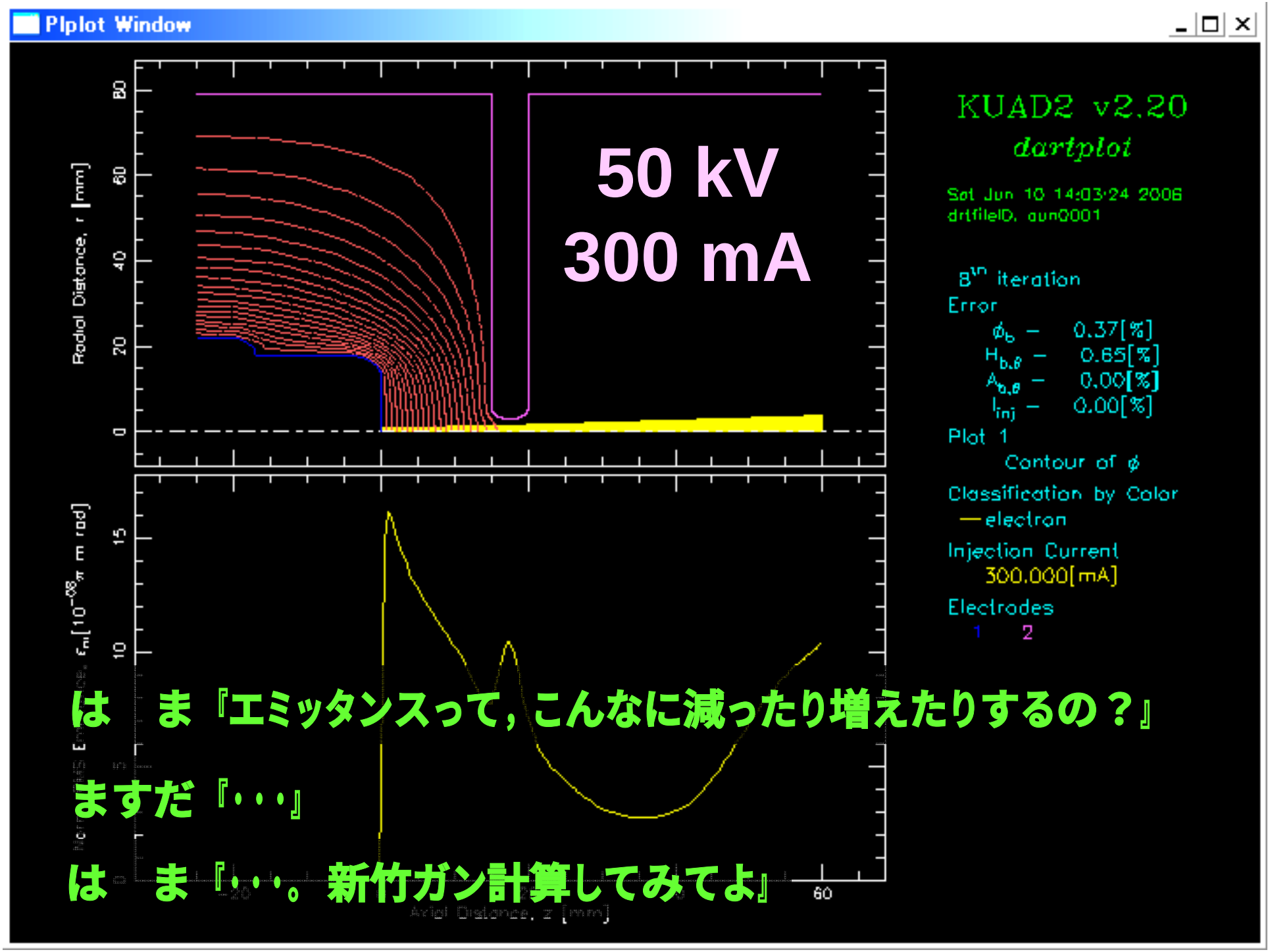
陰極近傍での空間電荷効果について

高輝度電子銃シミュレーション研究会
２００６年１２月７日
京大宇治キャンパス

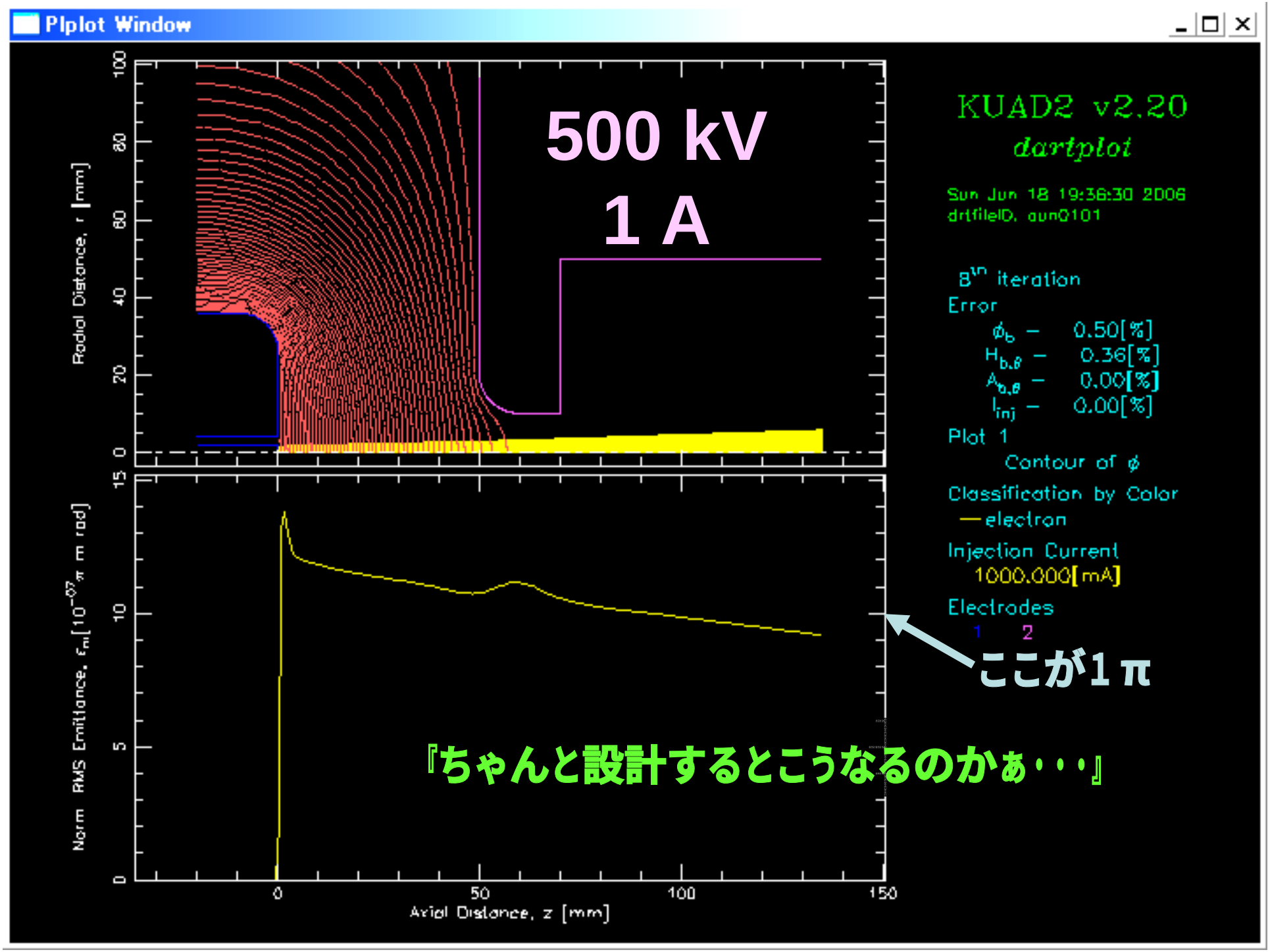
京都大学エネルギー理工学研究所
増　田　　開



は　ま『エミッタンスって，こんなに減ったり増えたりするの？』

ますだ『・・・』

は　ま『・・・。新竹ガン計算してみてよ』


Plplot Window
500 kV
1 A
KUAD2 v2.20
dartplot
Sun Jun 18 19:36:30 2006
drtfileID, aun0101
8th iteration
Error
ϕ_b – 0.50[%]
$H_{b,\theta}$ – 0.36[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ
Classification by Color
electron
Injection Current
1000.000[mA]
Electrodes
1 2
Radial Distance, r [mm]
Norm RMS Emittance, ε_n[10^{-07}π m rad]
Axial Distance, z [mm]
0
50
100
150
0
5
10
15
0
20
40
60
80
100
ここが1π
『ちゃんと設計するとこうなるのかぁ・・・』

エミッタンスの定義

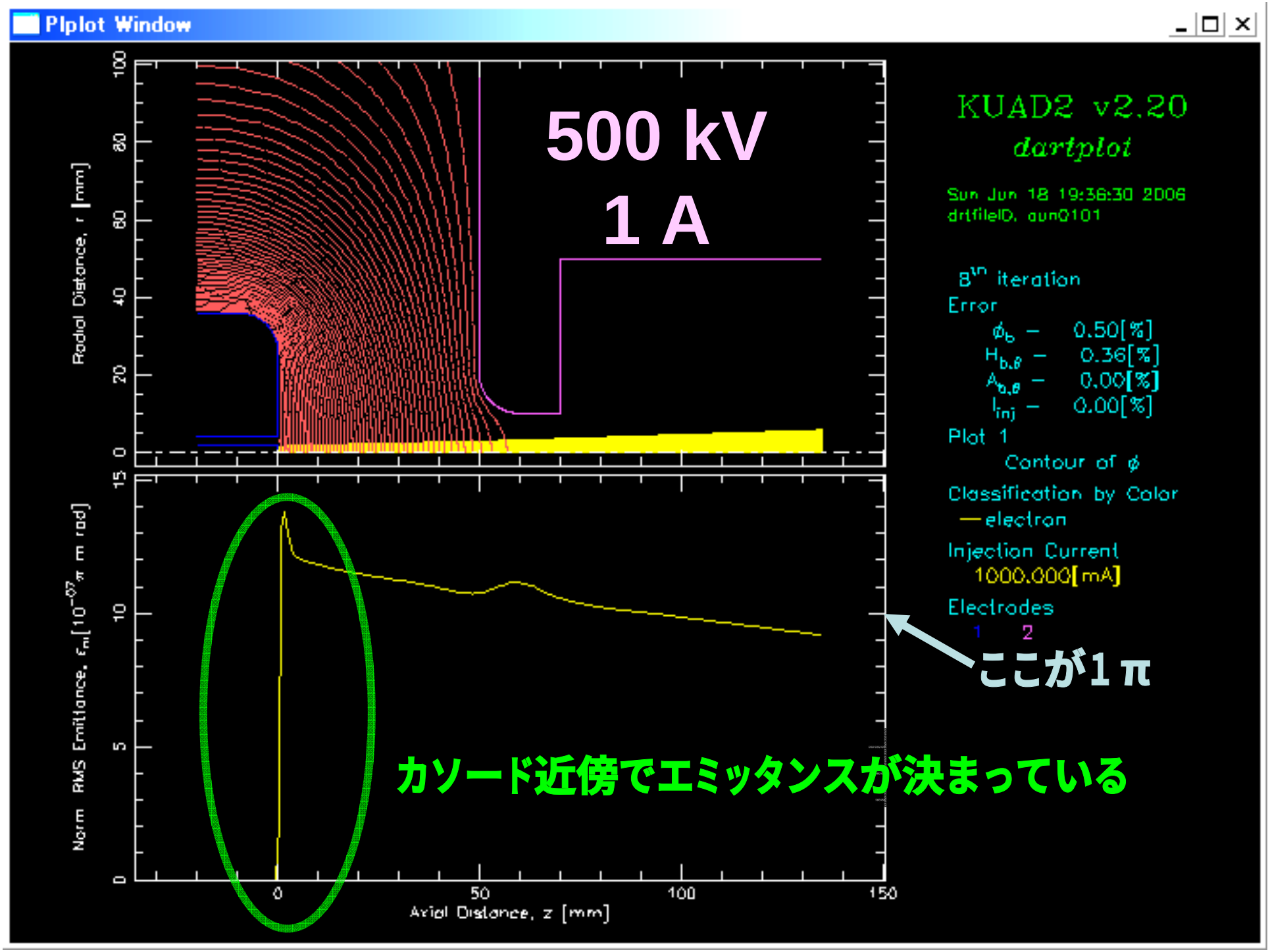
normalized rms *r*-emittance

$$\varepsilon_{\mathrm{n},r} = \sqrt{\left\langle r^2 \right\rangle \left\langle (\gamma\beta\alpha)^2 \right\rangle - \left\langle r\gamma\beta\alpha \right\rangle^2} \quad [\pi \text{ m rad}]$$

$$\alpha = \arctan\left(\frac{p_r}{p_z}\right) \quad [\text{rad}]$$

軸対称の場合．．．

$$\varepsilon_{\mathrm{n},r}^2 = 2\varepsilon_{\mathrm{n},x}^2 = 2\varepsilon_{\mathrm{n},y}^2$$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dartplot
Sun Jun 18 19:36:30 2006
dritfileID, aun0101
8th iteration
Error
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I_{inj} – 0.00[%]
Plot 1
Contour of ϕ
Classification by Color
electron
Injection Current
1000.000[mA]
Electrodes
1 2
Radial Distance, r [mm]
Norm RMS Emittance, ε_n[$10^{-07}\pi$ m rad]
Axial Distance, z [mm]
0
50
100
150
0
5
10
15
0
20
40
60
80
100
ここが1π
カソード近傍でエミッタンスが決まっている

カソード近傍での鏡像の効果

自由空間では．．．

$E_r \propto r$

ビームは広がっても
エミッタンスは増えない

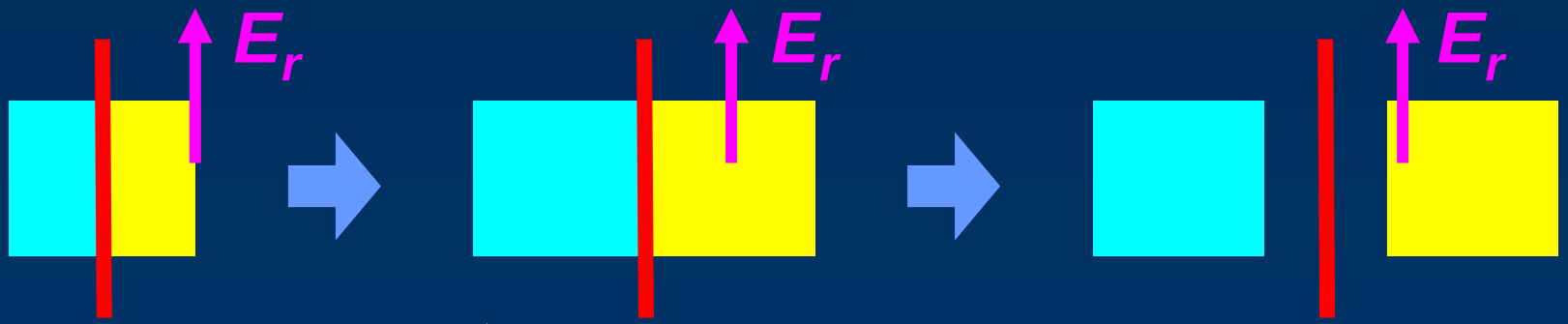
カソードがあると．．．

E_r **が** r **に比例しない**

正電荷の鏡像

電子ビーム（負電荷）

パルスビームだと．．．



鏡像の影響がヘッドとテイルで異なる

1. コードの概要

2D, FEM, PIC

2. DCビームへの鏡像の影響

どの程度？

3. DCビームへの熱エミッタンスの影響

$\varepsilon_{\mathrm{total}}^2 = \varepsilon_{\mathrm{th}}^2 + \varepsilon_{\mathrm{SC}}^2$ ？

4. パルスビームへの鏡像の影響

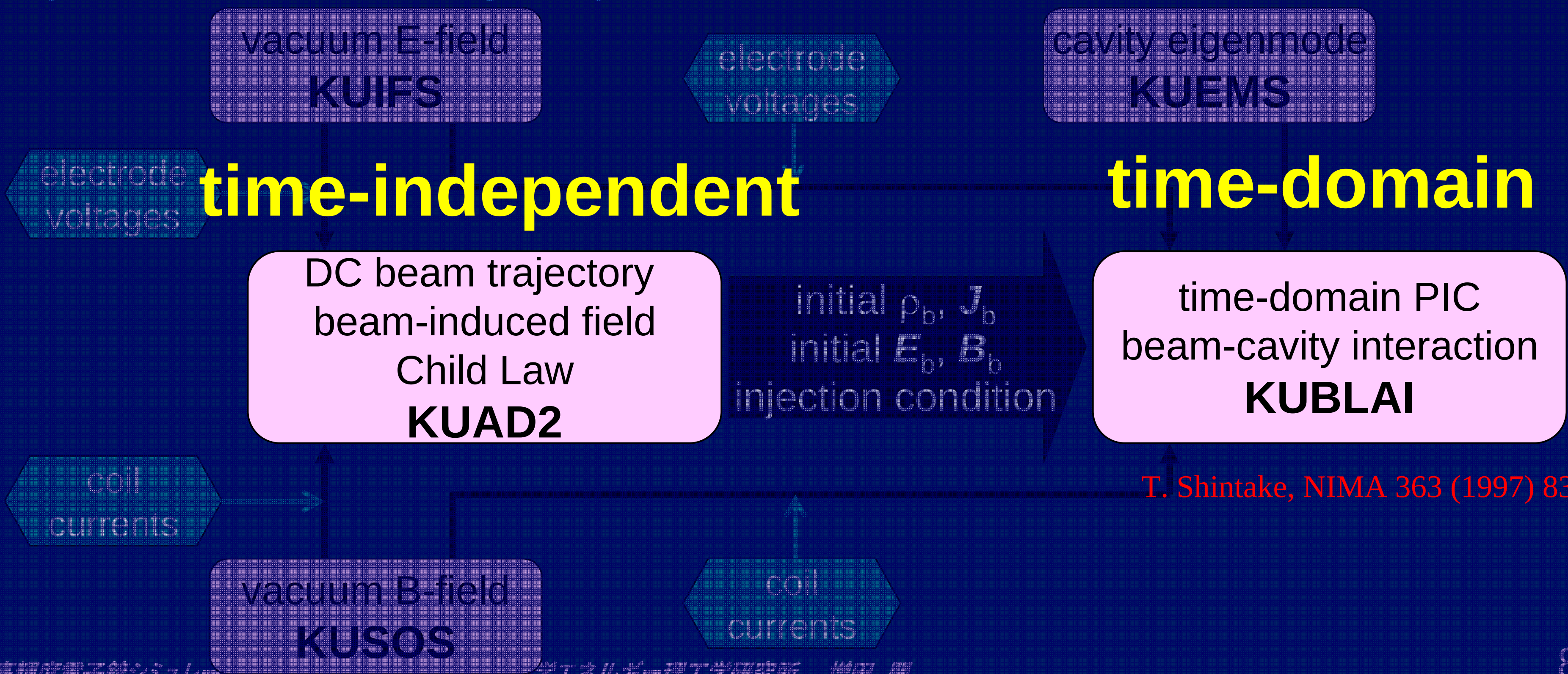
DCビーム との 違いは どの程度？

Group of 2-D Codes

for simulating charged particle dynamics in electromagnetic fields

K. Masuda, *PhD Thesis Kyoto Univ.* (1997).

Kyoto Univ. semi-Automatic meSH generator
Kyoto Univ. EigenMode Solver
Kyoto Univ. SOlenoidal field Solver
Kyoto Univ. Irrotational Field Solver
Kyoto Univ. Advanced Dart 2nd edition
Kyoto Univ. Beam Loading AnalysIs



T. Shintake, NIMA 363 (1997) 83.

Basic Equations and Formulations (1/2)
charged particle dynamics

$$\frac{dK}{dt} = q(\boldsymbol{u}\cdot\boldsymbol{E}) \qquad K = m_0 c^2(\gamma - 1) : \text{kinetic energy}$$

$$\frac{d\boldsymbol{p}}{dt} = q(\boldsymbol{E} + \boldsymbol{u}\times\boldsymbol{B}) \qquad \boldsymbol{p} = m_0\gamma\boldsymbol{u} : \text{momentum}$$

$$\gamma^2 = 1/\left\{1-(u/c)^2\right\}$$

$$\gamma^2 - (p/m_0 c)^2 = 1$$

$\frac{\partial}{\partial\theta} = 0$

KUBLAI

$$P_\theta = r(p_\theta + qA_\theta) = \text{const.}$$

$$\frac{dK}{dt} = q(\boldsymbol{u}\cdot\boldsymbol{E})$$

$$u_z = u_\sigma\cos\alpha$$

$$u_r = u_\sigma\sin\alpha$$

$$\frac{d\alpha}{dt} = \frac{1}{m_0\gamma u_\sigma}\left[-qu_\sigma B_\theta - q(E_z - u_\theta B_r)\sin\alpha + \left\{q(E_r + u_\theta B_z) + \frac{m_0\gamma u_\theta^{\,2}}{r}\right\}\cos\alpha\right]$$

$\frac{\partial}{\partial t} = 0$

KUAD2

$$P_\theta = r(p_\theta + qA_\theta) = \text{const.}$$

$$W = K + q\phi = \text{const.}$$

$$u_z = u_\sigma\cos\alpha$$

$$u_r = u_\sigma\sin\alpha$$

$$\frac{d\alpha}{dt} = \frac{1}{m_0\gamma u_\sigma}\left[-qu_\sigma B_\theta - q(E_z - u_\theta B_r)\sin\alpha + \left\{q(E_r + u_\theta B_z) + \frac{m_0\gamma u_\theta^{\,2}}{r}\right\}\cos\alpha\right]$$

Basic Equations and Formulations (2/2)

beam-induced electromagnetic fields

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\nabla \times \boldsymbol{H} = \frac{\partial \boldsymbol{D}}{\partial t} + \boldsymbol{J}$$

$$\nabla \cdot \boldsymbol{D} = \rho$$

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\frac{\partial}{\partial \theta} = 0$$

KUBLAI

$$\boldsymbol{E} = -\nabla \phi - \left\{ \frac{\partial (A_\theta \boldsymbol{i}_\theta)}{\partial t} + \frac{1}{c} \nabla \times (G_\theta \boldsymbol{i}_\theta) \right\}$$

$$\boldsymbol{B} = \mu H_\theta \boldsymbol{i}_\theta + \nabla \times (A_\theta \boldsymbol{i}_\theta)$$

$$-\nabla \cdot (\varepsilon \nabla \phi) = \rho$$

$$\nabla \times \left\{ \frac{1}{\mu_s} \nabla \times (A_\theta \boldsymbol{i}_\theta) \right\} + \varepsilon_s \frac{1}{c^2} \frac{\partial^2 (A_\theta \boldsymbol{i}_\theta)}{\partial t^2} = \mu_0 J_\theta \boldsymbol{i}_\theta$$

$$\nabla \times \left\{ \frac{1}{\varepsilon_s} \nabla \times (H_\theta \boldsymbol{i}_\theta) \right\} + \mu_s \frac{1}{c^2} \frac{\partial^2 (H_\theta \boldsymbol{i}_\theta)}{\partial t^2} = \nabla \times \left\{ \frac{1}{\varepsilon_s} (\boldsymbol{J} - J_\theta \boldsymbol{i}_\theta) \right\}$$

$$\nabla \times \nabla \times (G_\theta \boldsymbol{i}_\theta) = \mu_0 \mu_s \frac{1}{c} \frac{\partial (H_\theta \boldsymbol{i}_\theta)}{\partial t}$$

KUAD2

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

$$\boldsymbol{B} = \mu H_\theta \boldsymbol{i}_\theta + \nabla \times (A_\theta \boldsymbol{i}_\theta)$$

$$-\nabla \cdot (\varepsilon \nabla \phi) = \rho$$

$$\nabla \times \left\{ \frac{1}{\mu_s} \nabla \times (A_\theta \boldsymbol{i}_\theta) \right\} = \mu_0 J_\theta \boldsymbol{i}_\theta$$

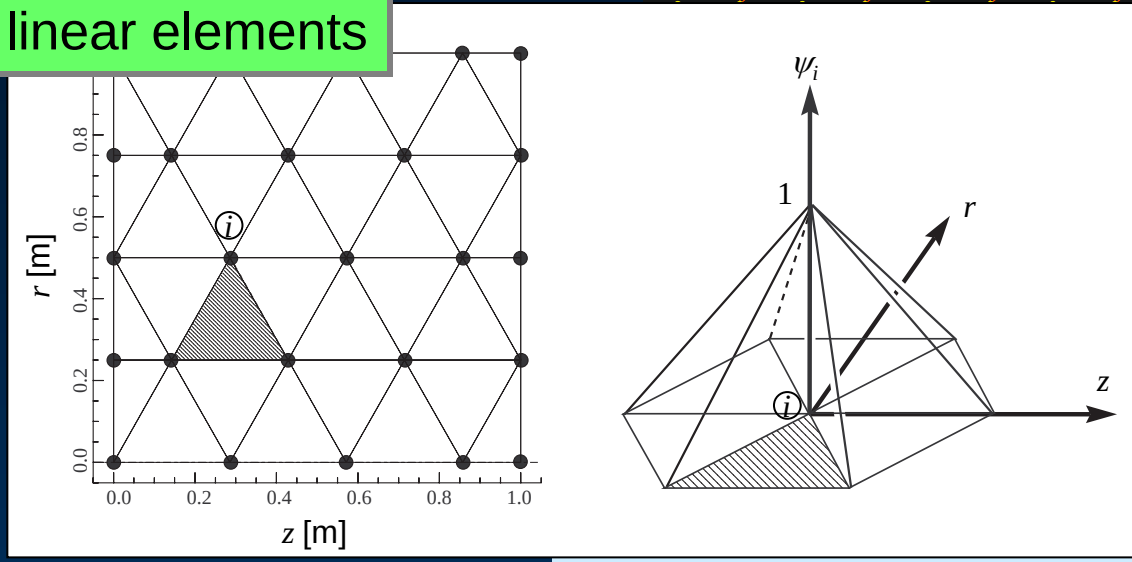
$$\nabla \times \left\{ \frac{1}{\varepsilon_s} \nabla \times (H_\theta \boldsymbol{i}_\theta) \right\} = \nabla \times \left\{ \frac{1}{\varepsilon_s} (\boldsymbol{J} - J_\theta \boldsymbol{i}_\theta) \right\}$$

