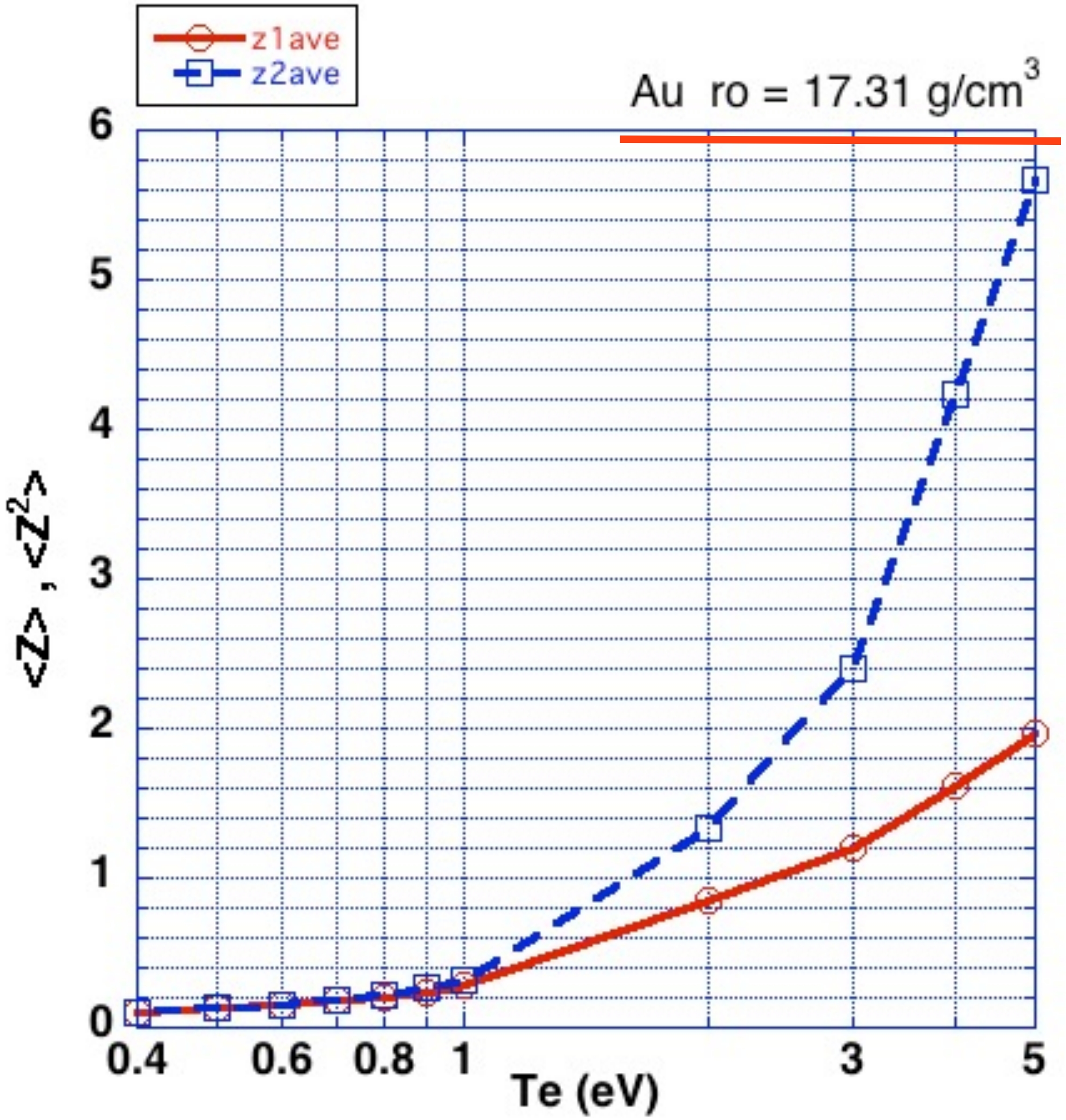
$I_i^{\text{eff}} = I_i - \Delta I_i$ effective ionization potential

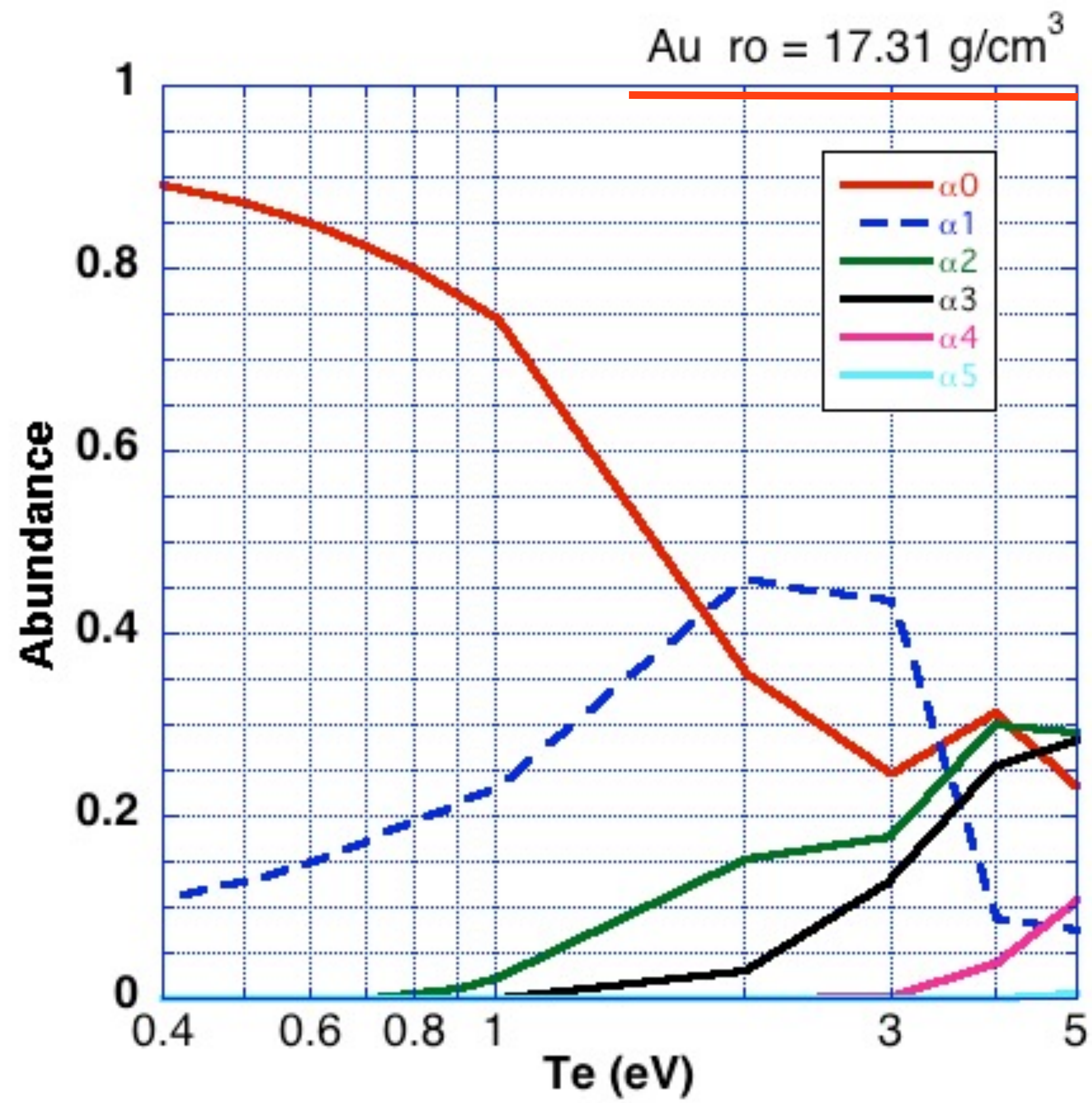
**$n_e$, $n_0$, $n_1$, $n_2$, ....$n_Z$ can be solved.**