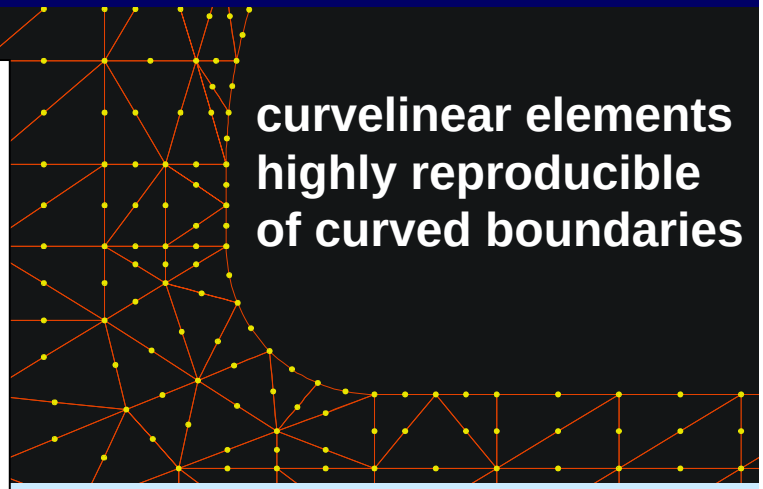
$$\frac{\partial}{\partial t} = 0$$

Common Features in KU-Codes (1/3)

FEM with with quadratic curvelinear elements

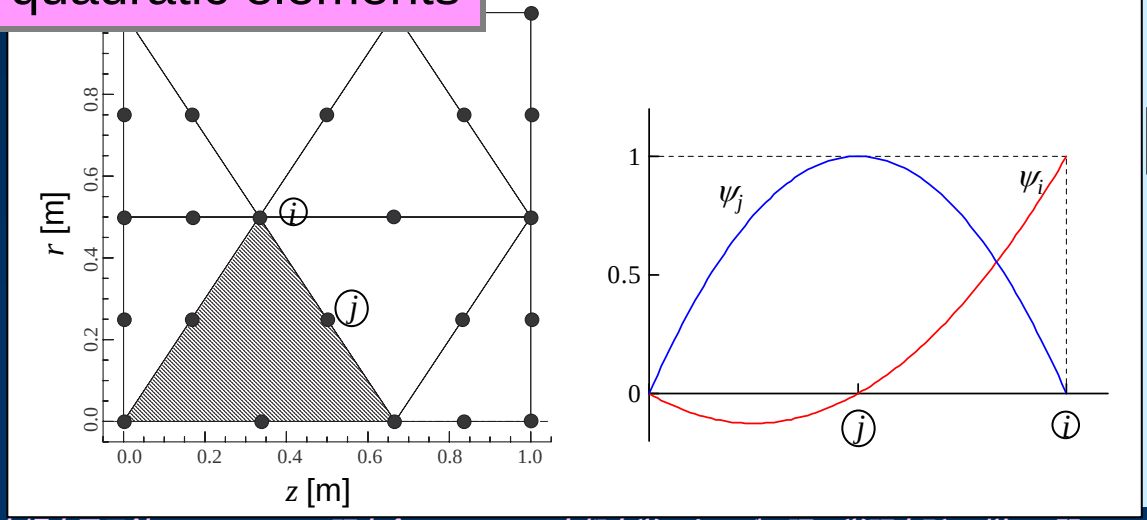
linear elements





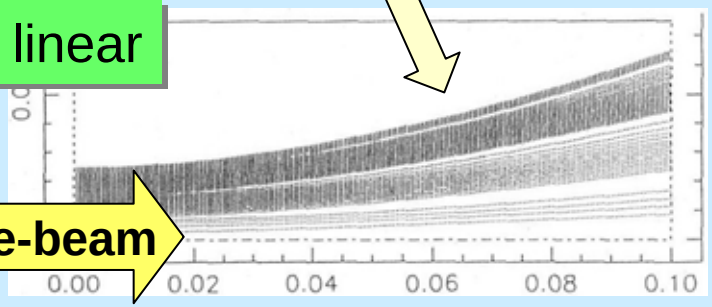
curvelinear elements highly reproducible of curved boundaries

quadratic elements



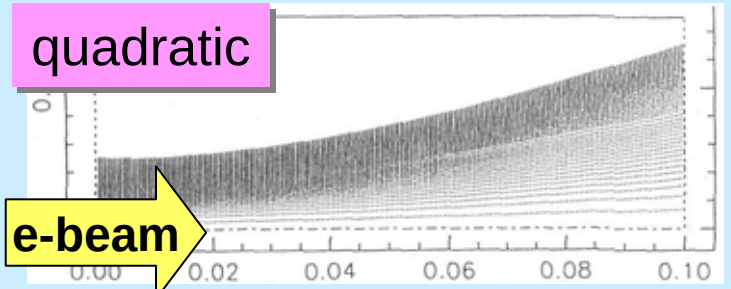
non-physical beam filamentation

linear



e-beam

quadratic



e-beam

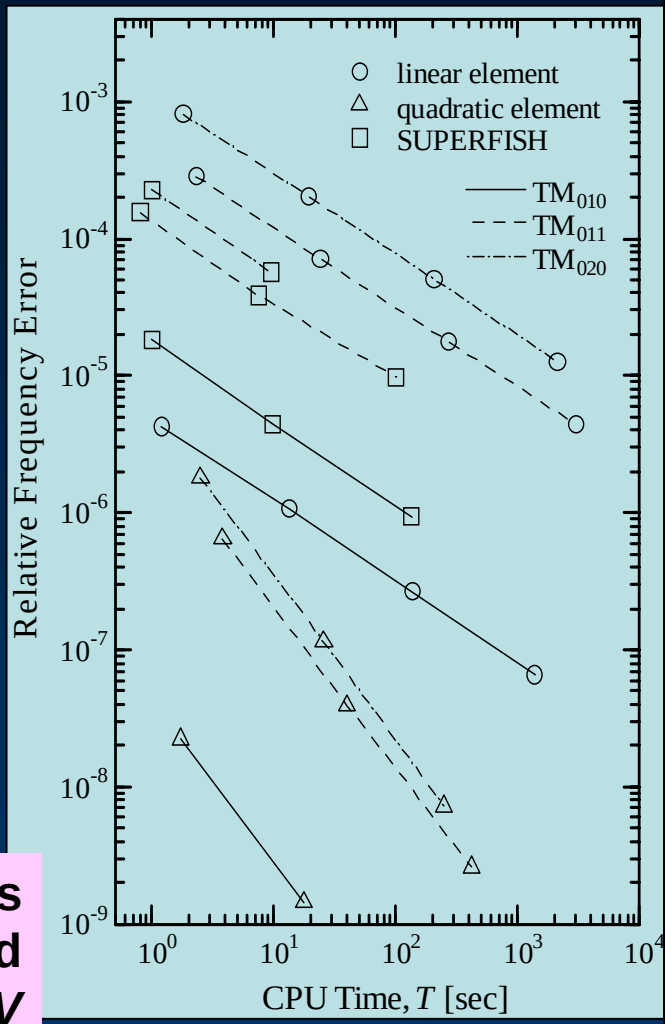
Common Features in KU-Codes (2/3)

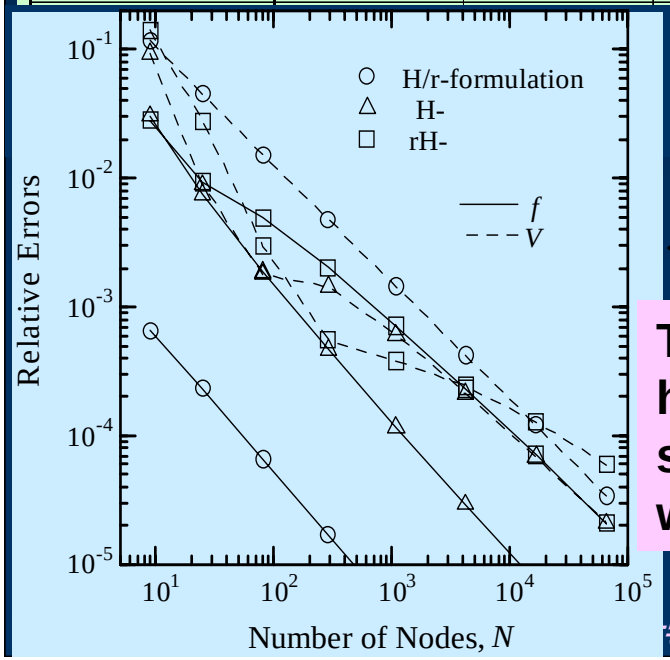
high accuracy in cylindrical symmetry

Review of the existing eigenmode solvers

code	independent variable	method	basis function
LALA	rH_θ	FEM	linear
SUPERFISH	H_θ	FDM	linear
PRUD-W	H_θ	FEM	quadratic
KUEMS	H_θ/r	FEM	quadratic
MAFIA (URMEL)	$\boldsymbol{E}, \boldsymbol{H}$	FDM	linear

Quadratic elements show much higher precision.





The H/r-formulation shows higher accuracy in *f*, and smooth convergence in *V* with increasing *N*.

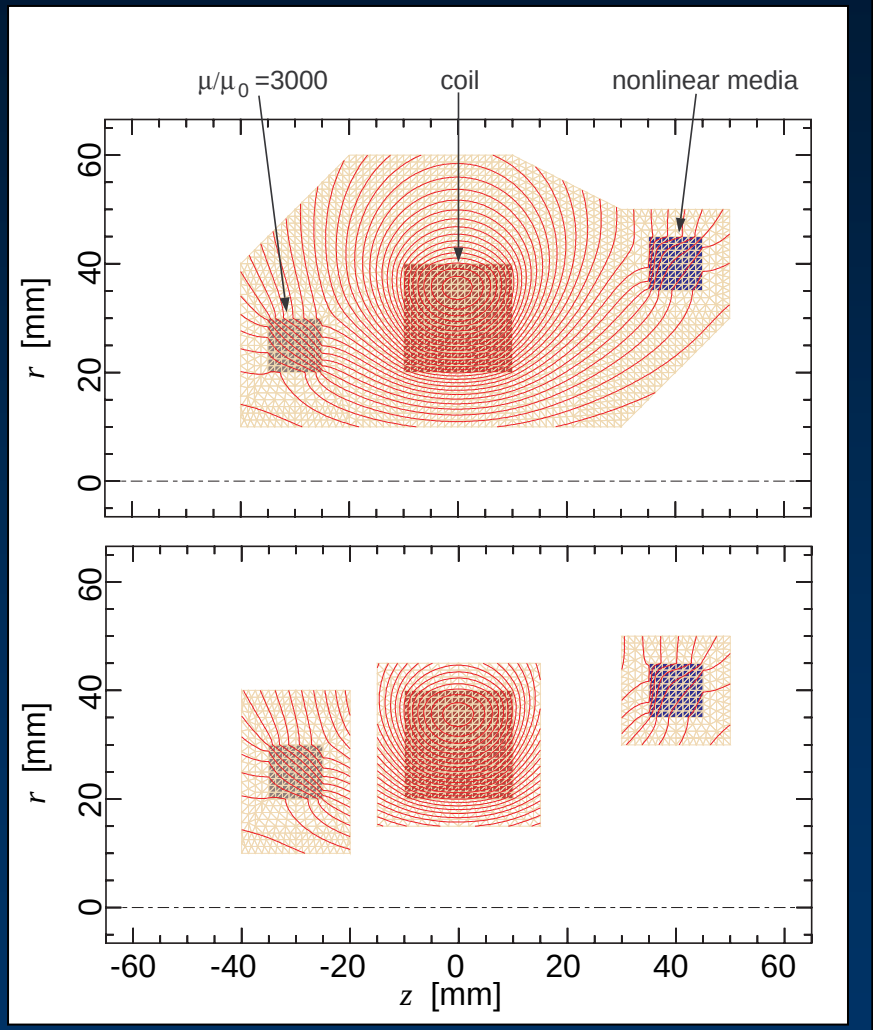
K. Masuda, *IEEE Trans. Microwave Theory Tech.* **46**-8 (1998) 1180.

Common Features in KU-Codes (3/3)
unbounded fields with nonlinear media

New FEM/MM-hybrid method

deals with unbounded problems including inhomogeneous and nonlinear media.

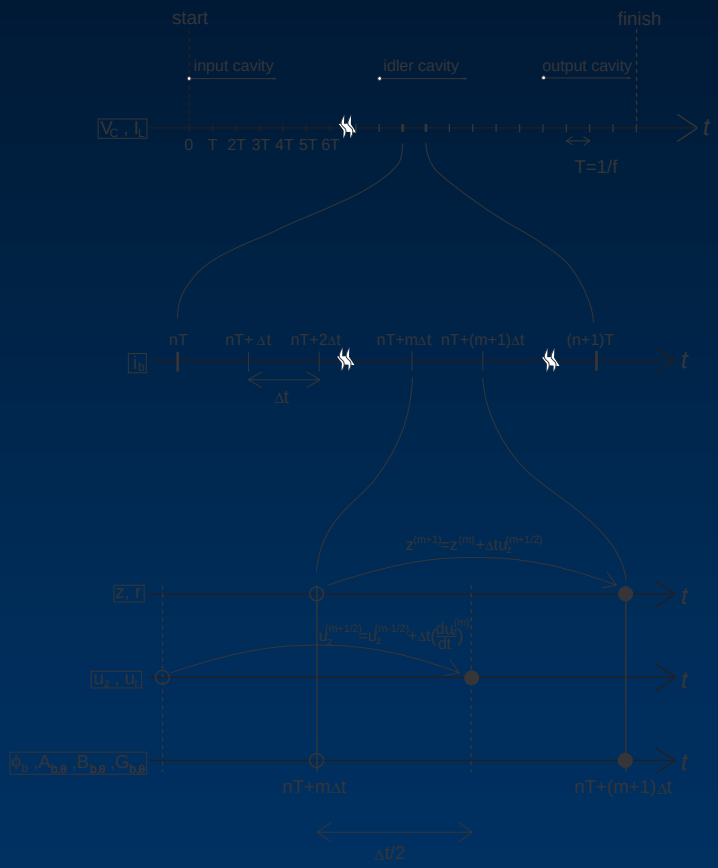
	unbounded problem	inhomogeneous media
finite methods (FEM, FDM)	X	O
boundary integral methods (BEM, MM)	O	X
hybrid methods	O	O



K. Masuda, *PhD Thesis Kyoto Univ.* (1997) Chapter 4.

Features of KUBLAI code

✓ **full Maxwell in time-domain**



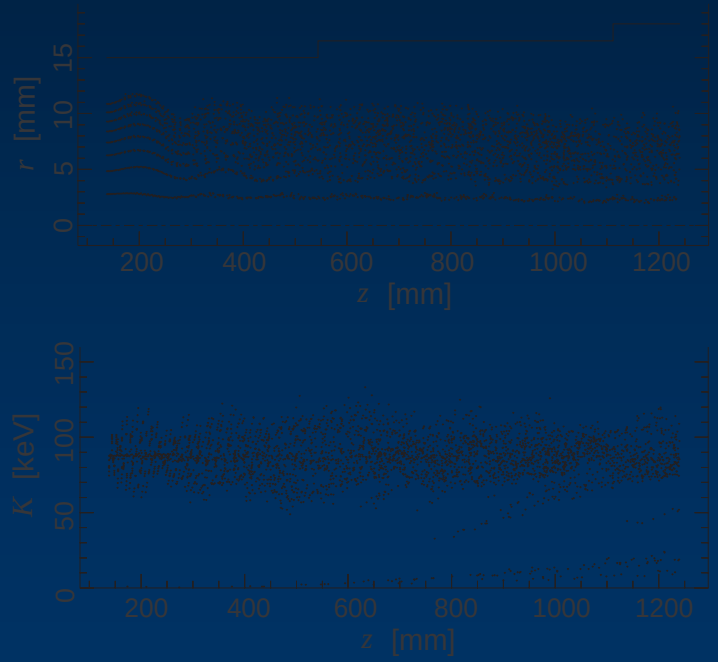
✓**modified Newmark method**

new method based on Newmark method

- **not requiring Courant-Freidrichs condition**

$$c\Delta t \le h\sqrt{\Delta z^2 + \Delta r^2}$$

- **highly stable for intense beams**

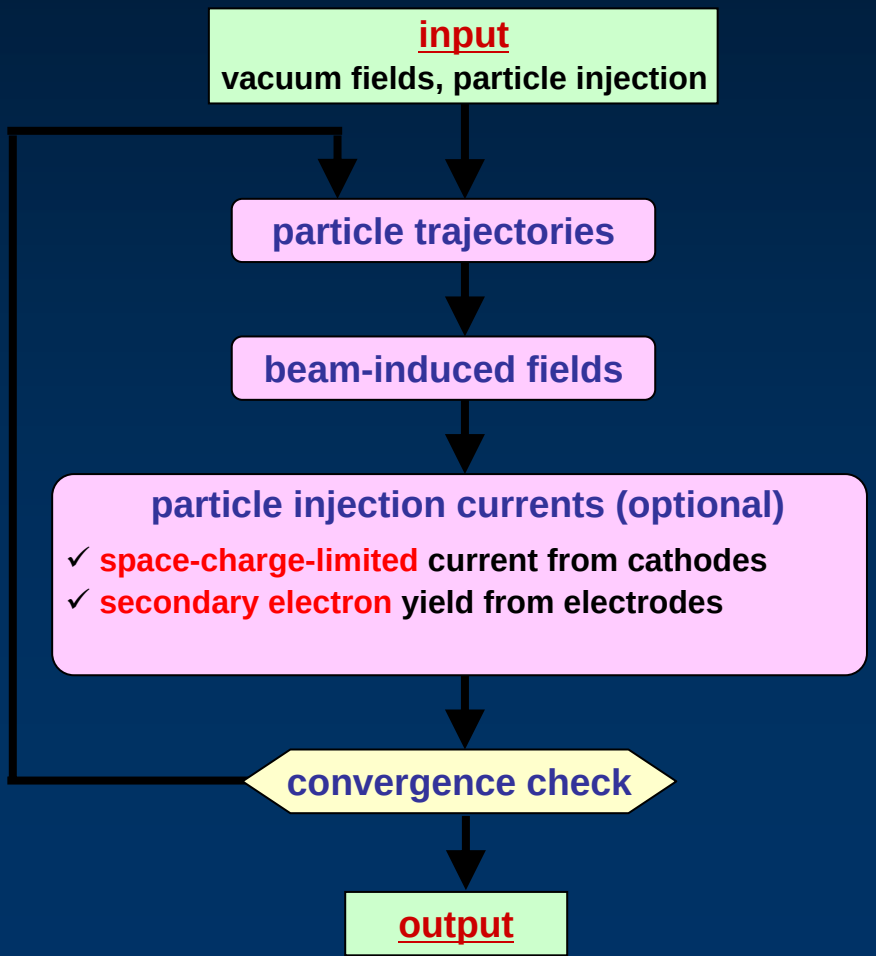


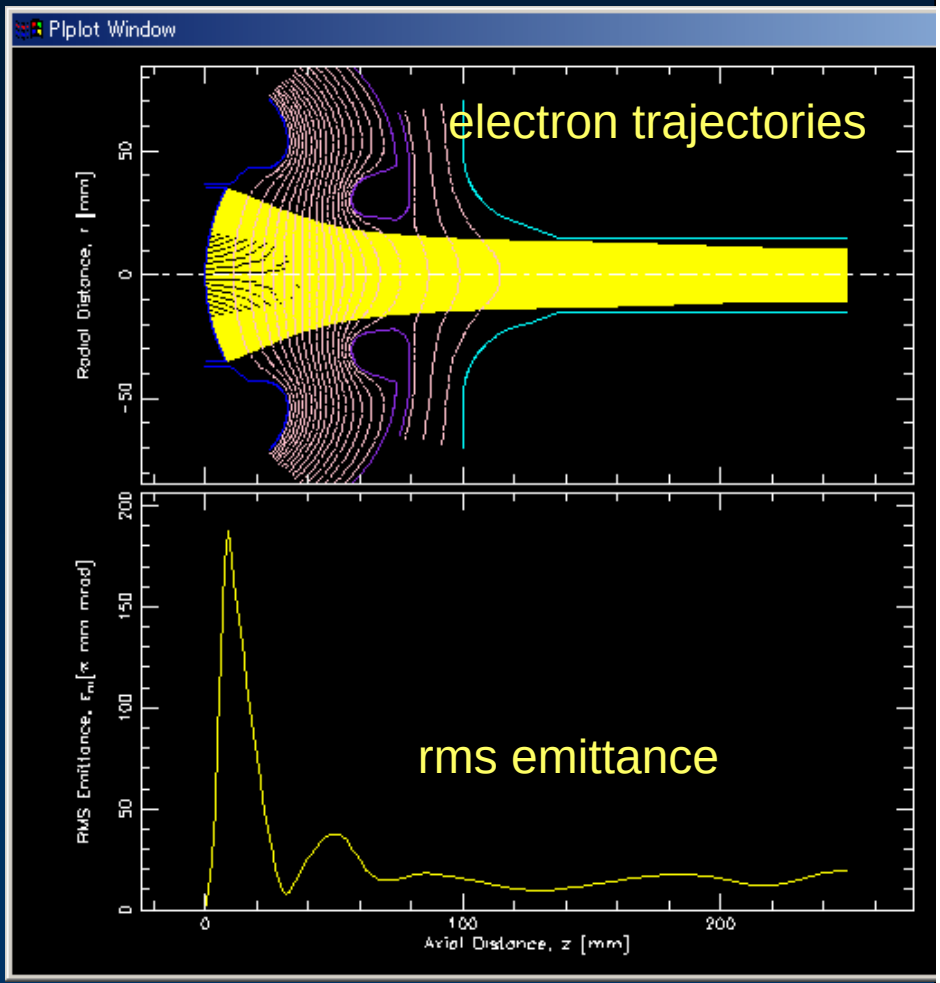
non-physical energy modulation and bunching of an intense dc beam by conventional methods

K. Masuda, *PhD Thesis Kyoto Univ.* (1997) Chapter 5.

Features of KUAD2 code

- ✓ dc beam only (in electro-magnetostatic fields)
- ✓ much faster than KUBLAI for dc beam simulations
- ✓ deal with space-charge limited flow (Child law)





Comparison between KUAD2 and KUBLAI

much faster convergence by KUAD2 for dc beam simulation

KUBLAI

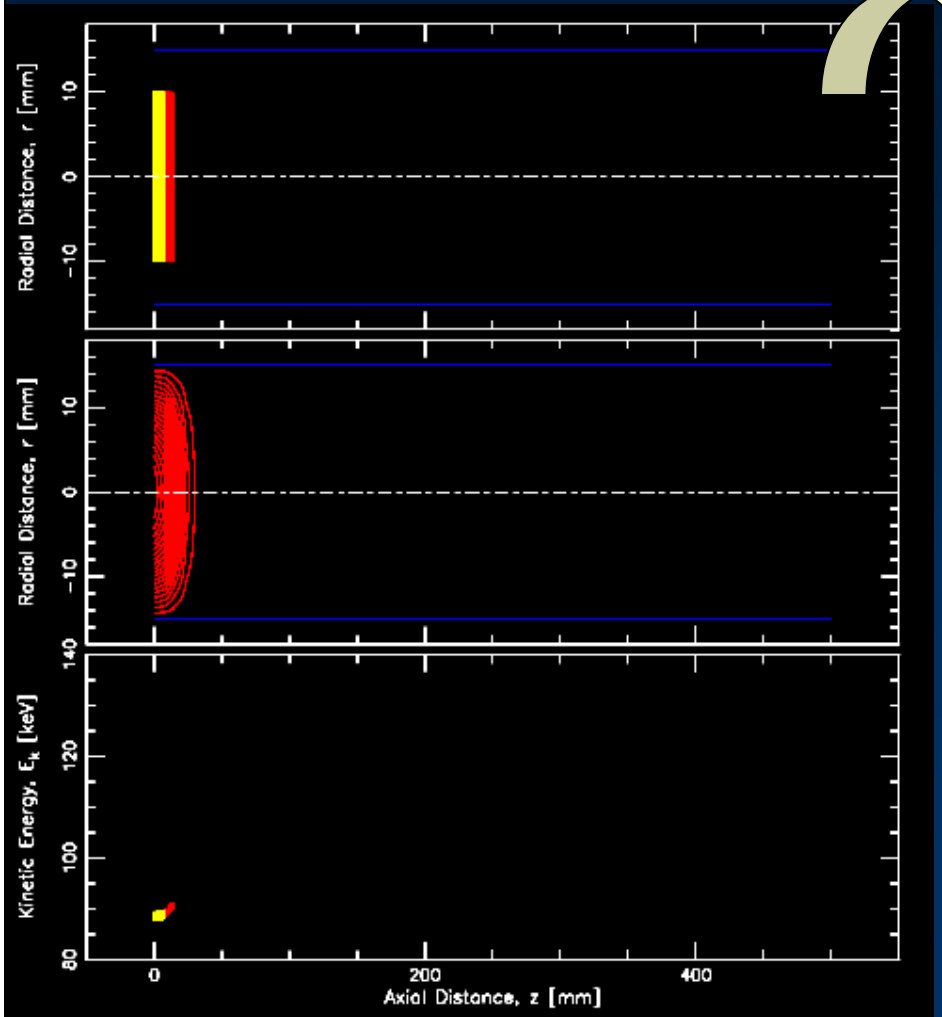
✓ time-domain

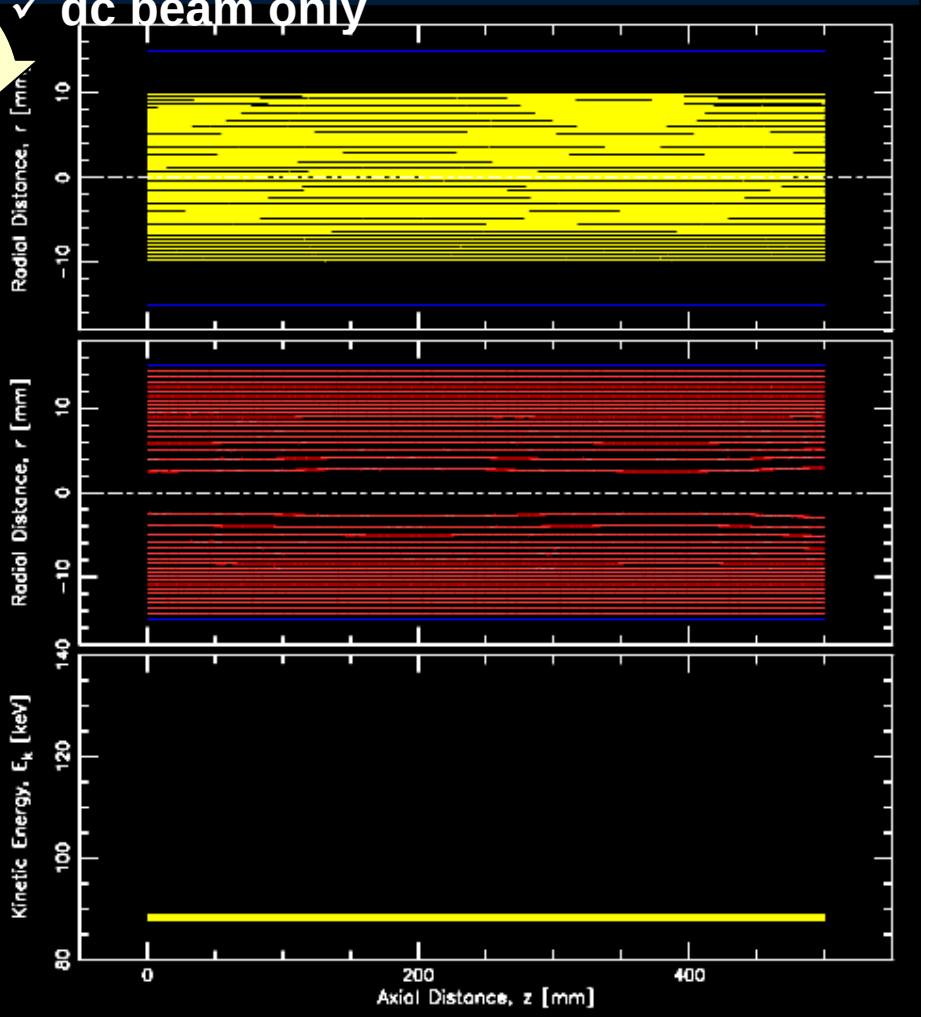
~1/30 CPU time

KUAD2

✓ electro-magnetostatic (iterative calc.)