**conductivity model**

**EOS (heat capacity) model**

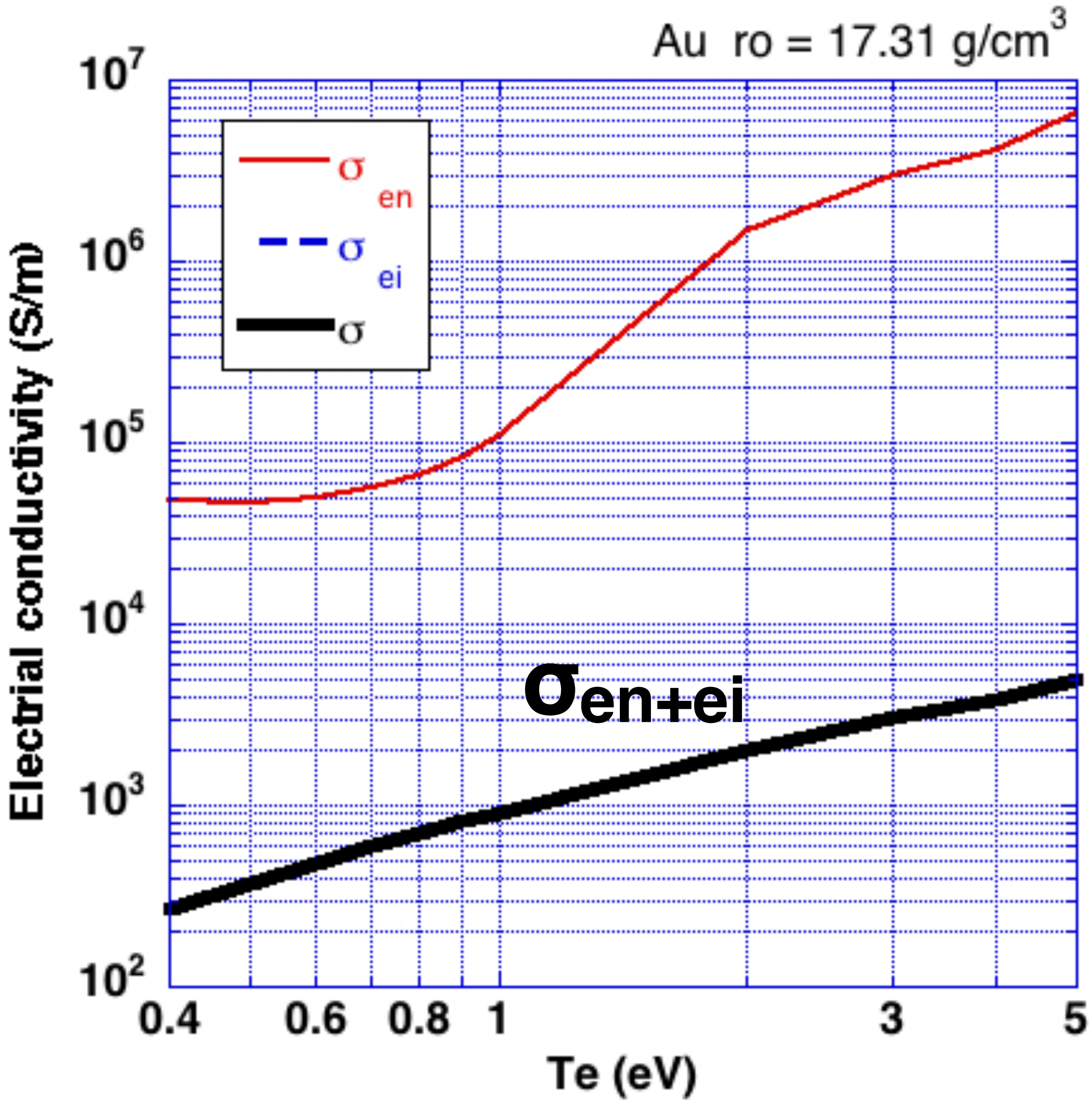
**We calculated the electrical conductivity*) of gold at liquid density and in the 0.4 to 5eV temperature range.**