✓ dc beam only



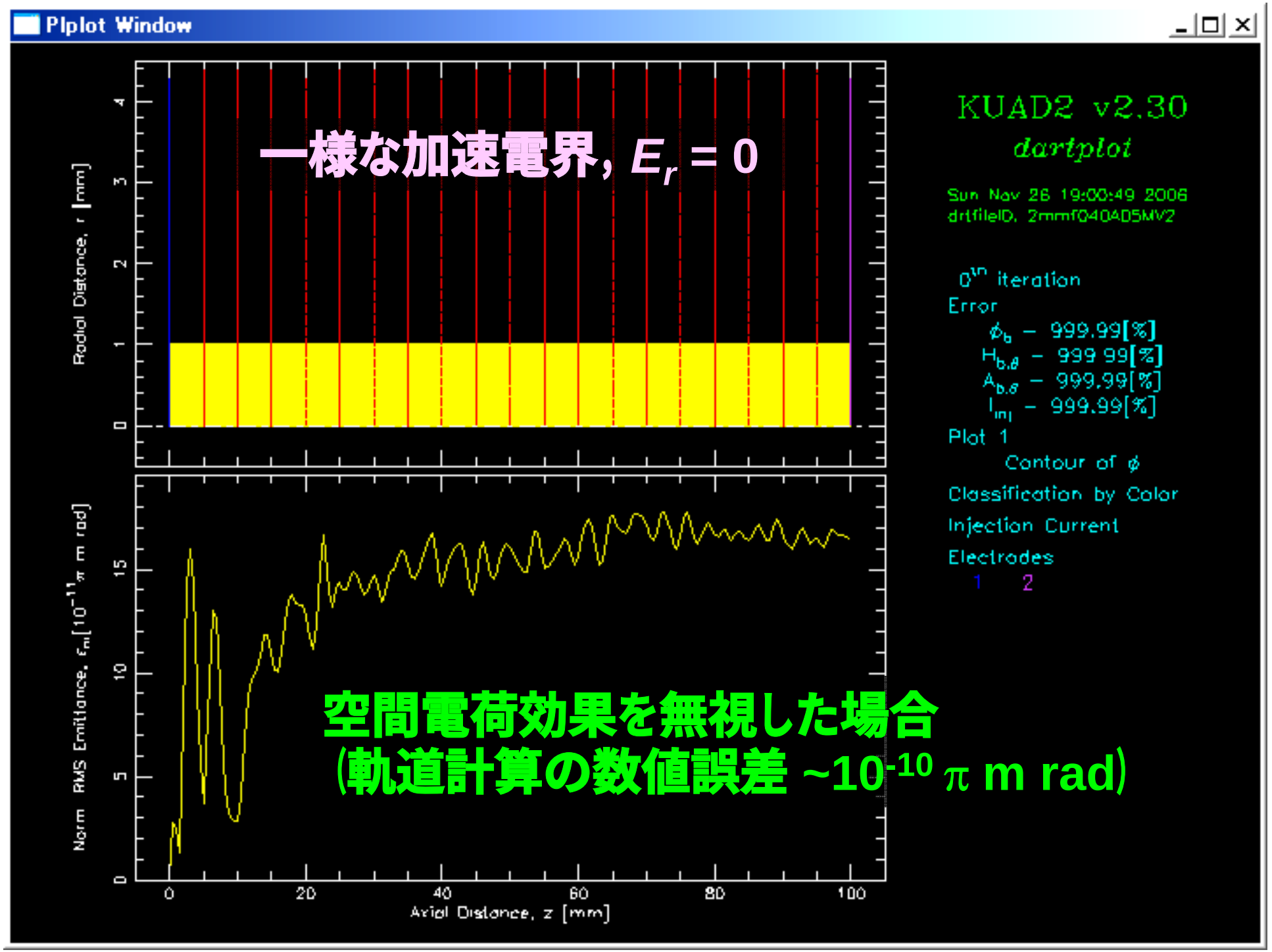


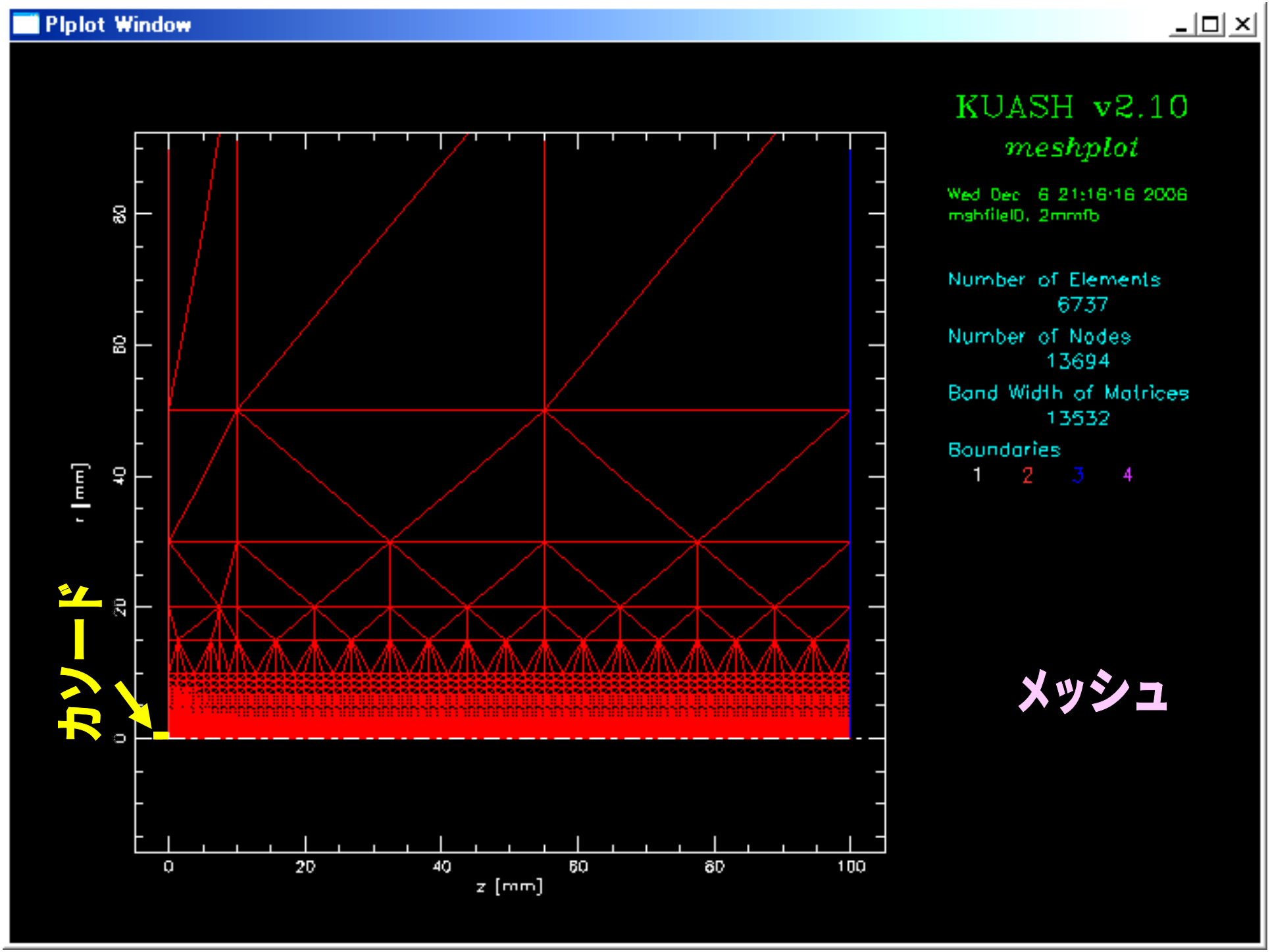
1. コードの概要

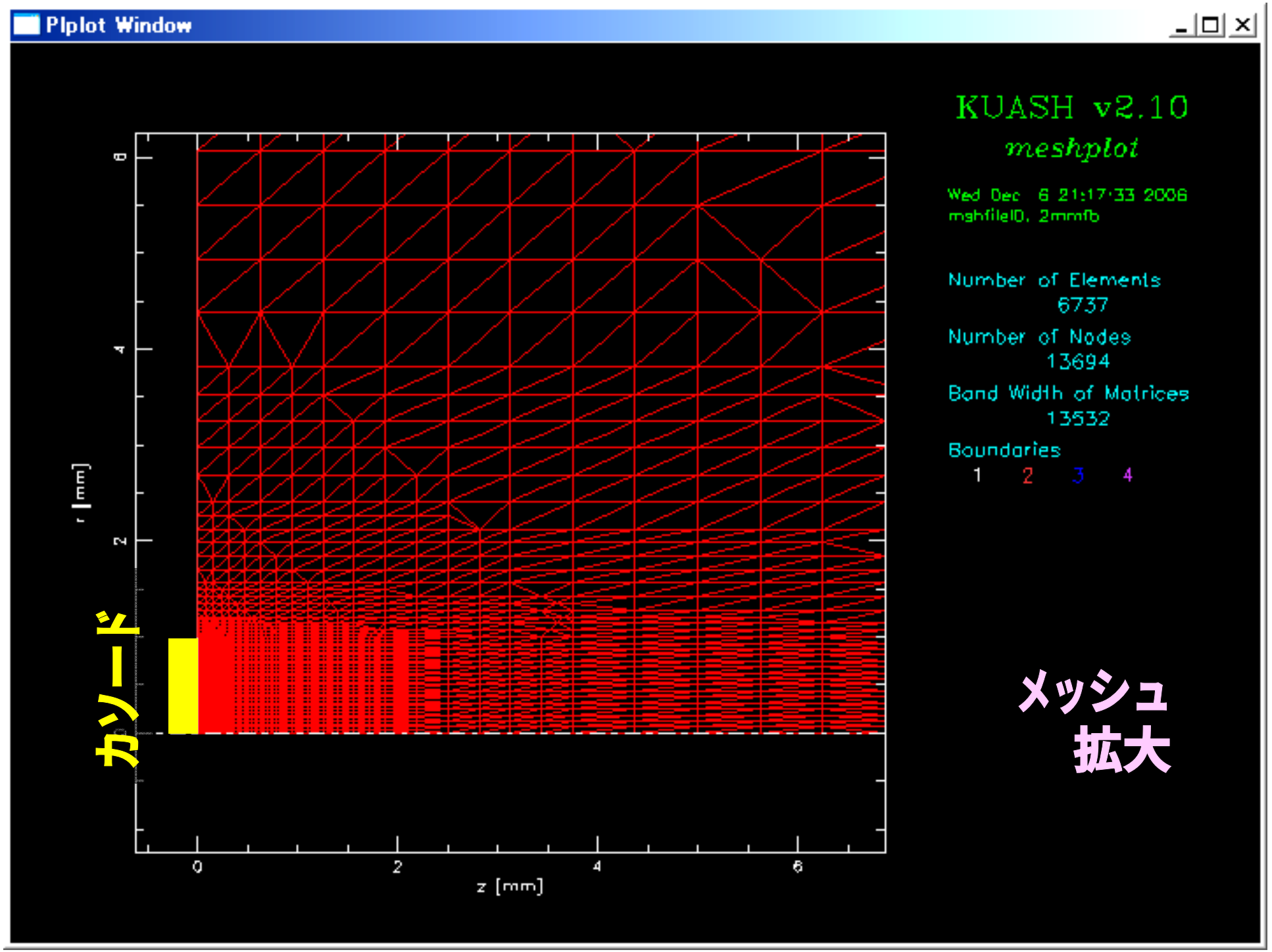
2. DCビームへの鏡像の影響

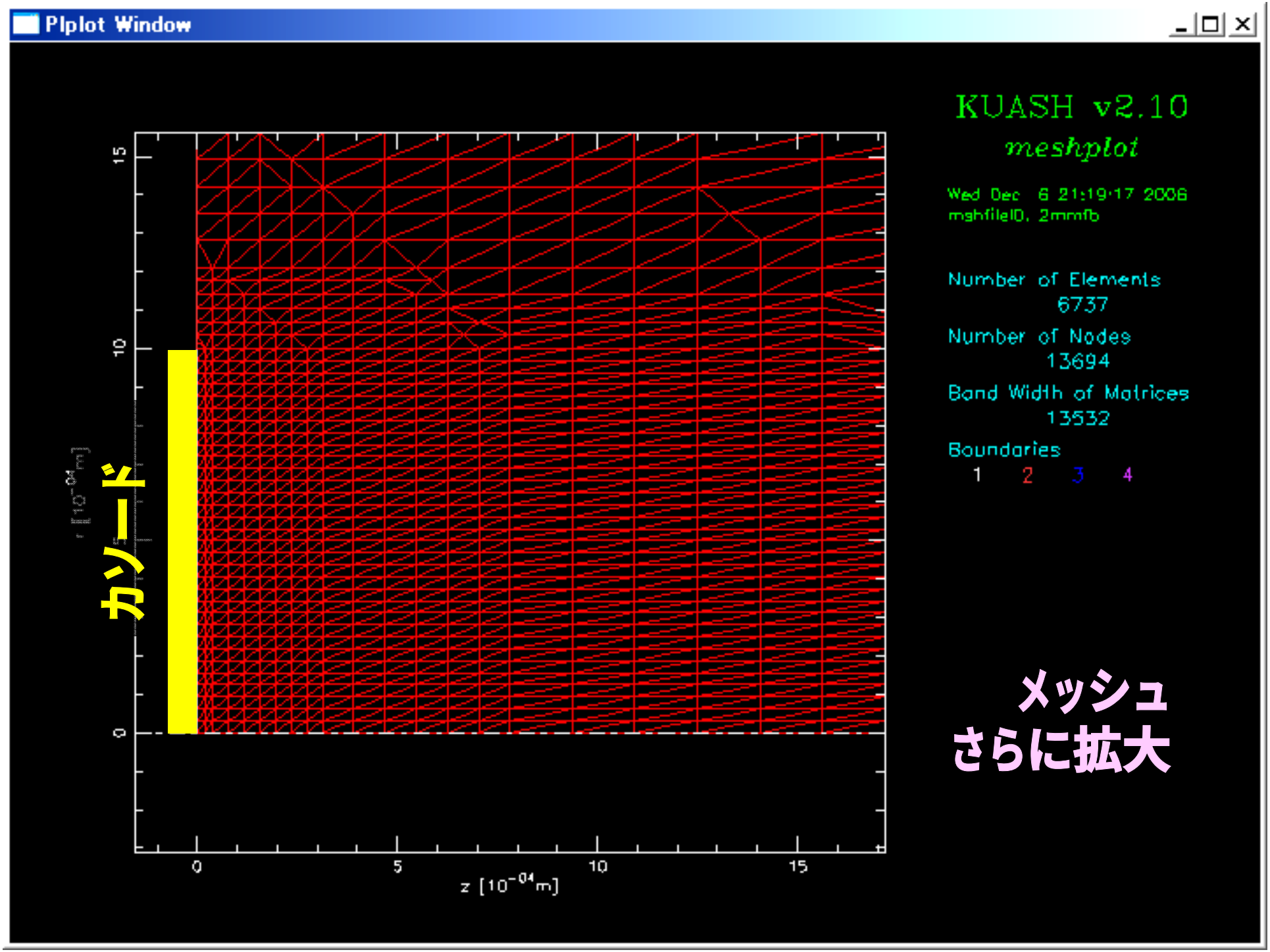
3. DCビームへの熱エミッタンスの影響

4. パルスビームへの鏡像の影響


Plplot Window
一様な加速電界, $E_r = 0$
Radial Distance, r [mm]
Norm RMS Emittance, ε_n[10^{-11}π m rad]
Axial Distance, z [mm]
0
20
40
60
80
100
KUAD2 v2.30
dartplot
Sun Nov 26 19:00:49 2006
drtfileID, 2mmf040405MV2
0th iteration
Error
ϕ_b - 999.99[%]
$H_{b,\theta}$ - 999.99[%]
$A_{b,\sigma}$ - 999.99[%]
I_{inj} - 999.99[%]
Plot 1
Contour of φ
Classification by Color
Injection Current
Electrodes
1 2
空間電荷効果を無視した場合
(軌道計算の数値誤差 ~10^{-10} π m rad)


Plplot Window
KUASH v2.10
meshplot
Wed Dec 6 21:16:16 2006
mshfileID, 2mmfb
Number of Elements
6737
Number of Nodes
13694
Band Width of Matrices
13532
Boundaries
1 2 3 4
r [mm]
z [mm]
0
20
40
60
80
100
カソード
メッシュ


Plplot Window
KUASH v2.10
meshplot
Wed Dec 6 21:17:33 2006
mshfileID, 2mmfb
Number of Elements
6737
Number of Nodes
13694
Band Width of Matrices
13532
Boundaries
1 2 3 4
r [mm]
z [mm]
0
2
4
6
8
カソード
メッシュ
拡大


Plplot Window
KUASH v2.10
meshplot
Wed Dec 6 21:19:17 2006
mshfileID, 2mmfb
Number of Elements
6737
Number of Nodes
13694
Band Width of Matrices
13532
Boundaries
1 2 3 4
カソード
メッシュ
さらに拡大
z [10^-04 m]
0
5
10
15

陰極直径：2 mmϕ

電　　界：5, 10, 20, 40, 80 MV/m

電流密度：10, 20, 40, 80, 160 A/cm^2

パルス長：5, 10, 20, 40 psec, DC

160 A/cm^2, 2 mmϕ, 20 psec → 0.1 nC

1. コードの概要

2. DCビームへの鏡像の影響

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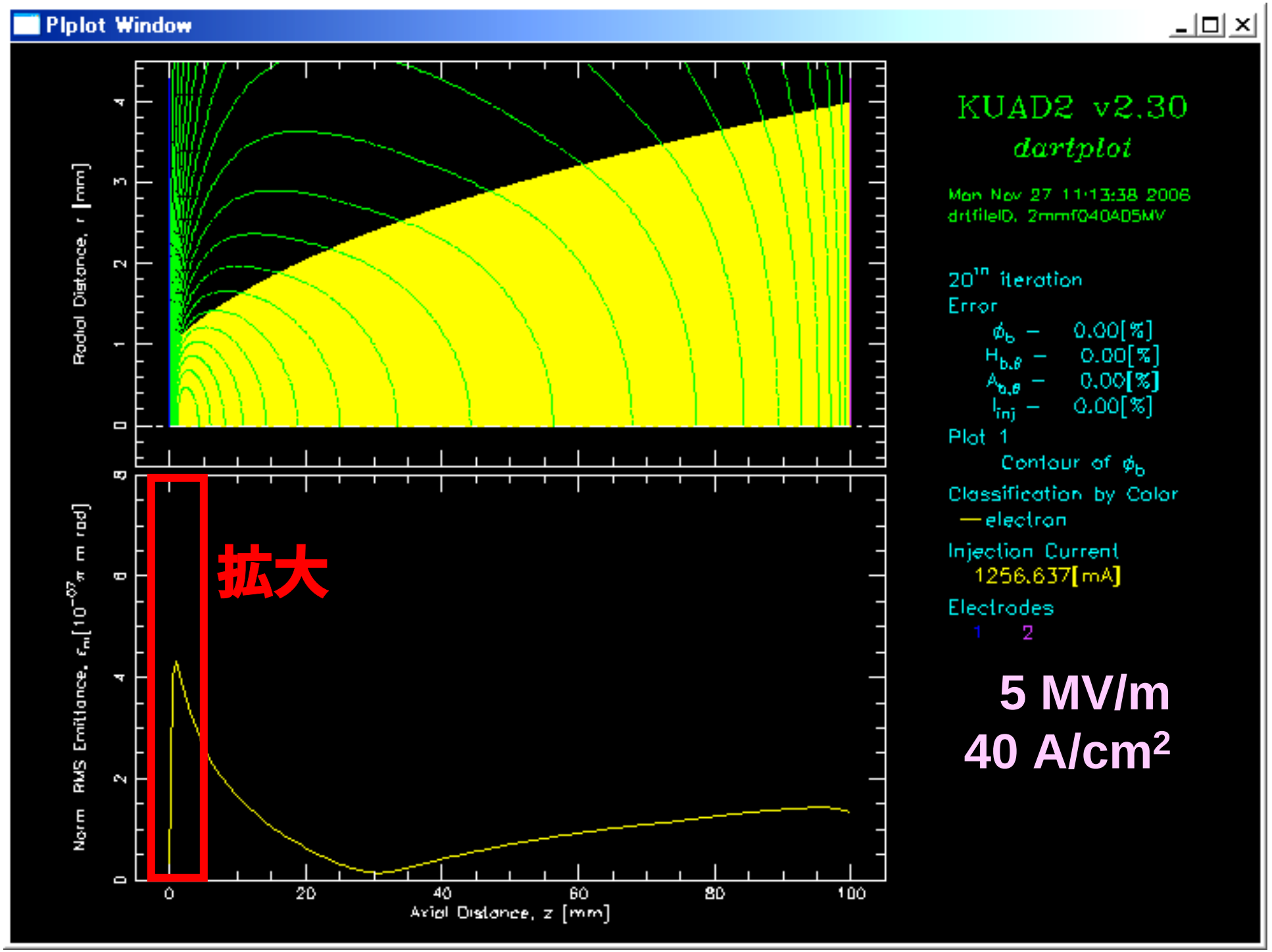
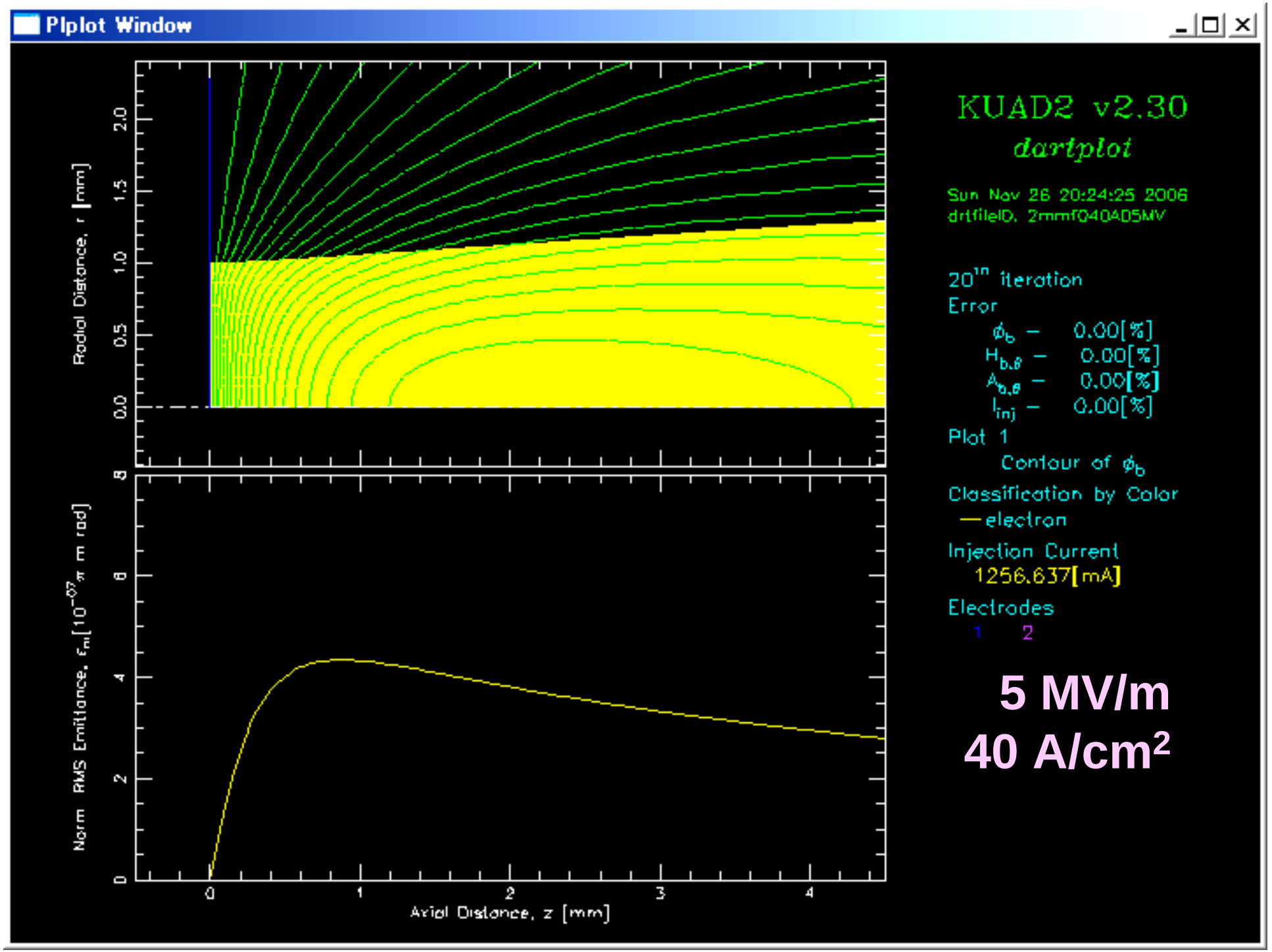
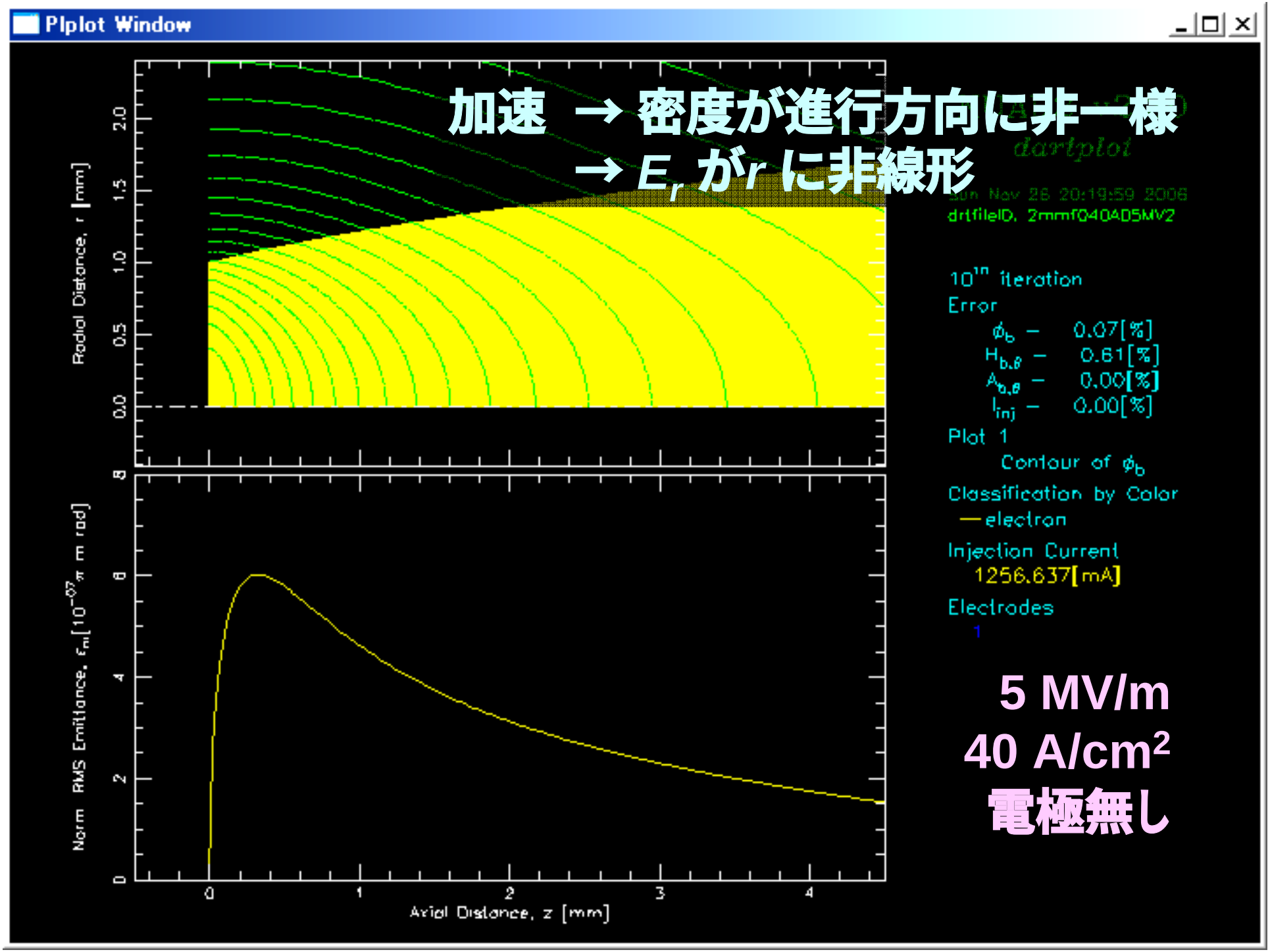
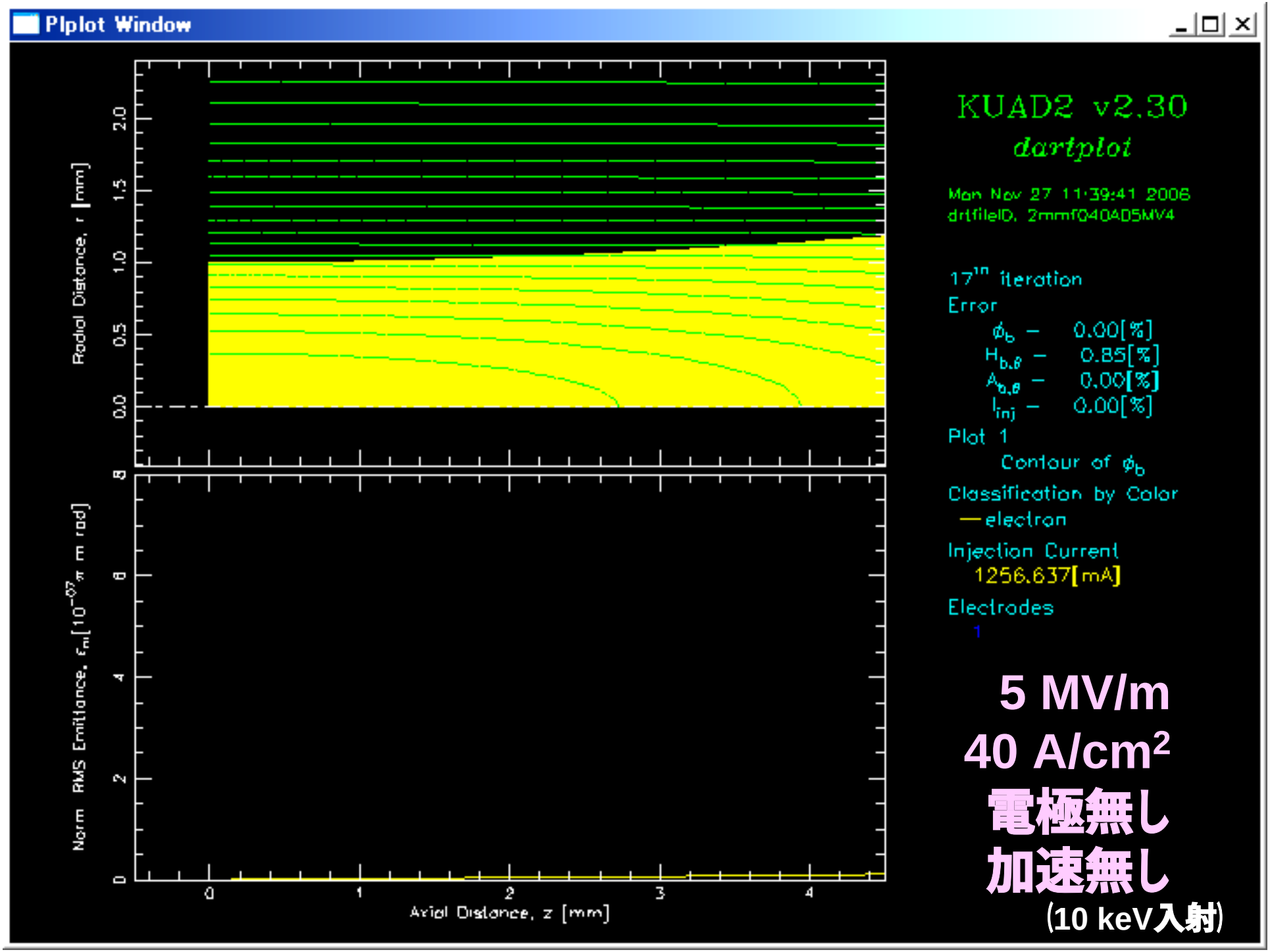
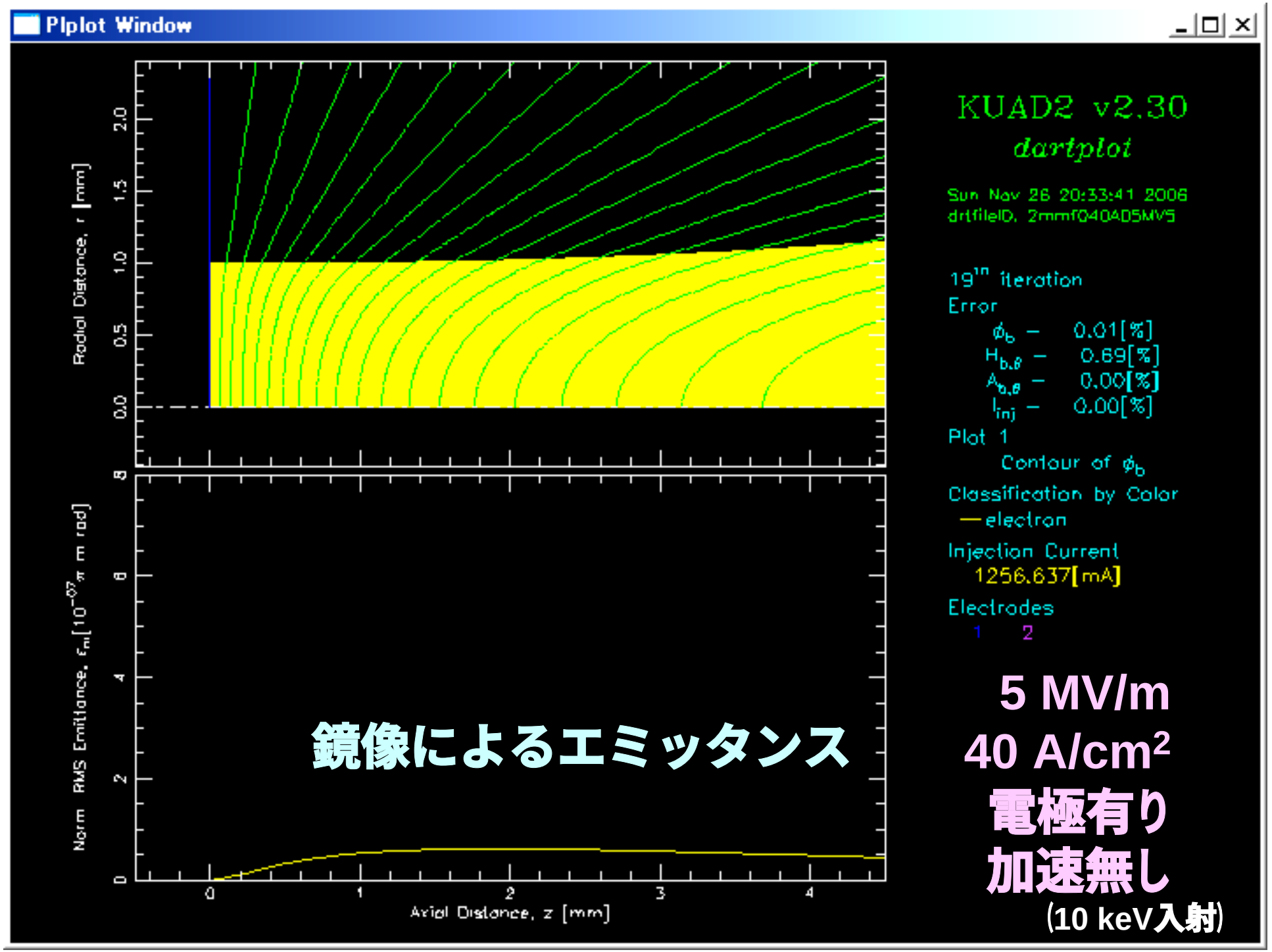

Plplot Window
Radial Distance, r [mm]
Norm RMS Emittance, $\varepsilon_{n,i}$[10^{-07} m rad]
Axial Distance, z [mm]
0
20
40
60
80
100
拡大
KUAD2 v2.30
dartplot
Mon Nov 27 11:13:38 2006
drtfileID, 2mmf040405MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
5 MV/m
40 A/cm²


Plplot Window
Radial Distance, r [mm]
0.0
0.5
1.0
1.5
2.0
Norm RMS Emittance, ε_n[10^{-07} m rad]
0
2
4
6
8
0
1
2
3
4
Axial Distance, z [mm]
KUAD2 v2.30
dartplot
Sun Nov 26 20:24:25 2006
drtfileID, 2mmf040405MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
5 MV/m
40 A/cm²


Plplot Window
加速 → 密度が進行方向に非一様
→ E_r が r に非線形
Radial Distance, r [mm]
Norm RMS Emittance, ε_n[10^{-07}π m rad]
Axial Distance, z [mm]
dartplot
Sun Nov 26 20:19:59 2006
drtfileID, 2mmf040405MV2
10th iteration
Error
ϕ_b – 0.07[%]
$H_{b,\theta}$ – 0.61[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1
5 MV/m
40 A/cm²
電極無し


Plplot Window
Radial Distance, r [mm]
0.0
0.5
1.0
1.5
2.0
Norm RMS Emittance, ε_n[10^{-07} m rad]
0
2
4
6
8
0
1
2
3
4
Axial Distance, z [mm]
KUAD2 v2.30
dartplot
Mon Nov 27 11:39:41 2006
drtfileID, 2mmf040405MV4
17th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.85[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1
5 MV/m
40 A/cm²
電極無し
加速無し
(10 keV入射)


Plplot Window
Radial Distance, r [mm]
0.0
0.5
1.0
1.5
2.0
Norm RMS Emittance, ε_n[10^{-07} π m rad]
0
2
4
6
8
0
1
2
3
4
Axial Distance, z [mm]
KUAD2 v2.30
dartplot
Sun Nov 26 20:33:41 2006
drtfileID, 2mmf040405MV5
19th iteration
Error
ϕ_b – 0.01[%]
$H_{b,\theta}$ – 0.69[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
鏡像によるエミッタンス
5 MV/m
40 A/cm²
電極有り
加速無し
(10 keV入射)

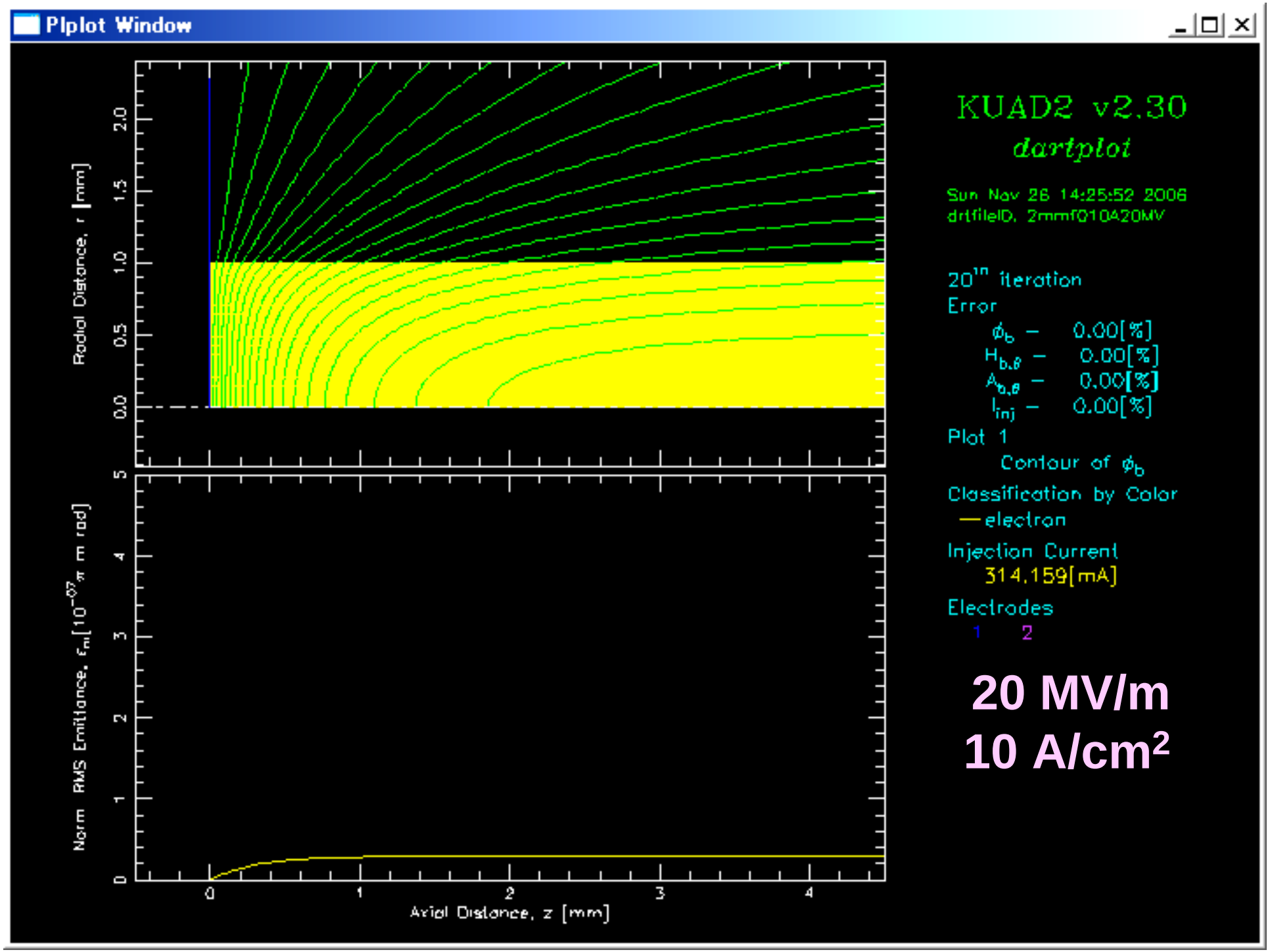
陰極近傍でエミッタンスが急激に増大

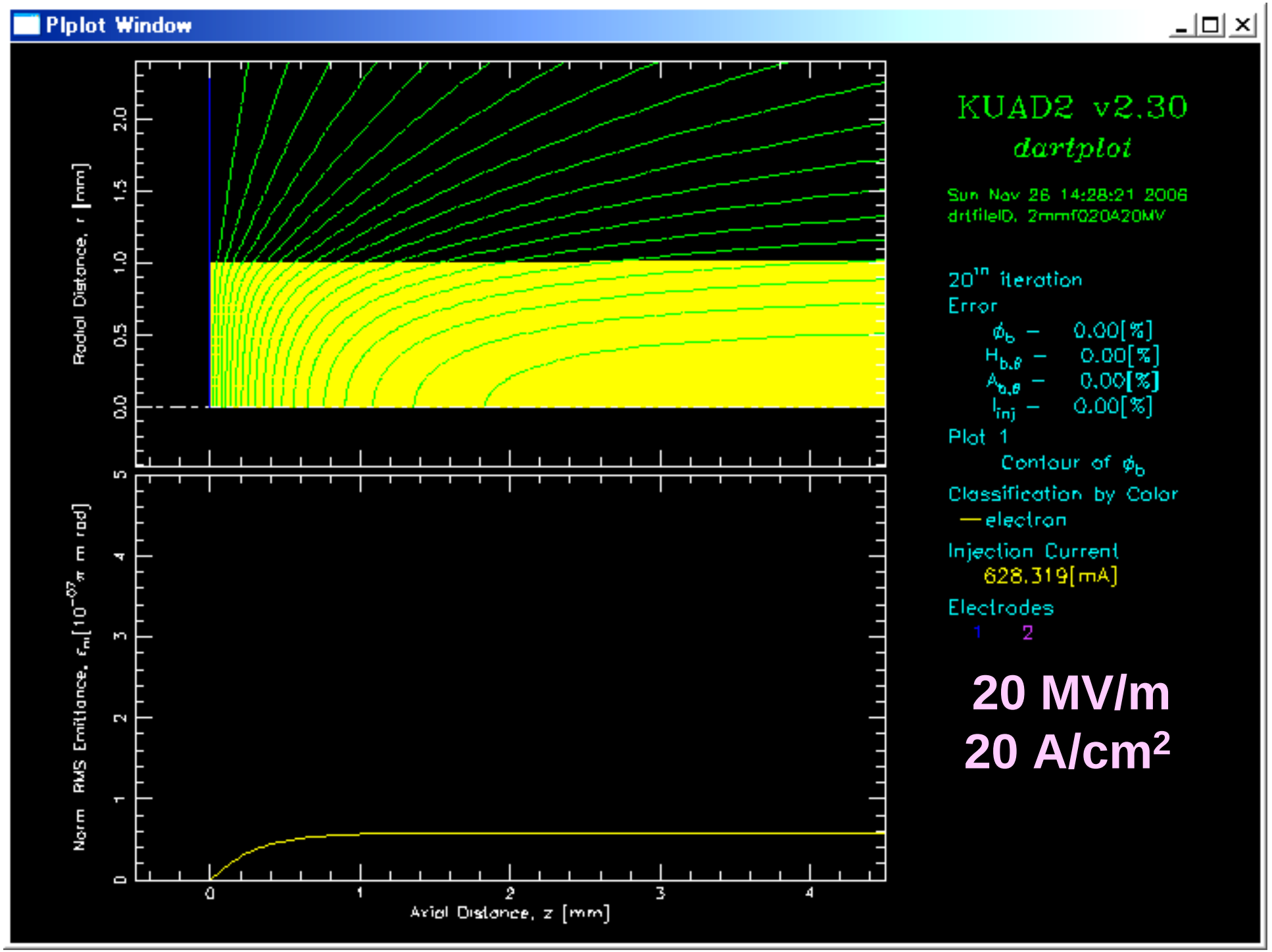
鏡像（陰極=dirichlet境界）が無くても，
ゼロエネルギーから加速するだけで増加

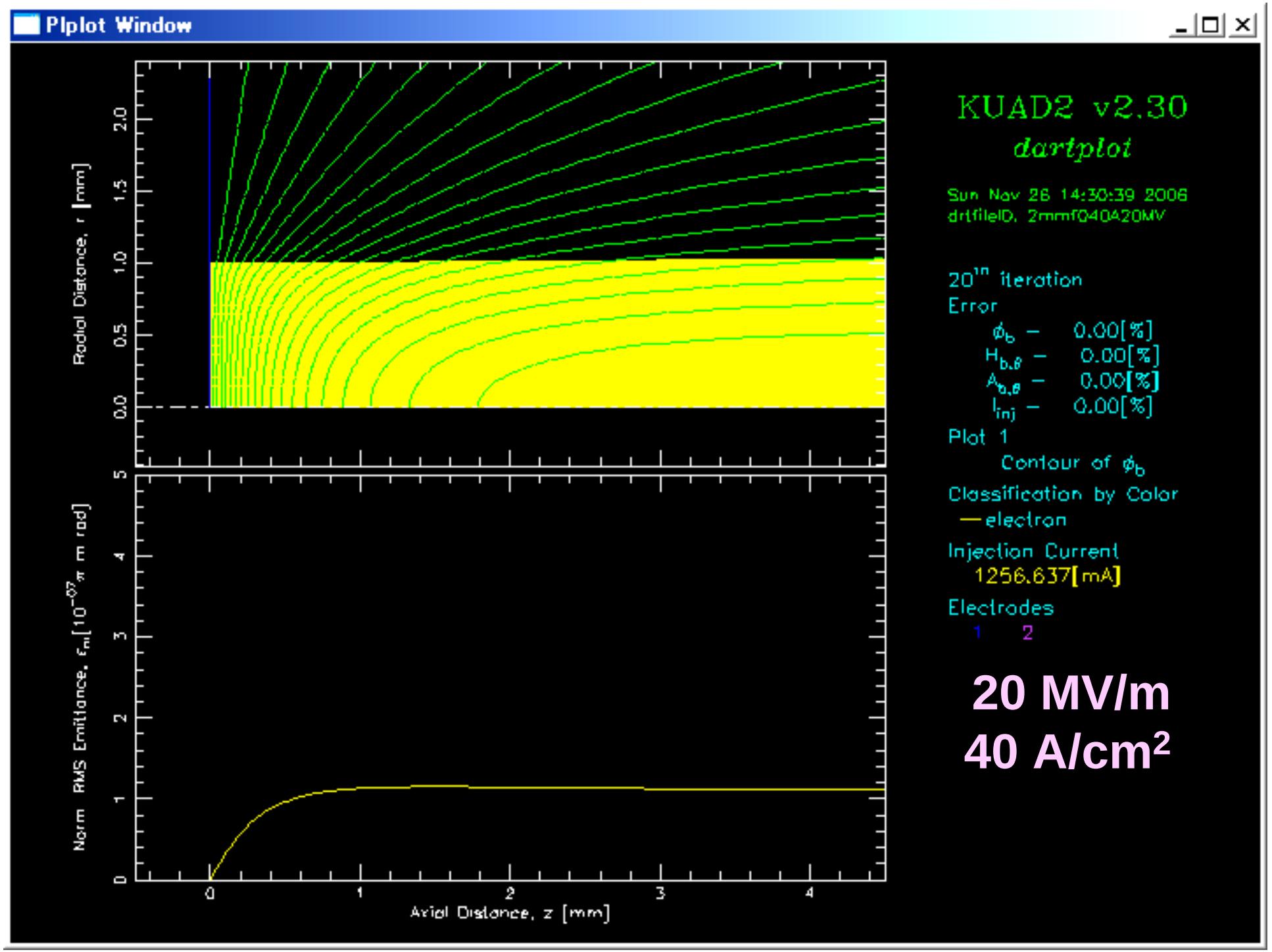
加速せず，dirichlet境界も無ければ，増えない
（一様ビーム → $E_r \propto r$ ）