*) Zhijian Fu et al., High Energy Density Physics 9 (2013) 781–786

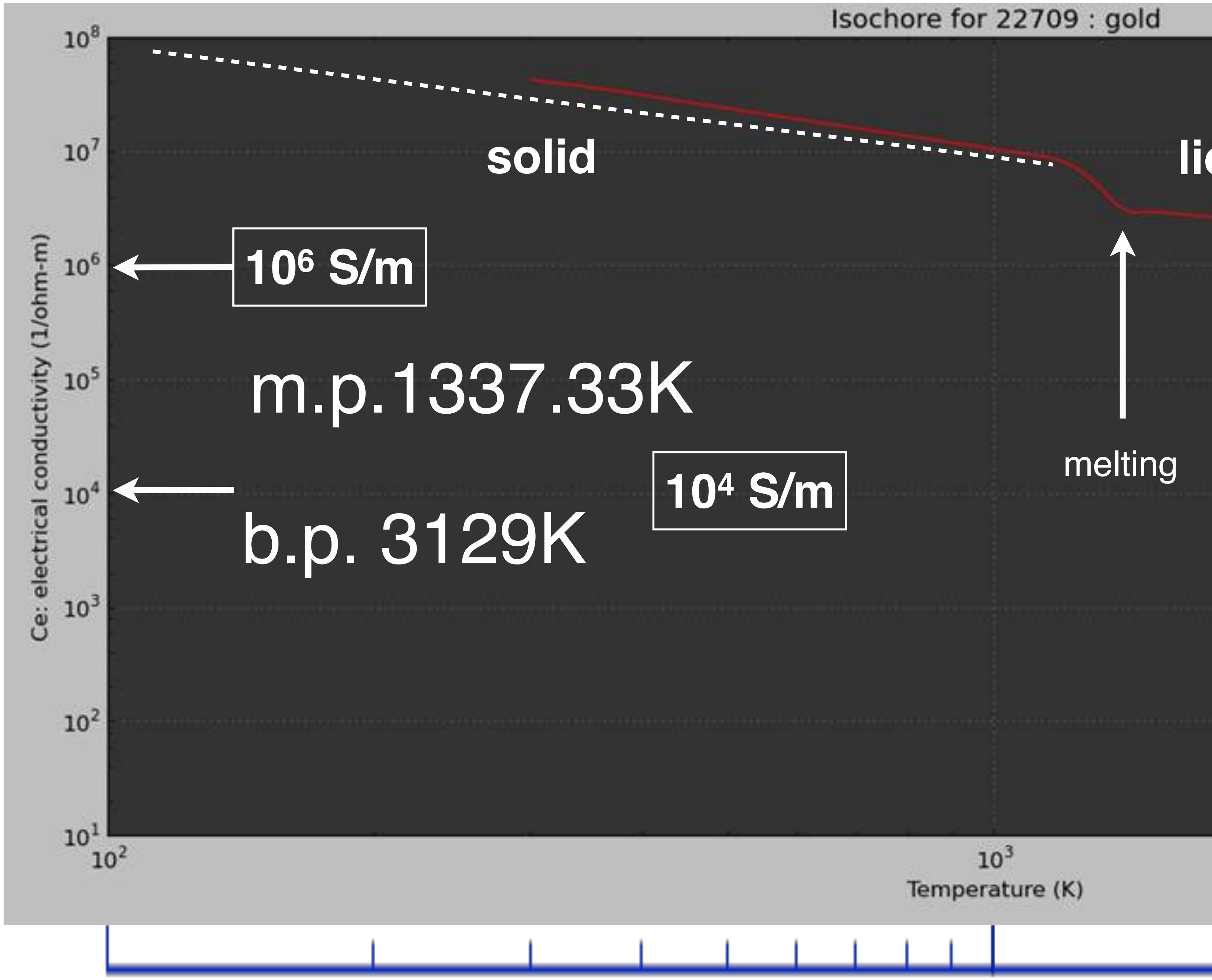
# Electrical conductivity of warm dense gold*) is governed by e-i collision