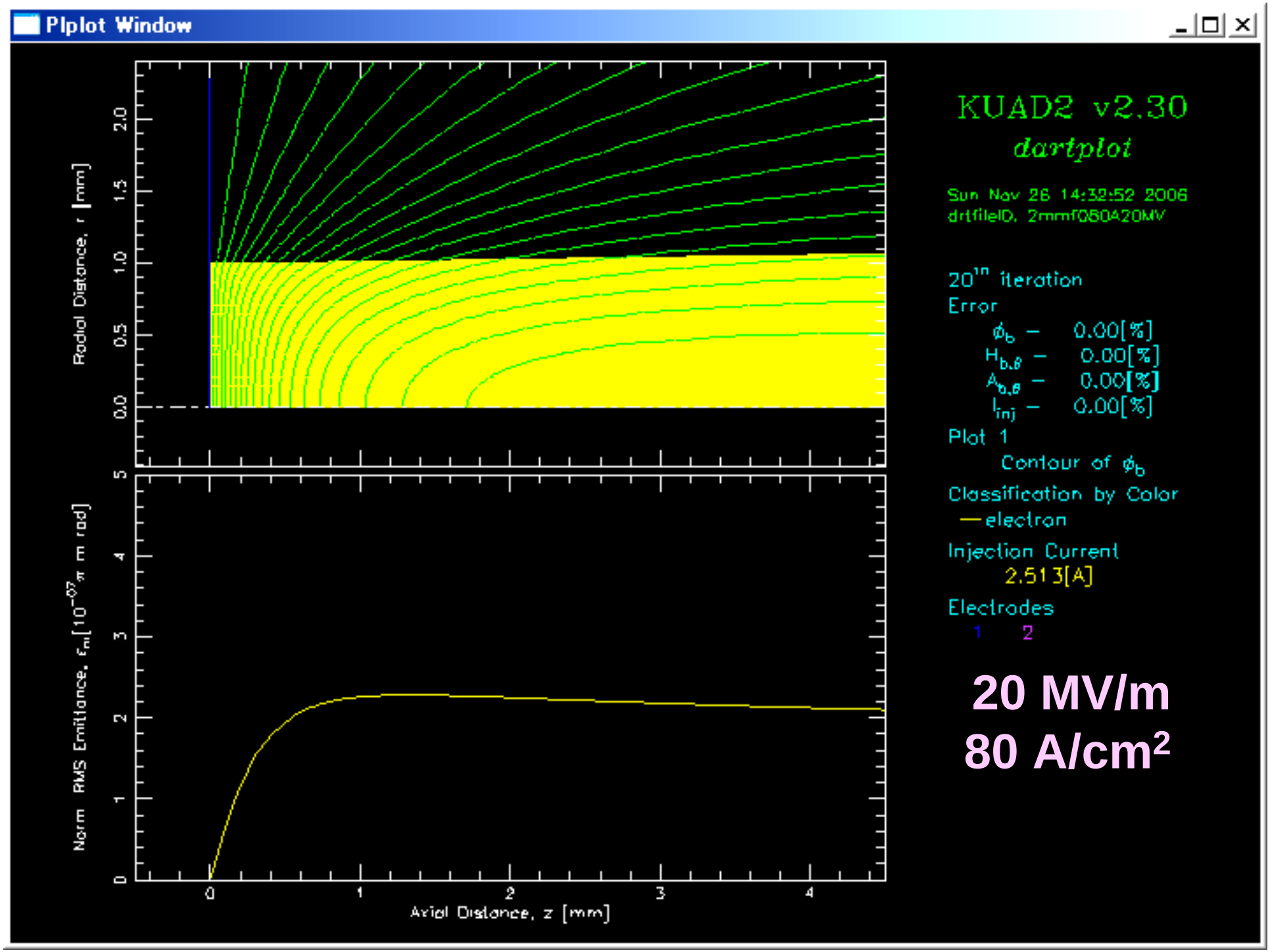
加速しなくても，dirichlet境界があると，増える
（鏡像によるエミッタンス増）

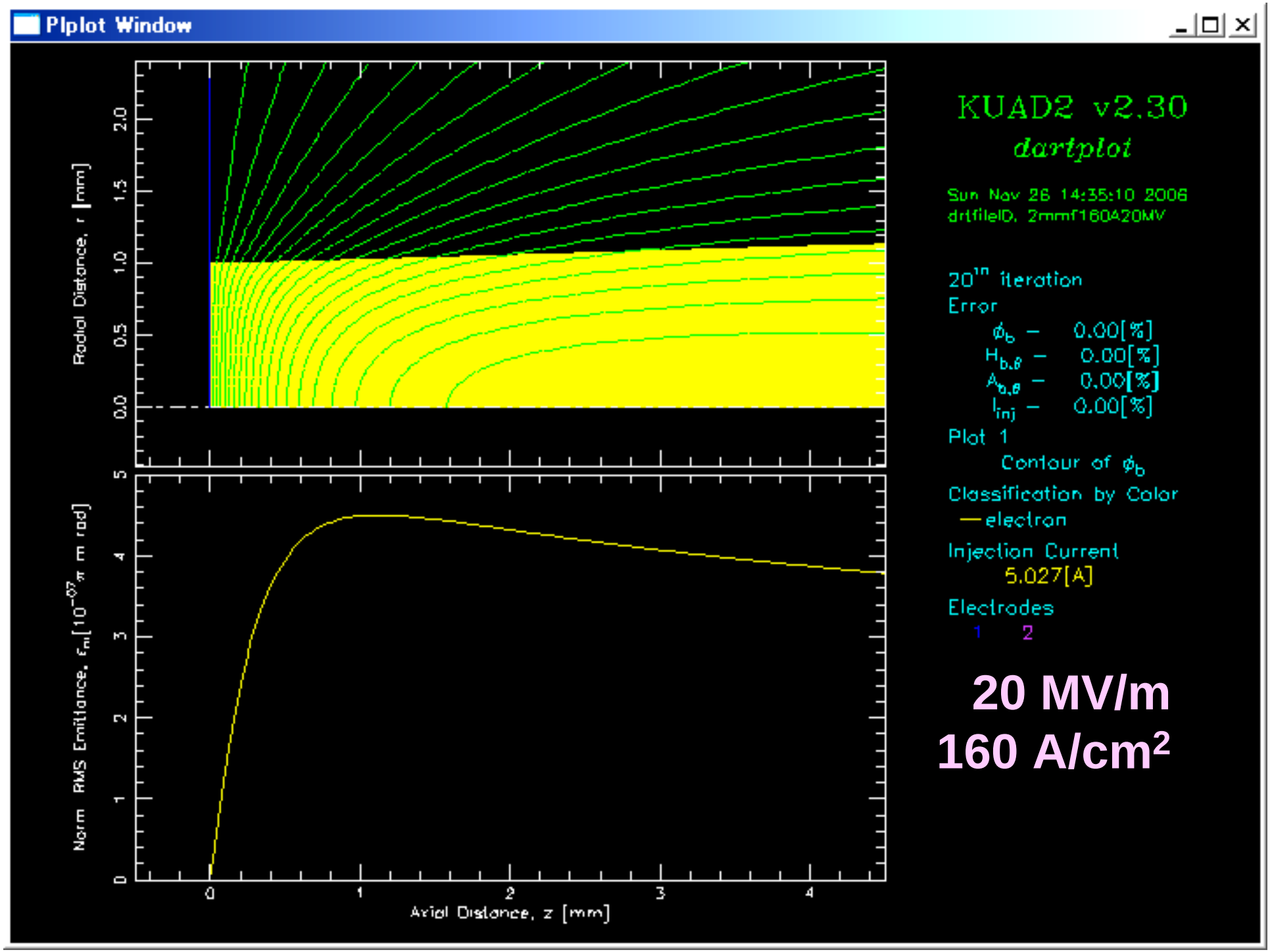
10, 20, 40, 80, 160 A/cm^2
20 MV/m


Plplot Window
Radial Distance, r [mm]
0.0
0.5
1.0
1.5
2.0
Norm RMS Emittance, ε_n[10^{-07} m rad]
0
1
2
3
4
5
0
1
2
3
4
Axial Distance, z [mm]
KUAD2 v2.30
dartplot
Sun Nov 26 14:25:52 2006
drtfileID, 2mmfQ10420MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
314.159[mA]
Electrodes
1 2
20 MV/m
10 A/cm²

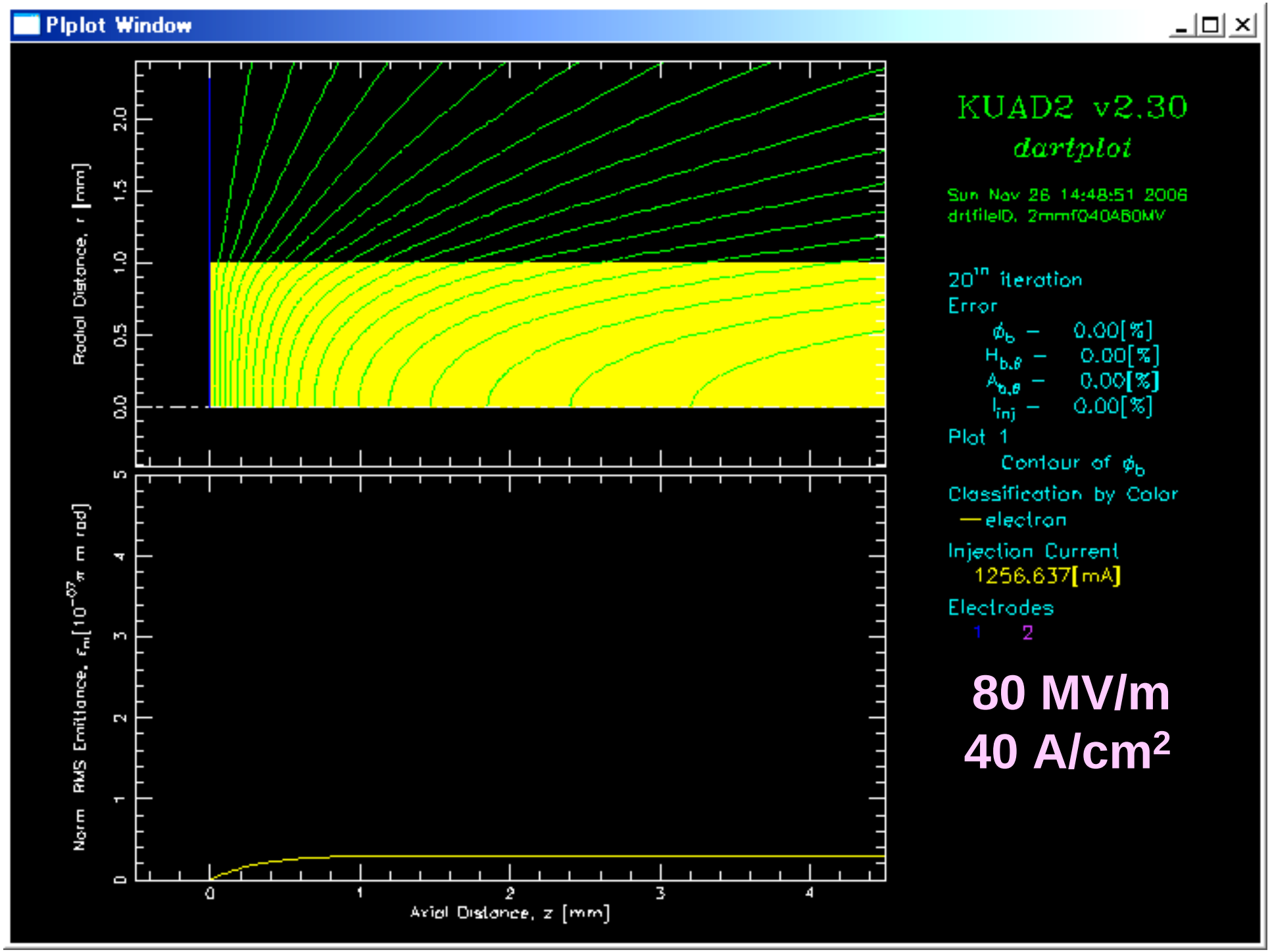

Plplot Window
Radial Distance, r [mm]
0.0
0.5
1.0
1.5
2.0
Norm RMS Emittance, ε_n[10^{-07} m rad]
0
1
2
3
4
5
0
1
2
3
4
Axial Distance, z [mm]
KUAD2 v2.30
dartplot
Sun Nov 26 14:28:21 2006
drtfileID, 2mmf020420MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
628.319[mA]
Electrodes
1 2
20 MV/m
20 A/cm²

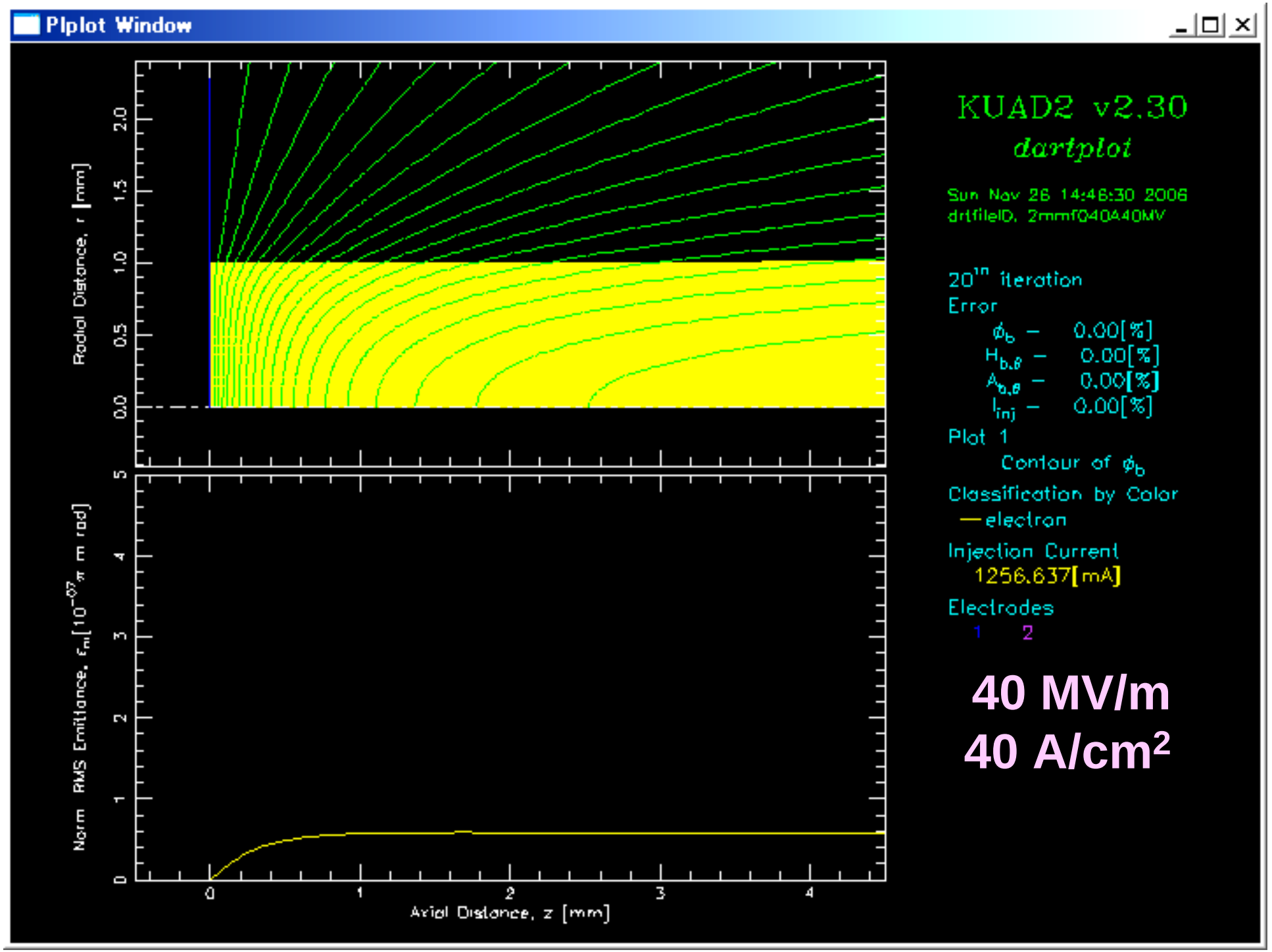

Plplot Window
Radial Distance, r [mm]
0.0
0.5
1.0
1.5
2.0
Norm RMS Emittance, ε_n[10^{-07} π m rad]
0
1
2
3
4
5
0
1
2
3
4
Axial Distance, z [mm]
KUAD2 v2.30
dartplot
Sun Nov 26 14:30:39 2006
drtfileID, 2mmf040420MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
20 MV/m
40 A/cm²

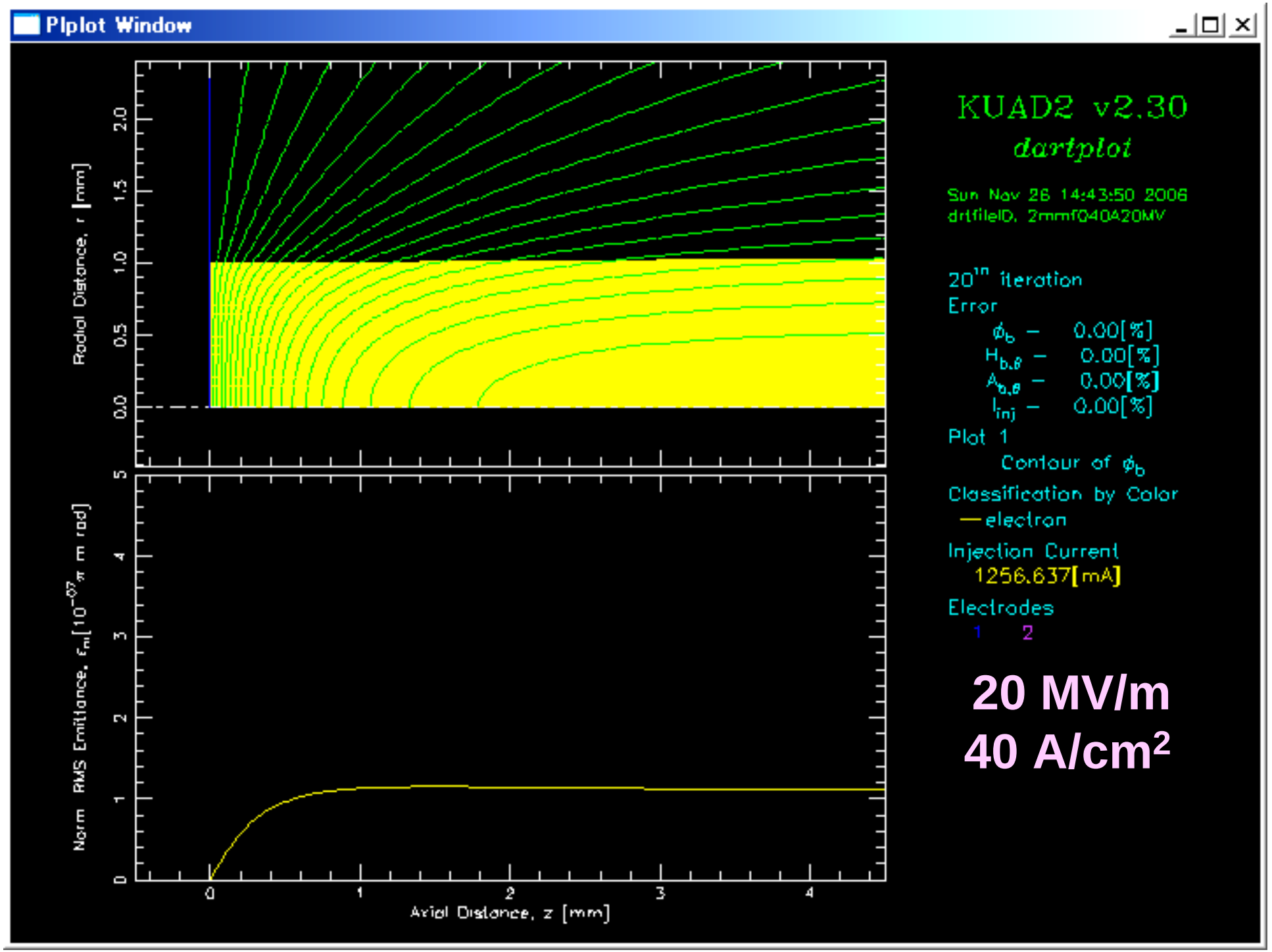

Plplot Window
Radial Distance, r [mm]
0.0
0.5
1.0
1.5
2.0
Norm RMS Emittance, ε_n[10^{-07} π m rad]
0
1
2
3
4
5
Axial Distance, z [mm]
KUAD2 v2.30
dartplot
Sun Nov 26 14:32:52 2006
drtfileID, 2mmfQ80420MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
2.513[A]
Electrodes
1 2
20 MV/m
80 A/cm²

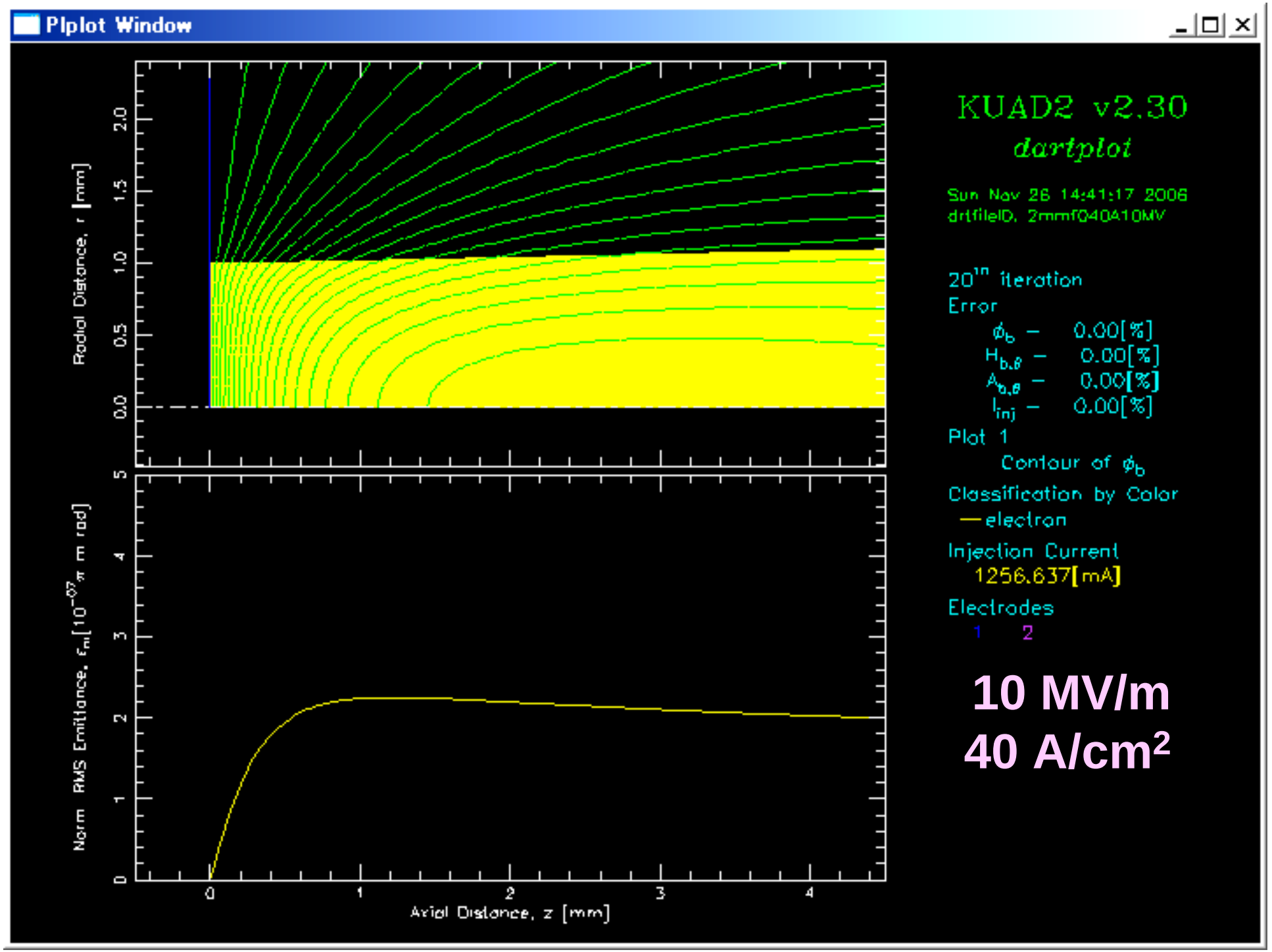

Plplot Window
Radial Distance, r [mm]
0.0
0.5
1.0
1.5
2.0
Norm RMS Emittance, ε_n[10^{-07} π m rad]
0
1
2
3
4
5
0
1
2
3
4
Axial Distance, z [mm]
KUAD2 v2.30
dartplot
Sun Nov 26 14:35:10 2006
drtfileID, 2mmf160420MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
5.027[A]
Electrodes
1 2
20 MV/m
160 A/cm²

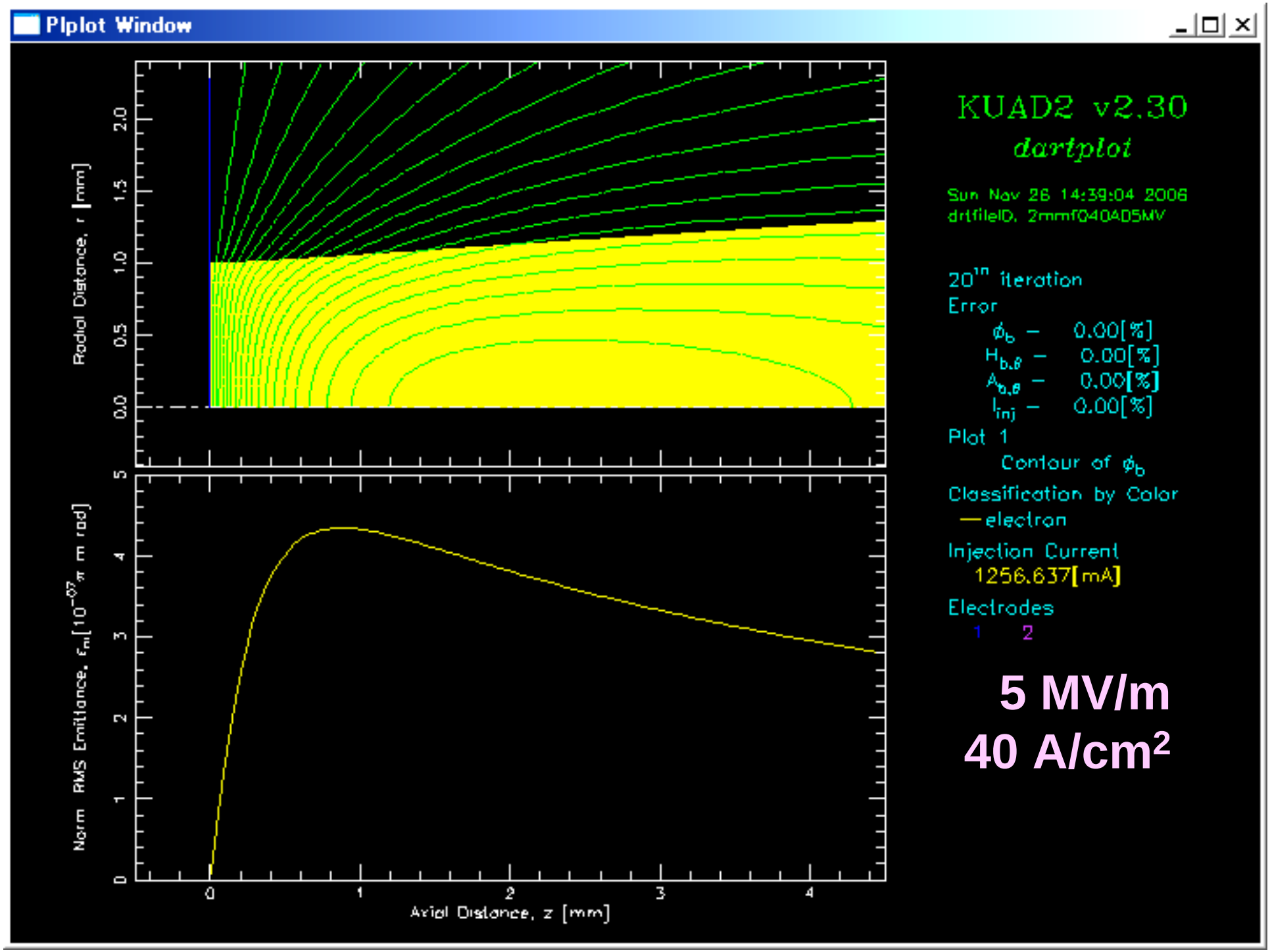
40 A/cm^2
5, 10, 20, 40, 80 MV/m


Plplot Window
Radial Distance, r [mm]
0.0
0.5
1.0
1.5
2.0
Norm RMS Emittance, ε_n[10^{-07} m rad]
0
1
2
3
4
5
Axial Distance, z [mm]
0
1
2
3
4
KUAD2 v2.30
dartplot
Sun Nov 26 14:48:51 2006
drtfileID, 2mmf040460MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
80 MV/m
40 A/cm²