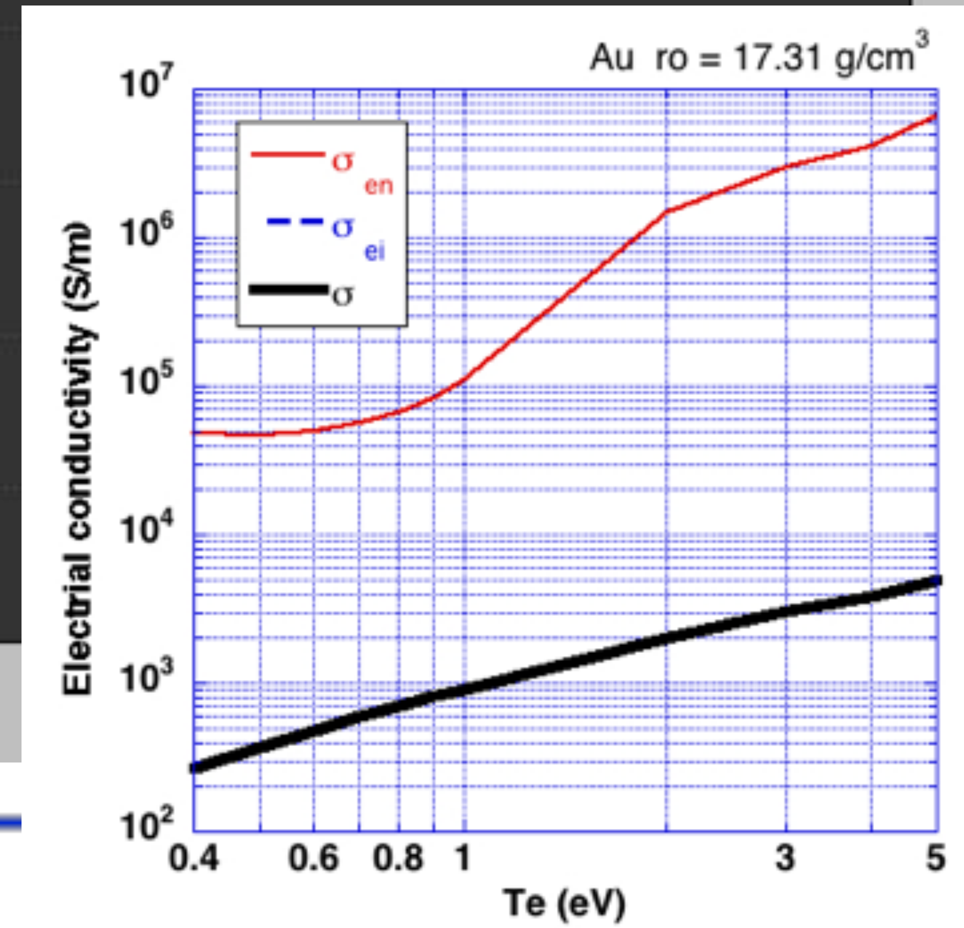



$$\frac{1}{\sigma} = \frac{1}{\sigma_{ei}} + \frac{1}{\sigma_{en}}$$

*) Zhijian Fu et al., High Energy Density Physics 9 (2013) 781–786

# Conductivity of gold




**We will calculate the magnetic diffusion with exact density and temperature.**

## Summary / Conclusion

In order to simulate the temporal evolution of magnetic field, we developed Maxwell solver in the cylindrical coordinates.

We have simulated the diffusion of externally applied magnetic field into the interior of the cone target with $10^6$ S/m.

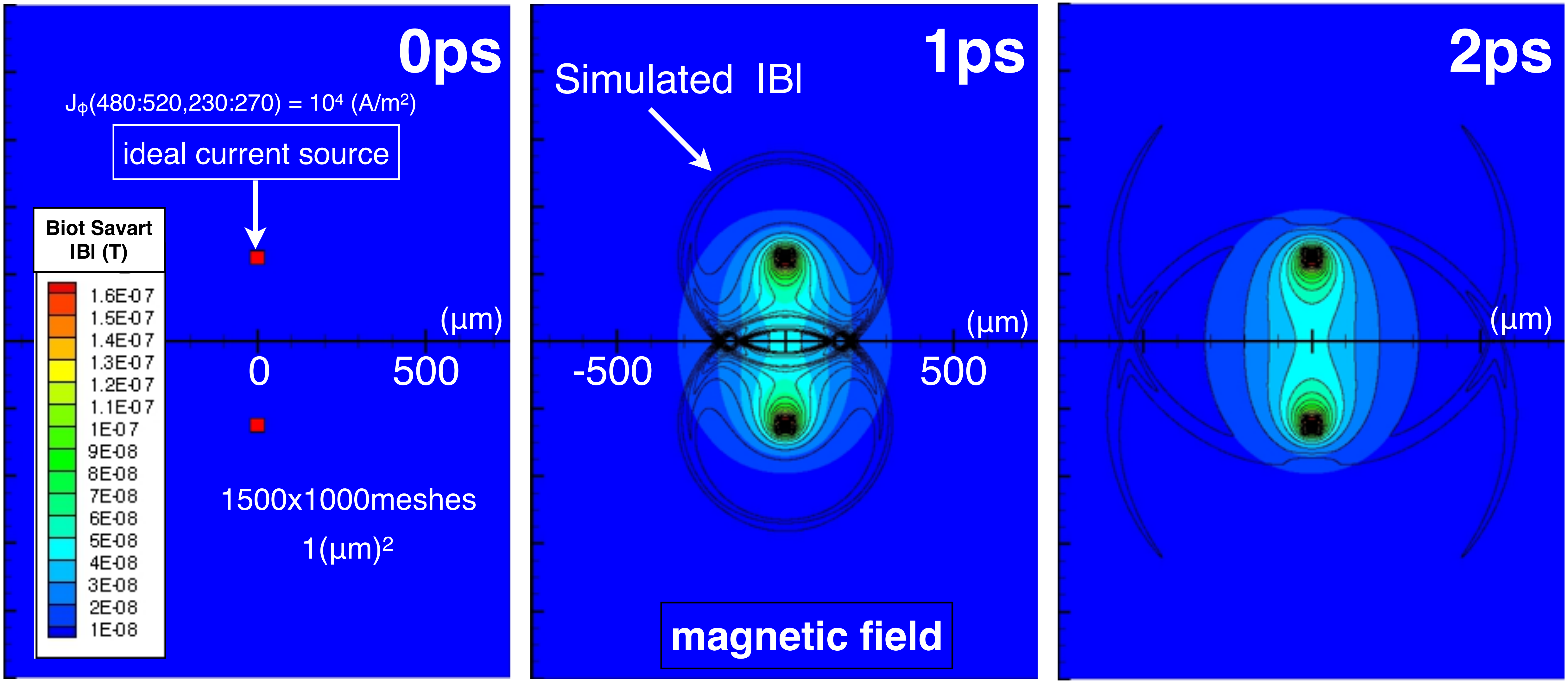
The surface of the cone can be heated by the eddy current. However the bulk of the gold wall remains at the temperature lower than 0.4 eV.

Magnetic diffusion time is 0.5ns / 40μm thick gold of $10^6$ S/m, which is short enough for our fast ignition exp. However, the intensity of magnetic field inside cone is reduced by the eddy current.

With $10^4$ S/m conductivity, the magnetic field can diffuse so faster and the intensity of magnetic field inside the cone is comparable to that outside the cone wall.

We calculated the electrical conductivity of gold in the range from 0.4 to 5 eV.

We will calculate EOS of warm dense matter and simulate the magnetic diffusion with hydro-motion in the next step.


0ps
Jφ(480:520,230:270) = 10⁴ (A/m²)
ideal current source
Biot Savart
IBI (T)
1.6E-07
1.5E-07
1.4E-07
1.3E-07
1.2E-07
1.1E-07
1E-07
9E-08
8E-08
7E-08
6E-08
5E-08
4E-08
3E-08
2E-08
1E-08
(μm)
0
500
1500x1000meshes
1(μm)²
1ps
Simulated IBI
(μm)
-500
500
magnetic field
2ps
(μm)