Plplot Window
Radial Distance, r [mm]
0.0
0.5
1.0
1.5
2.0
Norm RMS Emittance, ε_n[10^{-07} m rad]
0
1
2
3
4
5
0
1
2
3
4
Axial Distance, z [mm]
KUAD2 v2.30
dartplot
Sun Nov 26 14:46:30 2006
drtfileID, 2mmf040440MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
40 MV/m
40 A/cm²


Plplot Window
Radial Distance, r [mm]
0.0
0.5
1.0
1.5
2.0
Norm RMS Emittance, ε_n[10^{-07} m rad]
0
1
2
3
4
5
0
1
2
3
4
Axial Distance, z [mm]
KUAD2 v2.30
dartplot
Sun Nov 26 14:43:50 2006
drtfileID, 2mmf040420MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
20 MV/m
40 A/cm²


Plplot Window
Radial Distance, r [mm]
0.0
0.5
1.0
1.5
2.0
Norm RMS Emittance, ε_n[10^{-07} π m rad]
0
1
2
3
4
5
Axial Distance, z [mm]
0
1
2
3
4
KUAD2 v2.30
dartplot
Sun Nov 26 14:41:17 2006
drtfileID, 2mmf040410MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
10 MV/m
40 A/cm²


Plplot Window
Radial Distance, r [mm]
0.0
0.5
1.0
1.5
2.0
Norm RMS Emittance, $\varepsilon_{n,i}$ [10^{-07} π m rad]
0
1
2
3
4
5
Axial Distance, z [mm]
KUAD2 v2.30
dartplot
Sun Nov 26 14:39:04 2006
drtfileID, 2mmf040405MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
5 MV/m
40 A/cm²

norm. rms r-emittance @ z = 1 mm

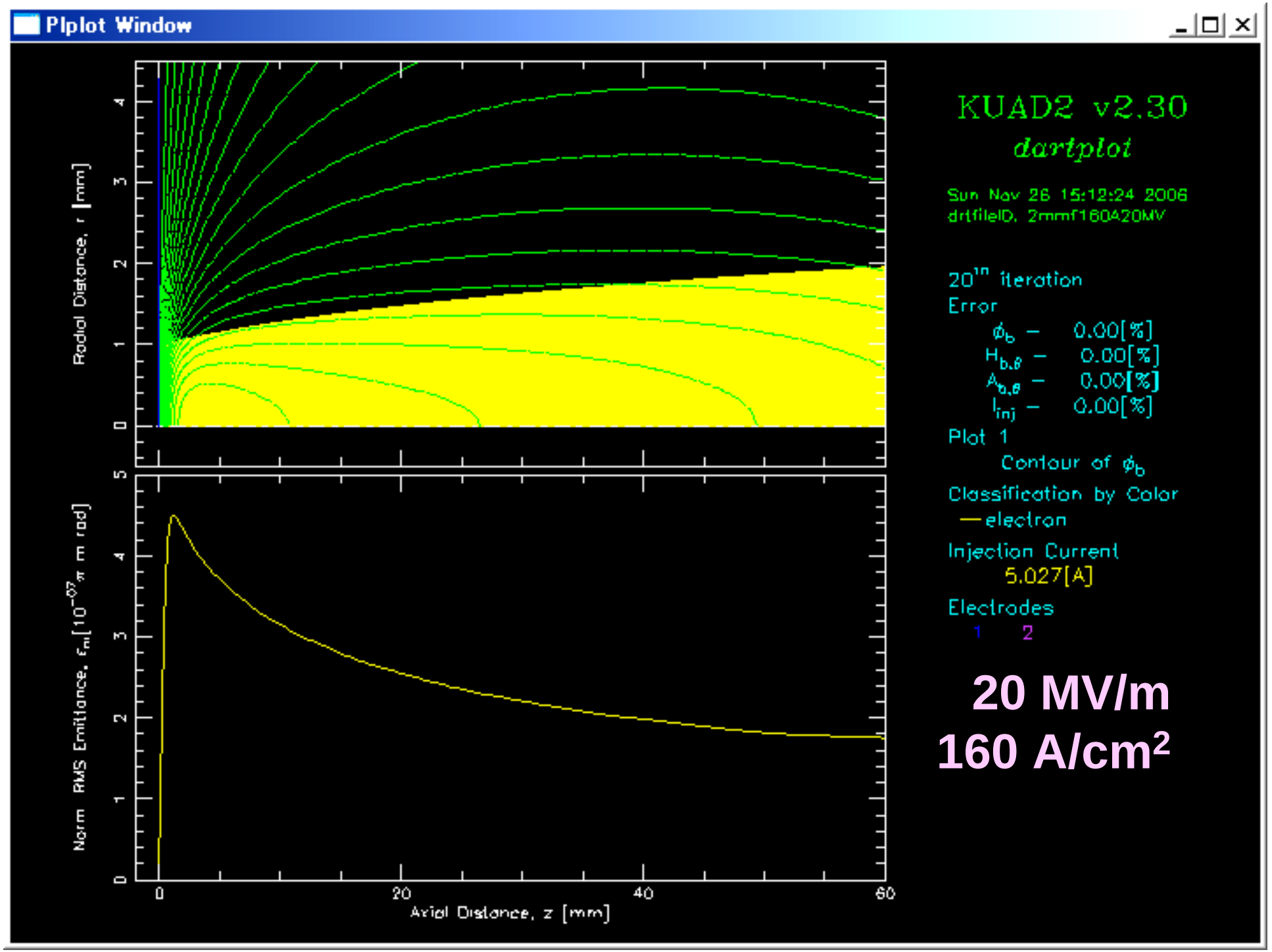
[π mm mrad]

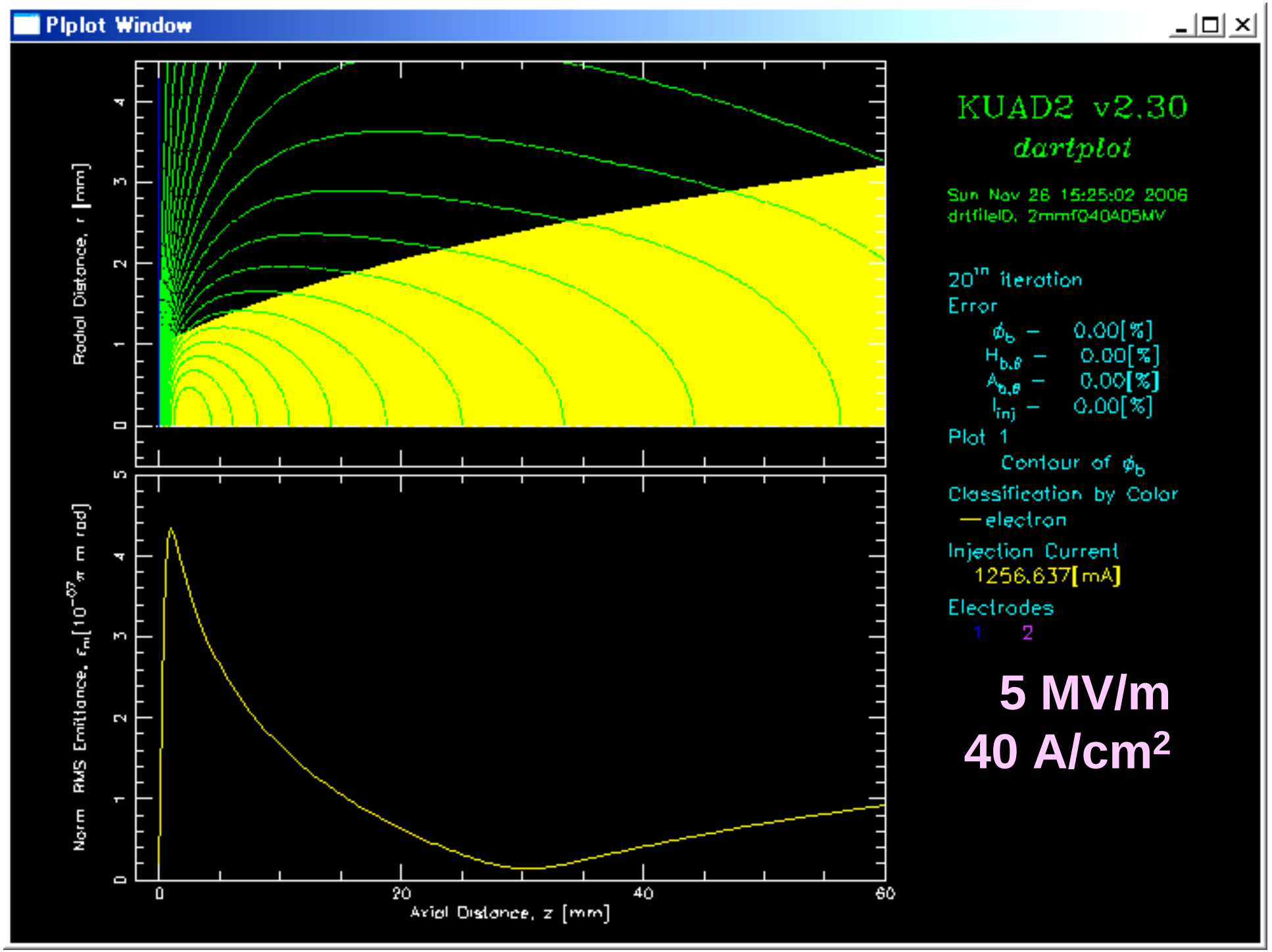
	10 A/cm^2	20	40	80	160
05 MV/m	0.11	0.22	0.43	S.C.L.	S.C.L.
10	0.056	0.11	0.22	0.44	0.82
20	0.028	0.057	0.11	0.23	0.45
40	0.014	0.029	0.057	0.11	0.23
80	0.0074	0.015	0.029	0.059	0.12

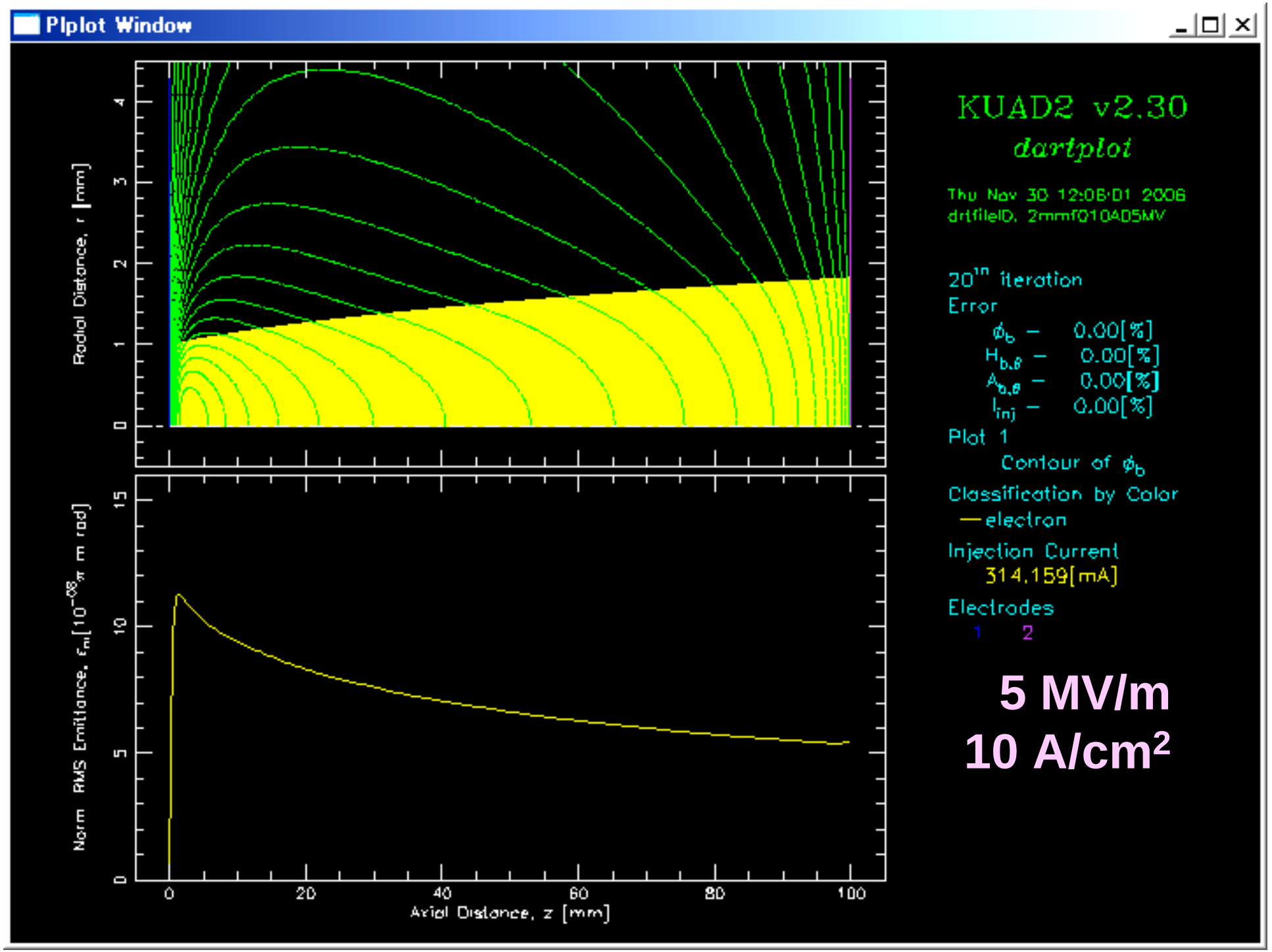
160 A/cm^2, 2 mmϕ, 20 psec → 0.1 nC

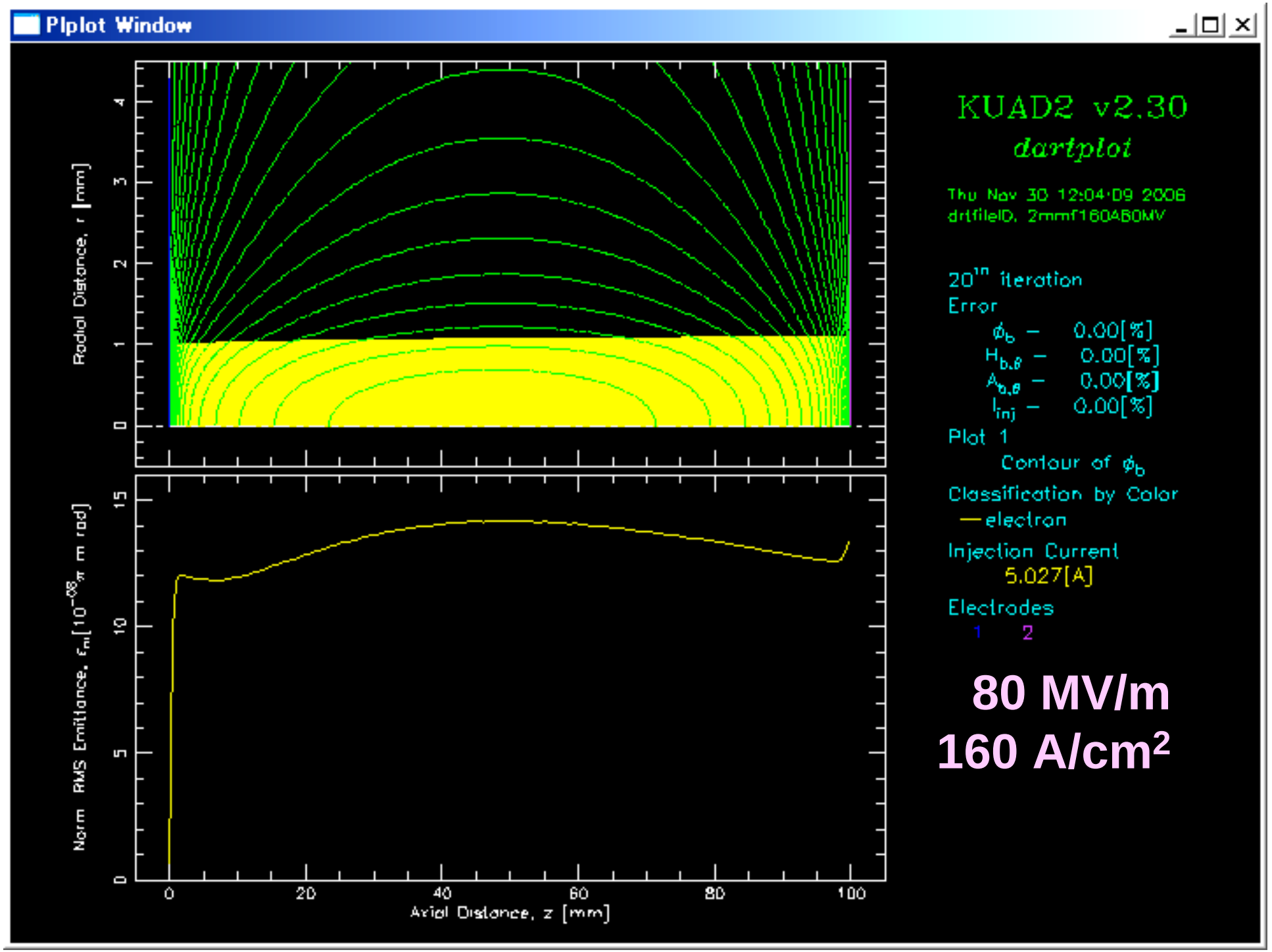
陰極近傍（z<1 mm）でエミッタンスが急激に増大

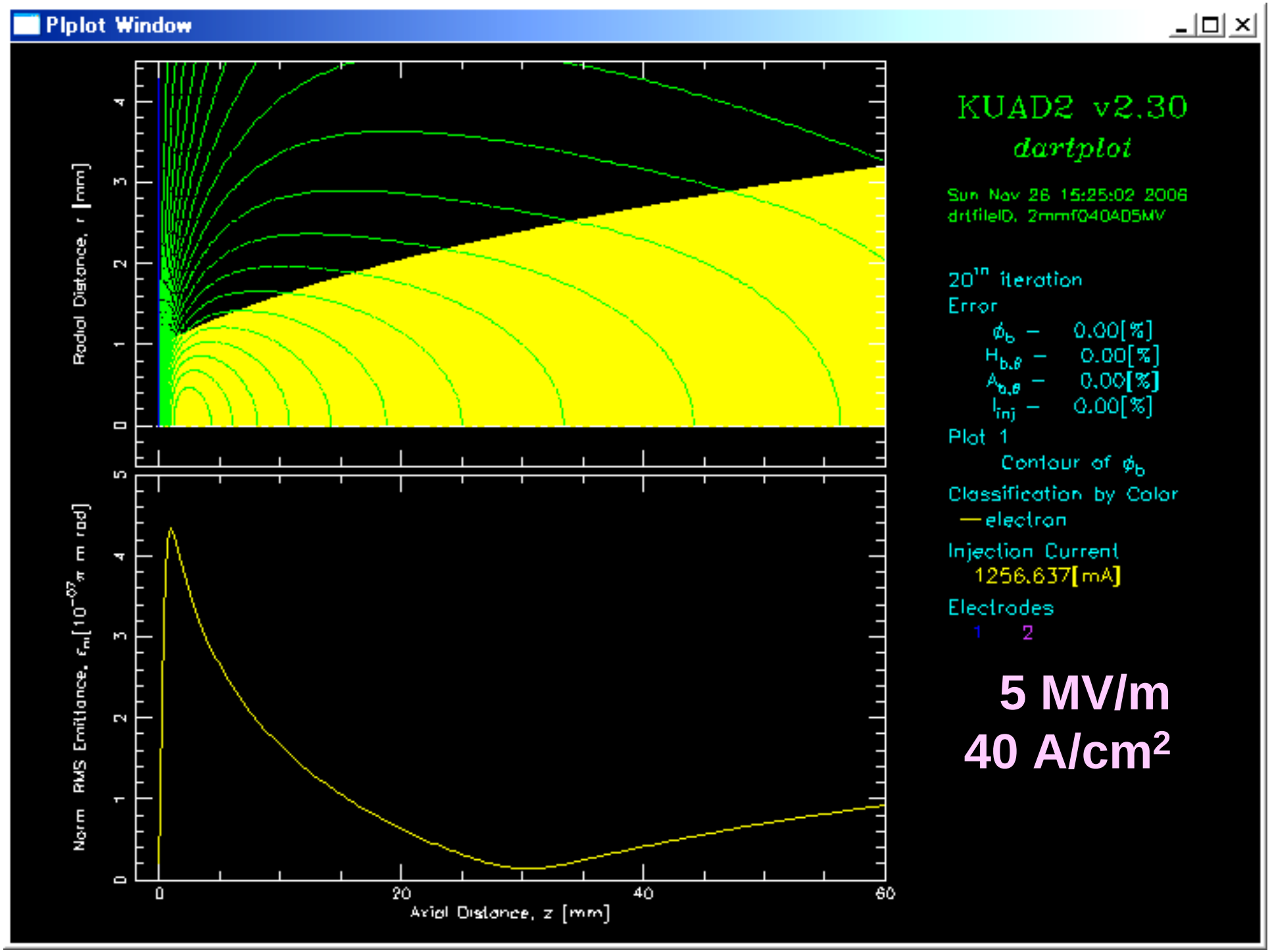
（エミッタンス@z=1mm）∝（電流密度）/（電界）

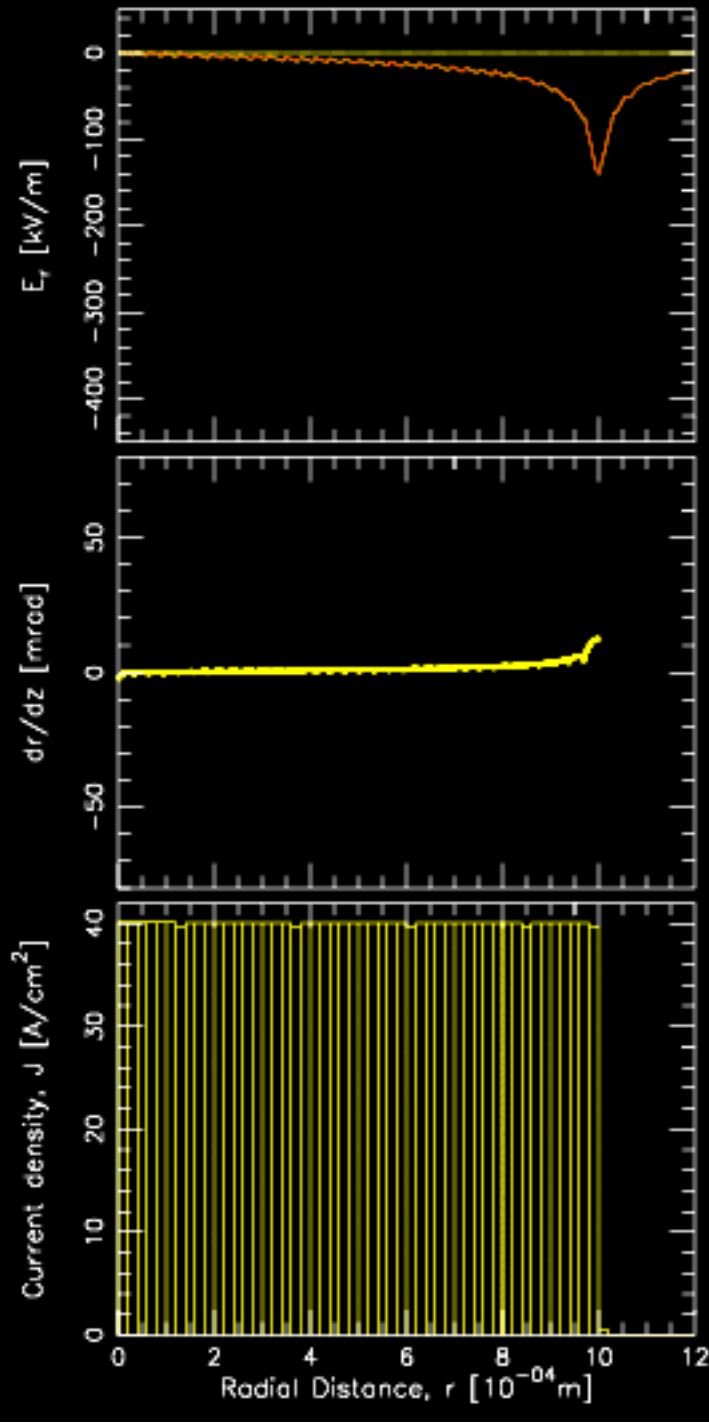

Plplot Window
Radial Distance, r [mm]
Norm RMS Emittance, ε_n[10^{-07} m rad]
Axial Distance, z [mm]
0
20
40
60
KUAD2 v2.30
dartplot
Sun Nov 26 15:12:24 2006
drtfileID, 2mmf160420MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
5.027[A]
Electrodes
1 2
20 MV/m
160 A/cm²


Plplot Window
Radial Distance, r [mm]
Norm RMS Emittance, $\varepsilon_{n,i}$ [10^{-07} π m rad]
Axial Distance, z [mm]
0
20
40
60
KUAD2 v2.30
dartplot
Sun Nov 26 15:25:02 2006
drtfileID, 2mmf040405MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
5 MV/m
40 A/cm²


Plplot Window
Radial Distance, r [mm]
Norm RMS Emittance, $\varepsilon_{n,i}$[10^{-08}π m rad]
Axial Distance, z [mm]
KUAD2 v2.30
dartplot
Thu Nov 30 12:08:01 2006
drtfileID, 2mmf0104D5MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
314.159[mA]
Electrodes
1 2
5 MV/m
10 A/cm²


Plplot Window
Radial Distance, r [mm]
Norm RMS Emittance, $\varepsilon_{n,i}$[10^{-08}π m rad]
Axial Distance, z [mm]
KUAD2 v2.30
dartplot
Thu Nov 30 12:04:09 2006
drtfileID, 2mmf160A60MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
5.027[A]
Electrodes
1 2
80 MV/m
160 A/cm²


Plplot Window
Radial Distance, r [mm]
Norm RMS Emittance, $\varepsilon_{n,i}$ [10^{-07} π m rad]
Axial Distance, z [mm]
0
20
40
60
KUAD2 v2.30
dartplot
Sun Nov 26 15:25:02 2006
drtfileID, 2mmf040405MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
5 MV/m
40 A/cm²



maximum $E_{0,r}$
0.022 [kV/m]

minimum $E_{0,r}$
−0.001 [kV/m]

maximum $E_{b,r}$
1.489 [kV/m]

minimum $E_{b,r}$
−139.526 [kV/m]

maximum dr/dz
12.411 [mrad]

minimum dr/dz
−2.439 [mrad]

$\sigma_{r'}$
3.491 [mrad]

$\epsilon_{n,r}$
2.421 [$10^{-08}\pi$ m rad]

maximum J
40.078 [A/cm^2]

minimum J
0.000 [A/cm^2]

KUAD2 v2.30

dartprof

Sun Nov 26 17:08:50 2006
drtfileID: 2mmf040AD5MV

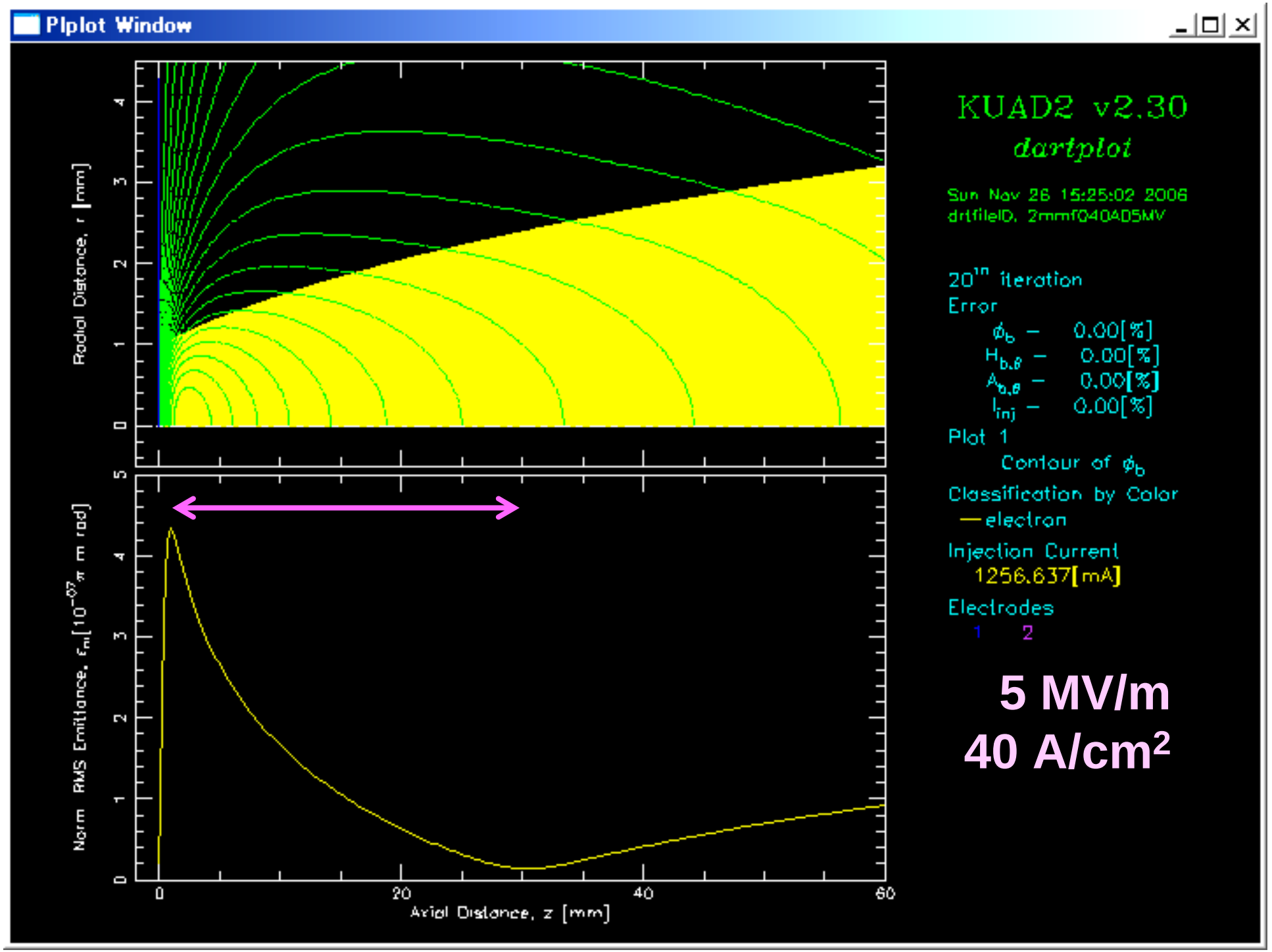
Monitor No. 1
electron
forward
z = 0.020[mm]

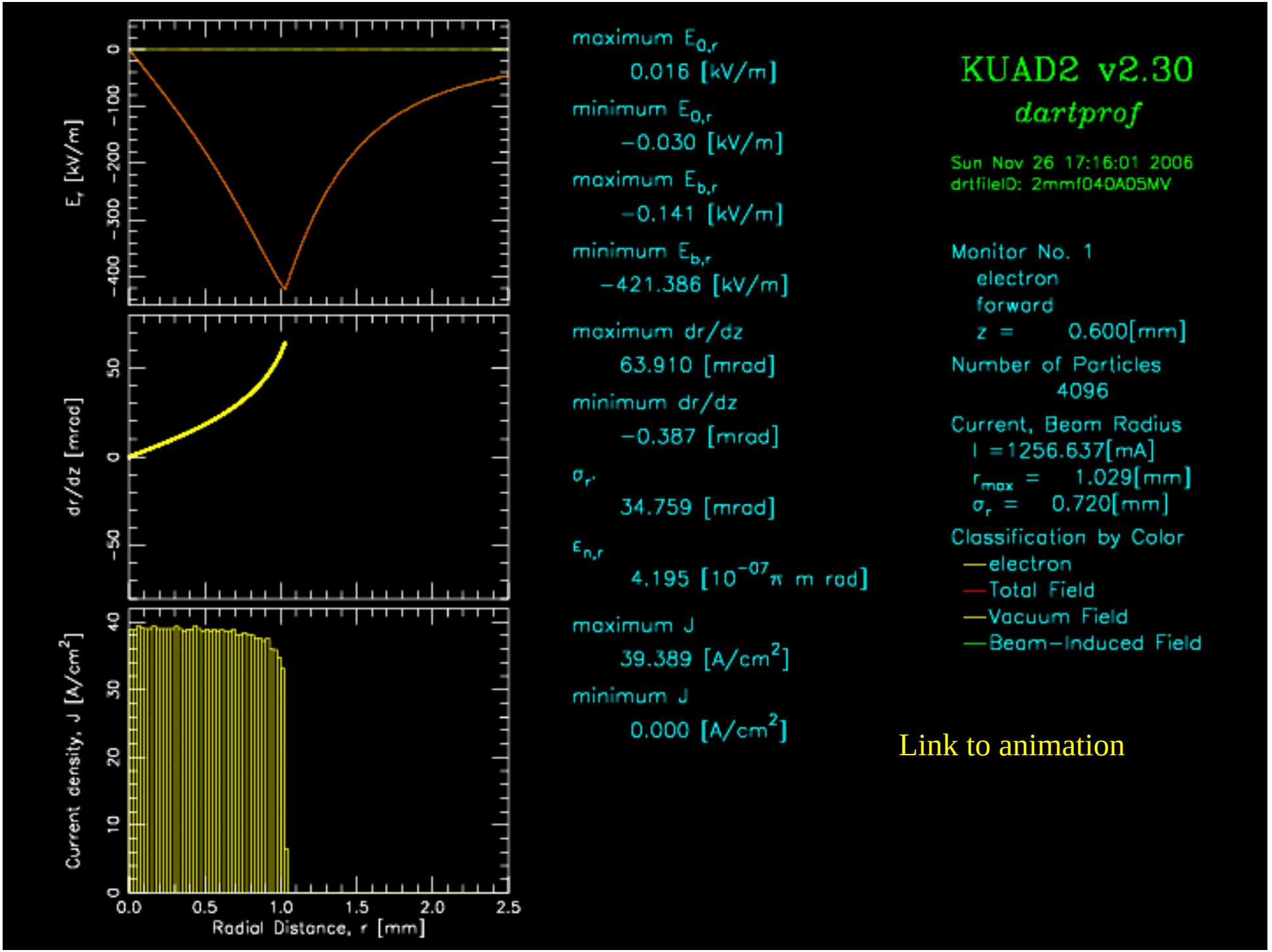
Number of Particles
4096

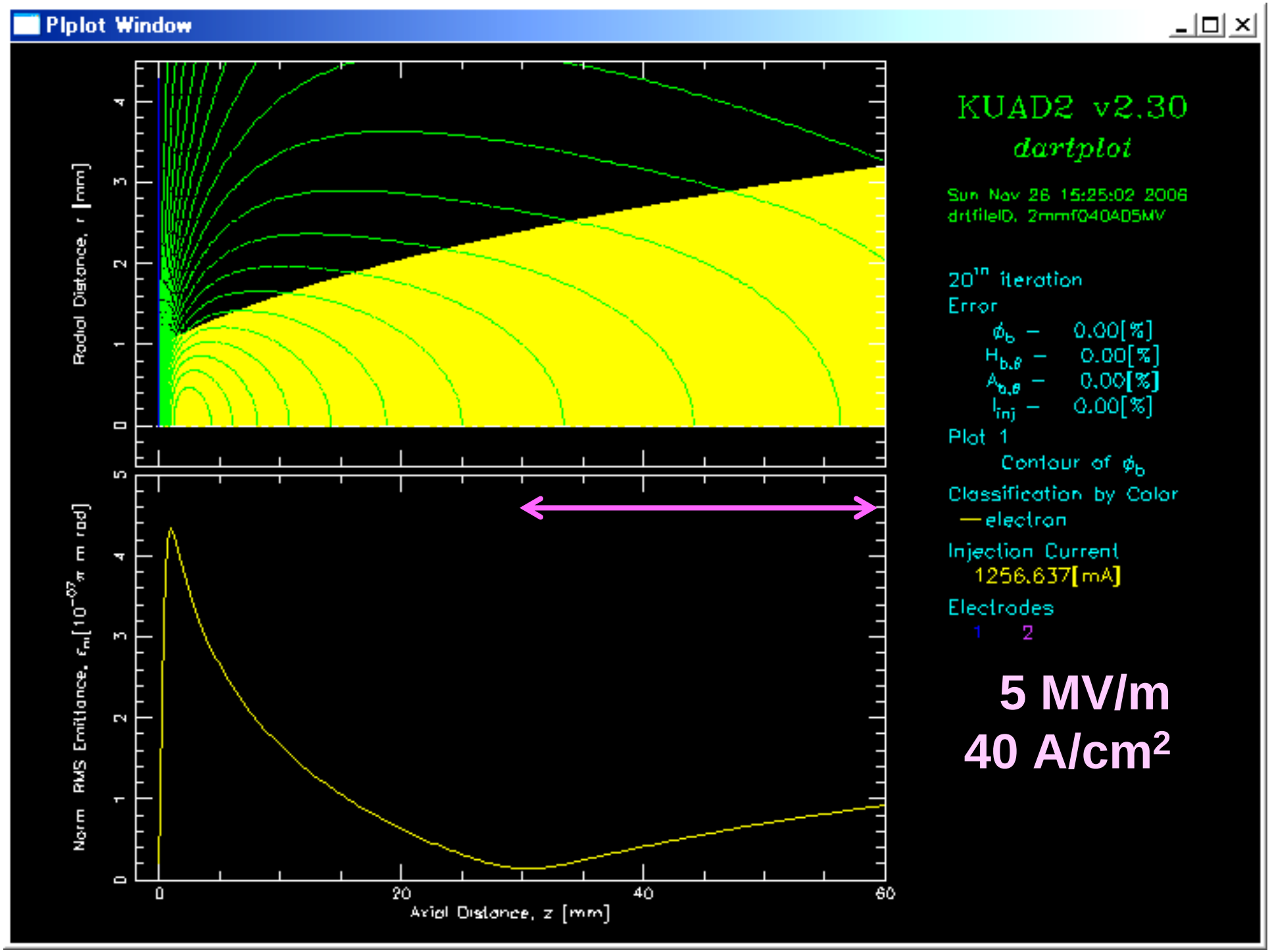
Current, Beam Radius
I =1256.637[mA]
r_{max} = 10.000[10^{-04}
σ_r = 7.071[10^{-04}m

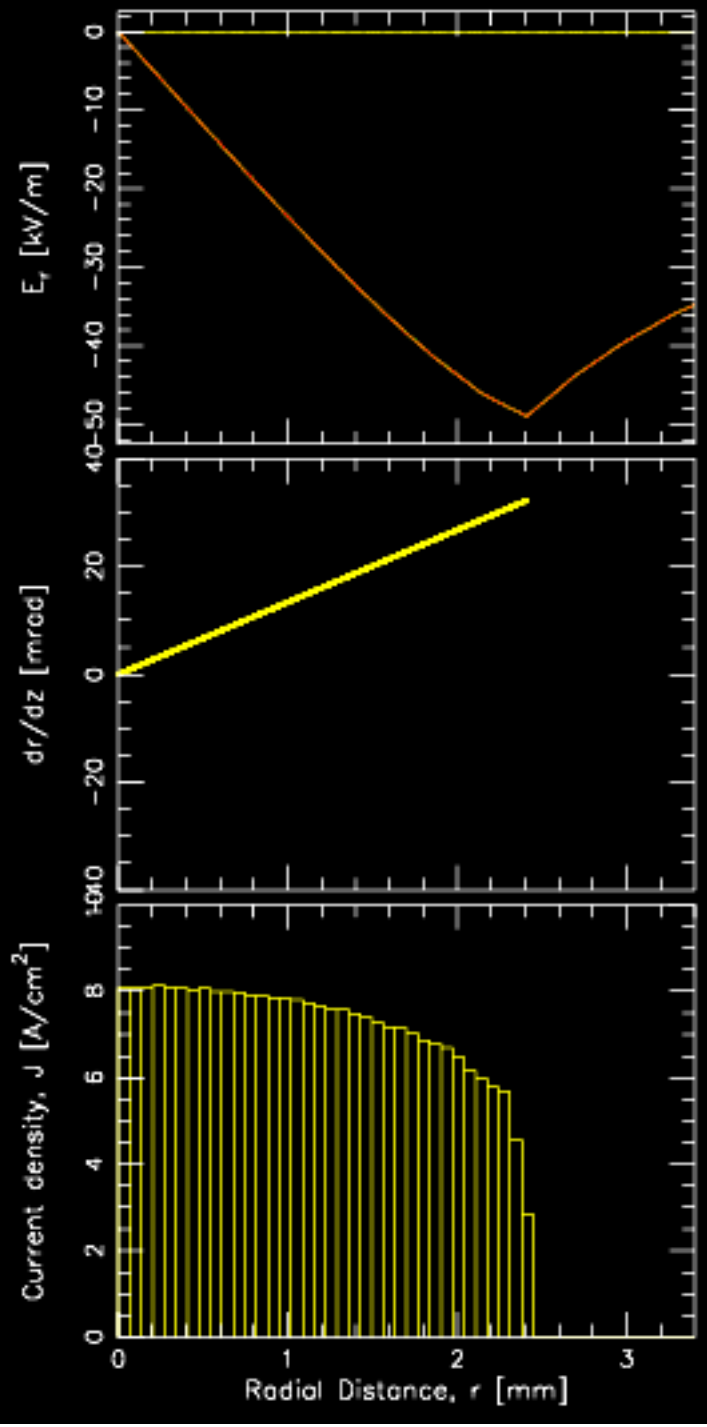
Classification by Color
—electron
—Total Field
—Vacuum Field
—Beam−Induced Field

Link to animation


Plplot Window
Radial Distance, r [mm]
Norm RMS Emittance, ε_n[10^{-07} m rad]
Axial Distance, z [mm]
0
20
40
60
KUAD2 v2.30
dartplot
Sun Nov 26 15:25:02 2006
drtfileID, 2mmf040405MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
5 MV/m
40 A/cm²


E_r [kV/m]
0
−100
−200
−300
−400
dr/dz [mrad]
50
0
−50
Current density, J [A/cm^2]
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
Radial Distance, r [mm]
maximum $E_{0,r}$
0.016 [kV/m]
minimum $E_{0,r}$
−0.030 [kV/m]
maximum $E_{b,r}$
−0.141 [kV/m]
minimum $E_{b,r}$
−421.386 [kV/m]
maximum dr/dz
63.910 [mrad]
minimum dr/dz
−0.387 [mrad]
$\sigma_{r'}$
34.759 [mrad]
$\epsilon_{n,r}$
4.195 [$10^{-07}\pi$ m rad]
maximum J
39.389 [A/cm^2]
minimum J
0.000 [A/cm^2]
KUAD2 v2.30
dartprof
Sun Nov 26 17:16:01 2006
drtfileID: 2mmf040AD5MV
Monitor No. 1
electron
forward
z = 0.600[mm]
Number of Particles
4096
Current, Beam Radius
I =1256.637[mA]
r_{max} = 1.029[mm]
σ_r = 0.720[mm]
Classification by Color
—electron
—Total Field
—Vacuum Field
—Beam−Induced Field
Link to animation


Plplot Window
Radial Distance, r [mm]
Norm RMS Emittance, ε_n[10^{-07} m rad]
Axial Distance, z [mm]
0
20
40
60
KUAD2 v2.30
dartplot
Sun Nov 26 15:25:02 2006
drtfileID, 2mmf040405MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
5 MV/m
40 A/cm²



maximum $E_{0,r}$
0.022 [kV/m]
minimum $E_{0,r}$
−0.014 [kV/m]
maximum $E_{b,r}$
−0.040 [kV/m]
minimum $E_{b,r}$
−48.940 [kV/m]
maximum dr/dz
32.141 [mrad]
minimum dr/dz
0.005 [mrad]
$\sigma_{r'}$
21.973 [mrad]
$\epsilon_{n,r}$
13.668 [$10^{-09}\pi$ m rad]
maximum J
8.130 [A/cm^2]
minimum J
0.000 [A/cm^2]

KUAD2 v2.30

dartprof

Sun Nov 26 16:45:36 2006
drtfileID: 2mmf040AD5MV

Monitor No. 1
electron
forward
z = 30.600[mm]
Number of Particles
4096
Current, Beam Radius
I =1256.637[mA]
r_{max} = 2.409[mm]
σ_r = 1.642[mm]
Classification by Color
—electron
—Total Field
—Vacuum Field
—Beam−Induced Field

Link to animation

陰極近傍 (z<1 mm) の空間電荷効果で,

電流密度分布 が 一様ではなくなり. . .

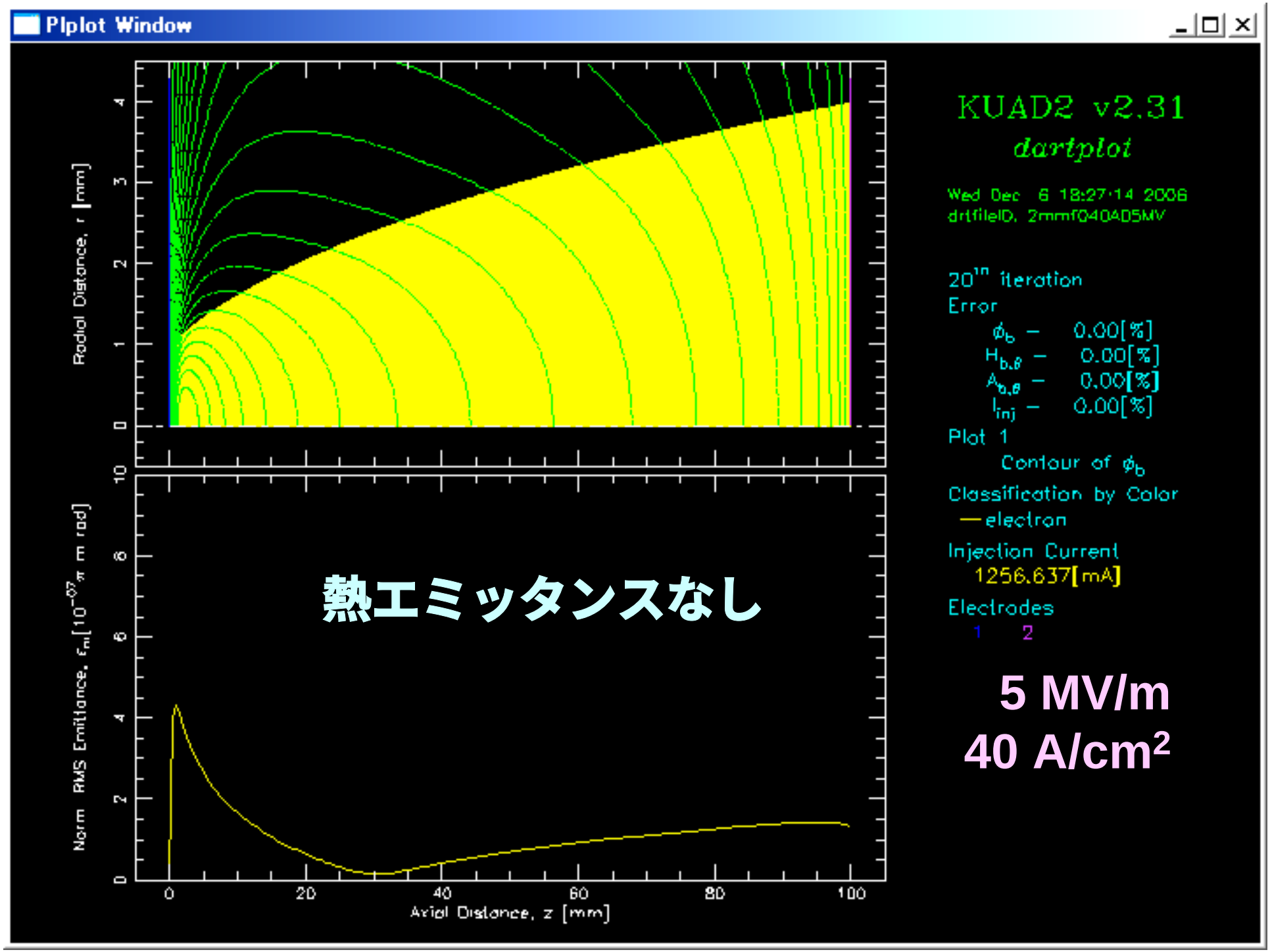
陰極を離れた後の エミッタンスの増減 に影響

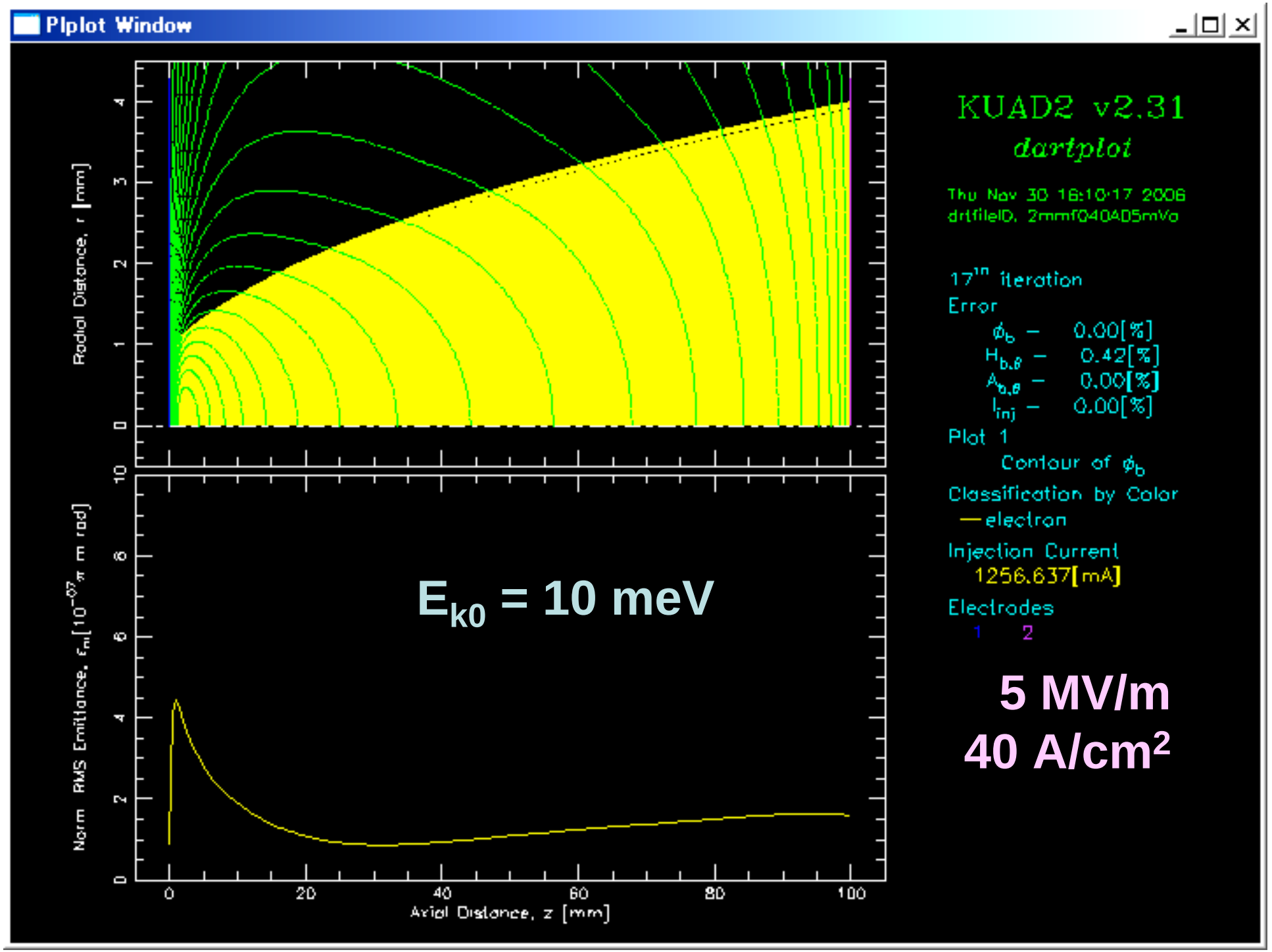
1. コードの概要

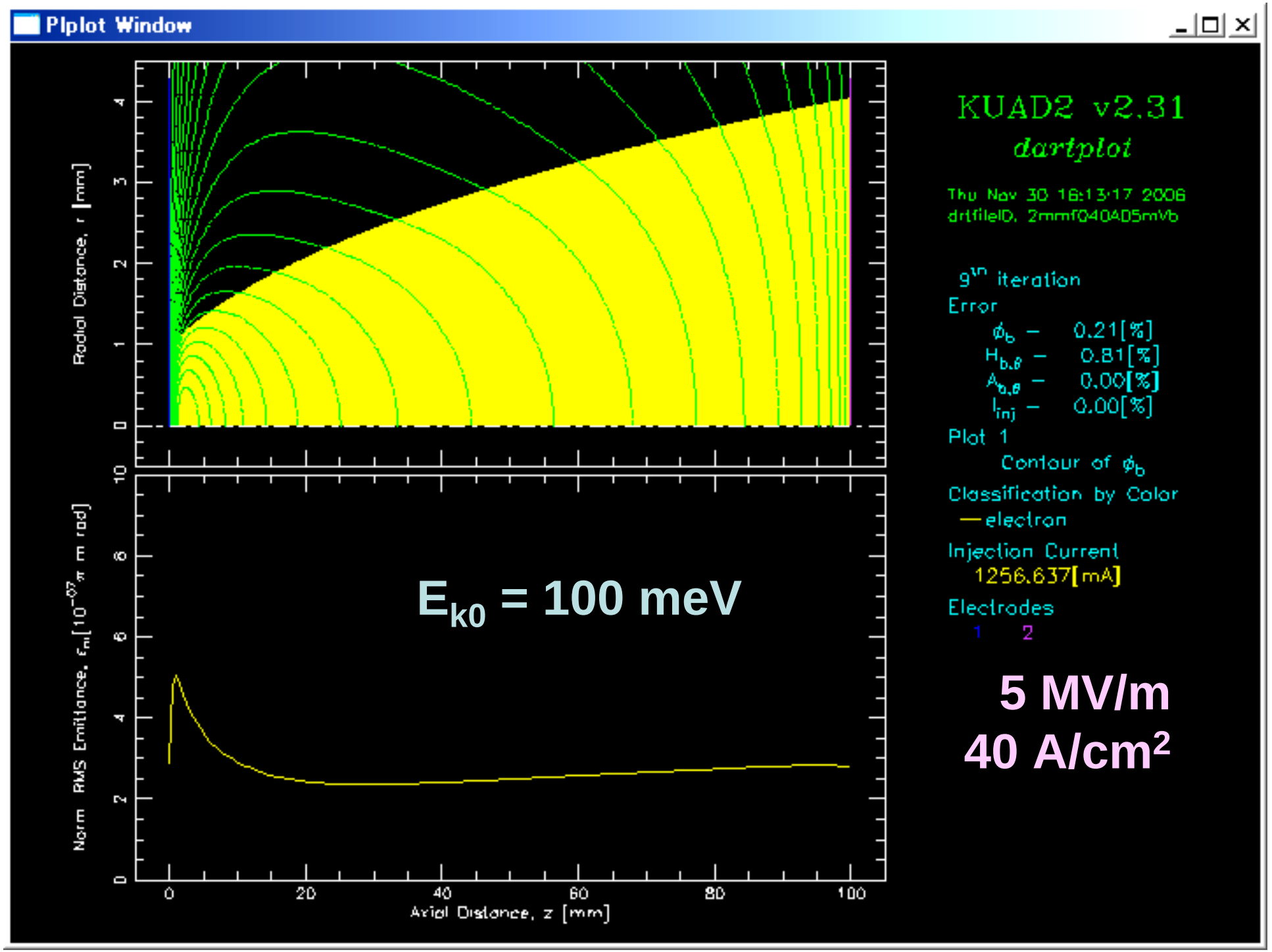
2. DCビームへの鏡像の影響

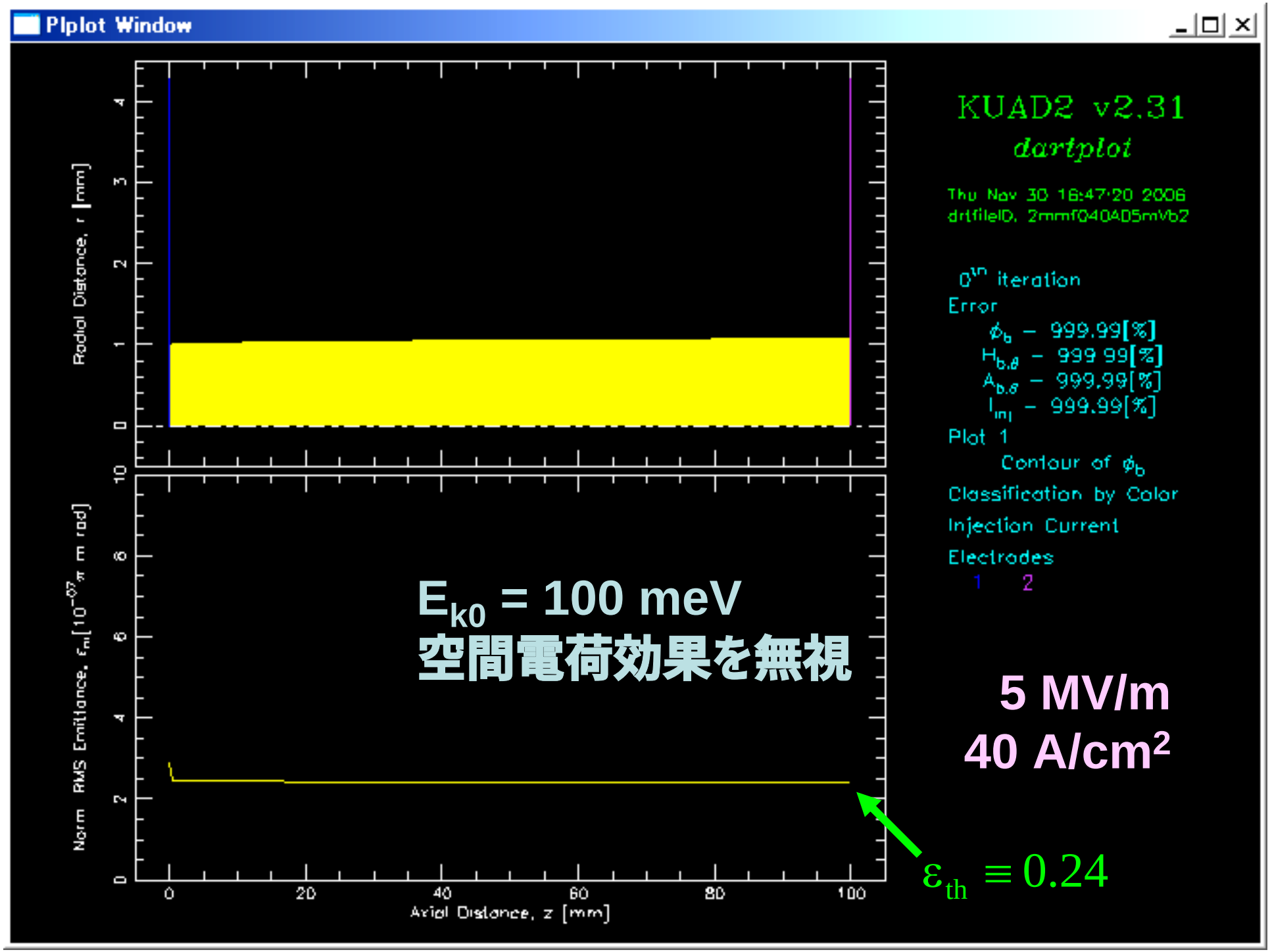
3. DCビームへの熱エミッタンスの影響

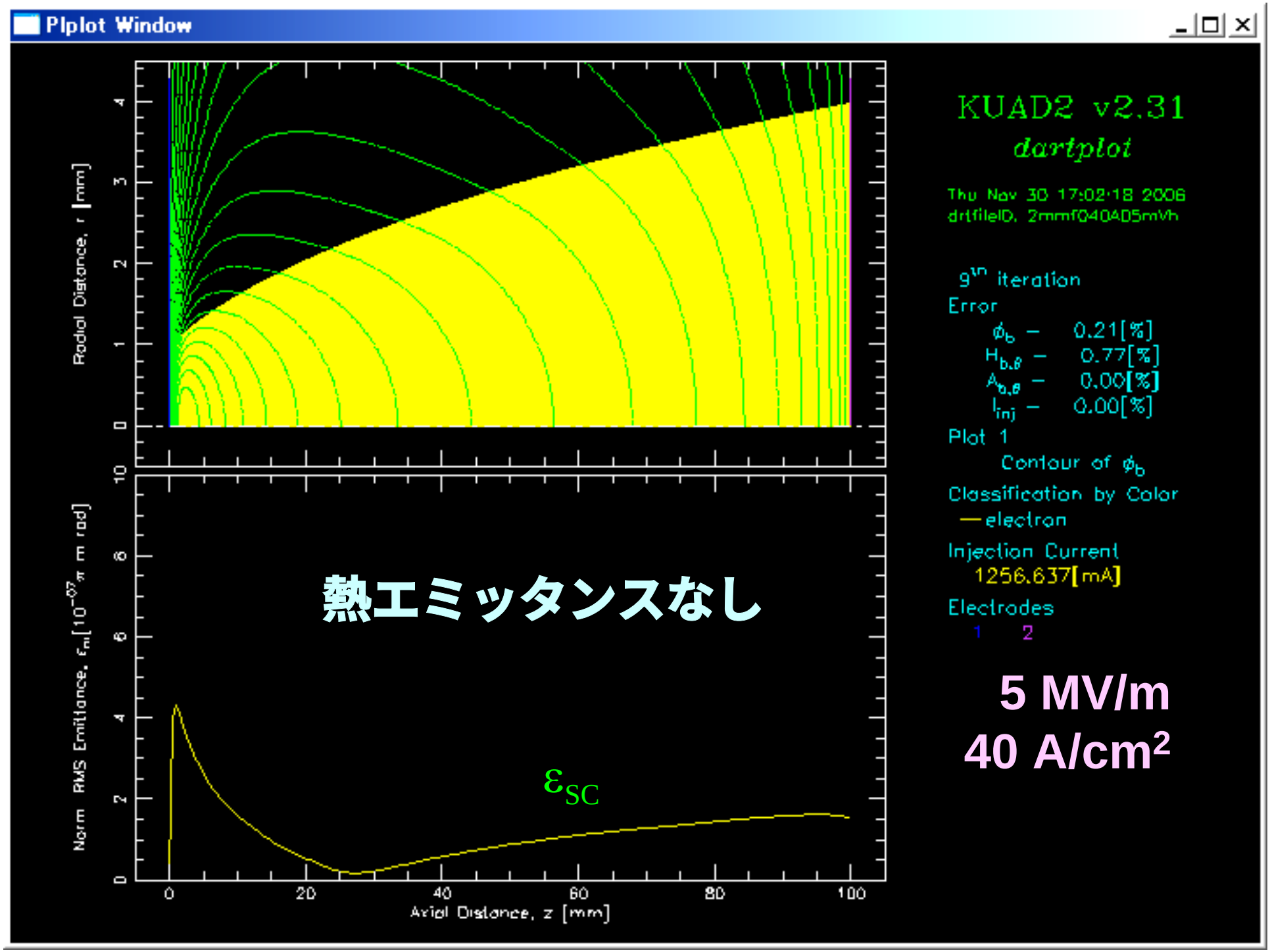
4. パルスビームへの鏡像の影響

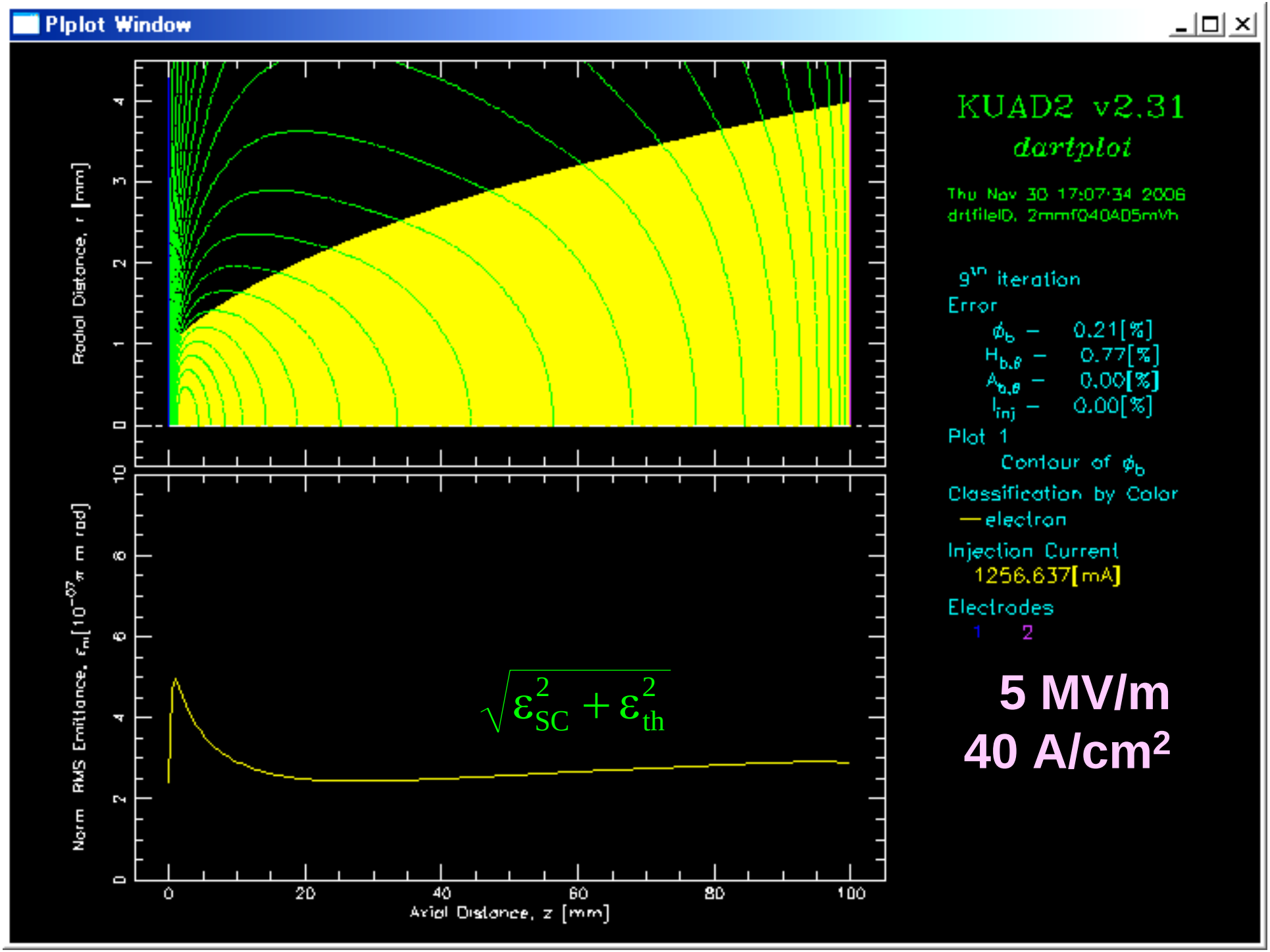

Plplot Window
Radial Distance, r [mm]
Norm RMS Emittance, ε_n[10^{-07}π m rad]
Axial Distance, z [mm]
0
20
40
60
80
100
KUAD2 v2.31
dartplot
Wed Dec 6 18:27:14 2006
drtfileID, 2mmf040405MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
熱エミッタンスなし
5 MV/m
40 A/cm²

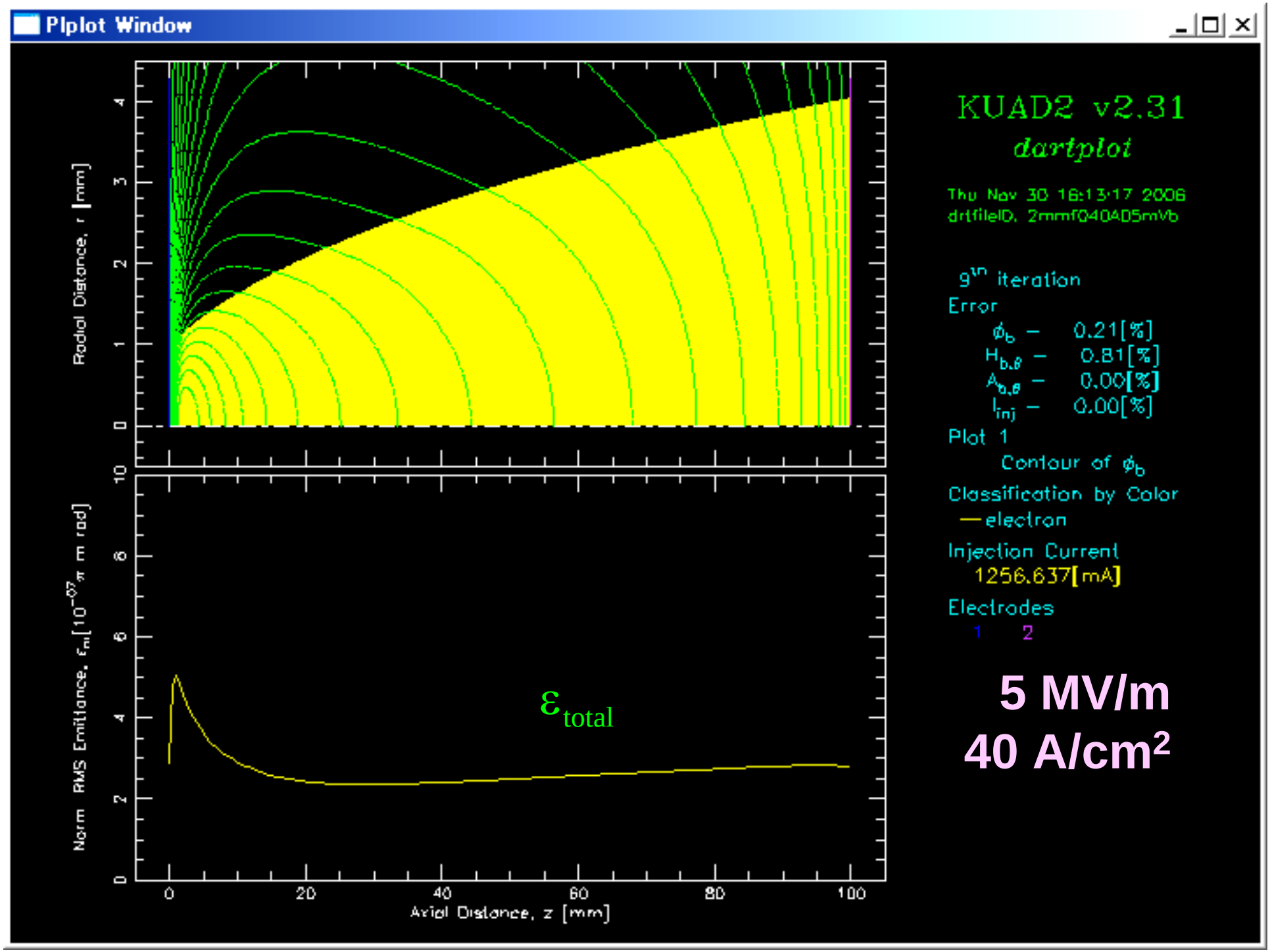

Plplot Window
Radial Distance, r [mm]
Norm RMS Emittance, ε_n[10^{-07} π m rad]
Axial Distance, z [mm]
E_{k0} = 10 meV
KUAD2 v2.31
dartplot
Thu Nov 30 16:10:17 2006
drtfileID, 2mmf040405mVo
17th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.42[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
5 MV/m
40 A/cm²


Plplot Window
KUAD2 v2.31
dartplot
Thu Nov 30 16:13:17 2006
drtfileID, 2mmf040405mVb
9th iteration
Error
ϕ_b – 0.21[%]
$H_{b,\theta}$ – 0.81[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
Radial Distance, r [mm]
Norm RMS Emittance, ε_n[10^{-07}π m rad]
Axial Distance, z [mm]
0
20
40
60
80
100
E_{k0} = 100 meV
5 MV/m
40 A/cm²


Plplot Window
Radial Distance, r [mm]
Norm RMS Emittance, ε_n[10^{-07}π m rad]
Axial Distance, z [mm]
0
20
40
60
80
100
KUAD2 v2.31
dartplot
Thu Nov 30 16:47:20 2006
drtfileID, 2mmf040405mVb2
0th iteration
Error
ϕ_b – 999.99[%]
$H_{b,\theta}$ – 999.99[%]
$A_{b,\sigma}$ – 999.99[%]
I_{inj} – 999.99[%]
Plot 1
Contour of ϕ_b
Classification by Color
Injection Current
Electrodes
1 2
E_{k0} = 100 meV
空間電荷効果を無視
5 MV/m
40 A/cm²
$\varepsilon_{th} \equiv 0.24$


Plplot Window
Radial Distance, r [mm]
Norm RMS Emittance, ε_n[10^{-07}π m rad]
Axial Distance, z [mm]
0
20
40
60
80
100
KUAD2 v2.31
dartplot
Thu Nov 30 17:02:18 2006
drtfileID, 2mmf040405mVh
9th iteration
Error
ϕ_b – 0.21[%]
$H_{b,\theta}$ – 0.77[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
熱エミッタンスなし
ε_{SC}
5 MV/m
40 A/cm²


Plplot Window
Radial Distance, r [mm]
Norm RMS Emittance, ε_n[10^{-07} π m rad]
Axial Distance, z [mm]
$\sqrt{\varepsilon_{SC}^2 + \varepsilon_{th}^2}$
KUAD2 v2.31
dartplot
Thu Nov 30 17:07:34 2006
drtfileID, 2mmf040405mVh
9th iteration
Error
ϕ_b – 0.21[%]
$H_{b,\theta}$ – 0.77[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
5 MV/m
40 A/cm²


Plplot Window
Radial Distance, r [mm]
Norm RMS Emittance, ε_n[10^{-07} π m rad]
Axial Distance, z [mm]
ε_{total}
KUAD2 v2.31
dartplot
Thu Nov 30 16:13:17 2006
drtfileID, 2mmf040405mVb
g^{th} iteration
Error
ϕ_b – 0.21[%]
$H_{b,\theta}$ – 0.81[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
1256.637[mA]
Electrodes
1 2
5 MV/m
40 A/cm²

$$\varepsilon_{\mathrm{total}}^2 = \varepsilon_{\mathrm{th}}^2 + \varepsilon_{\mathrm{SC}}^2$$ は成り立っている

1. コードの概要

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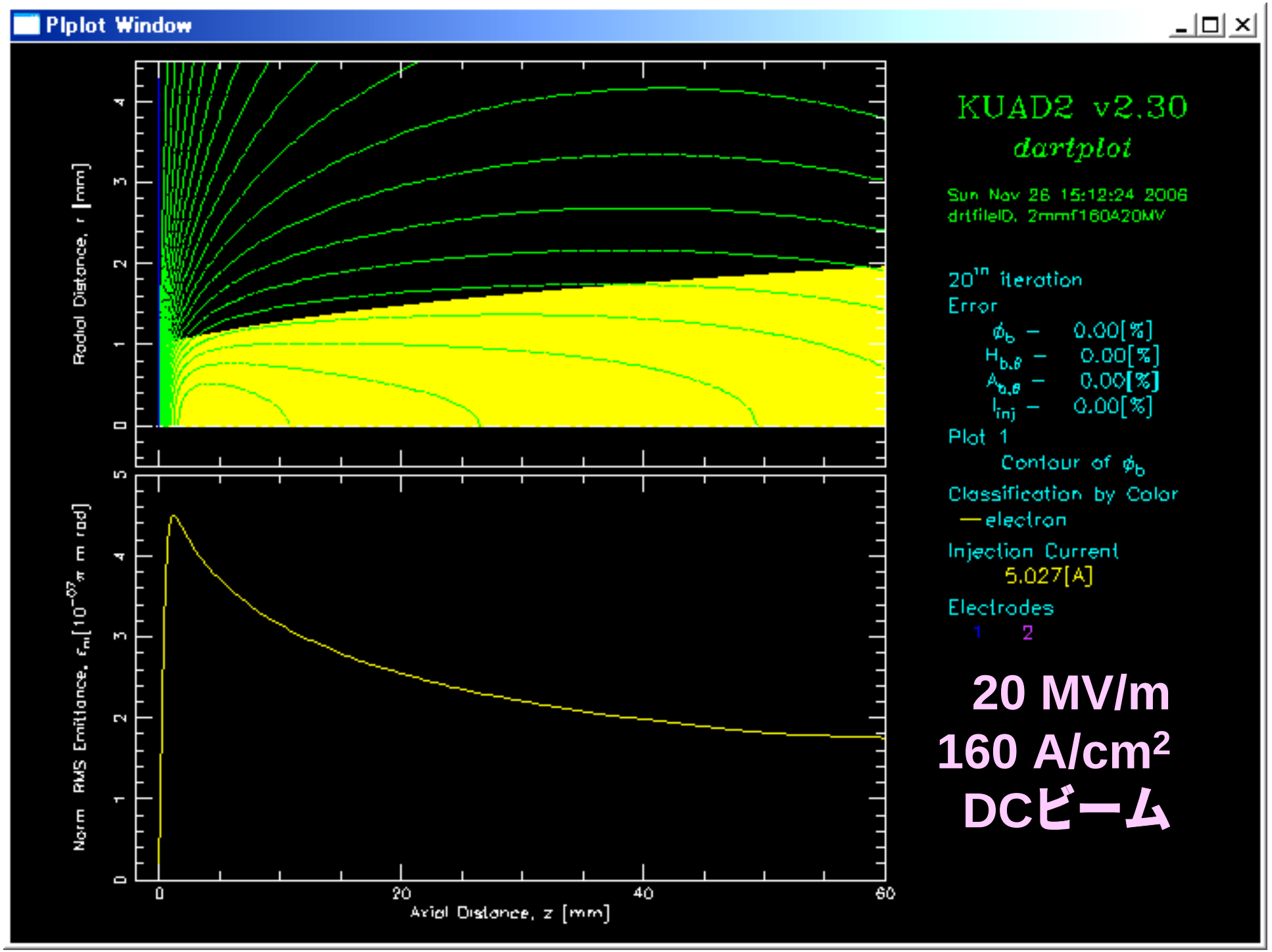
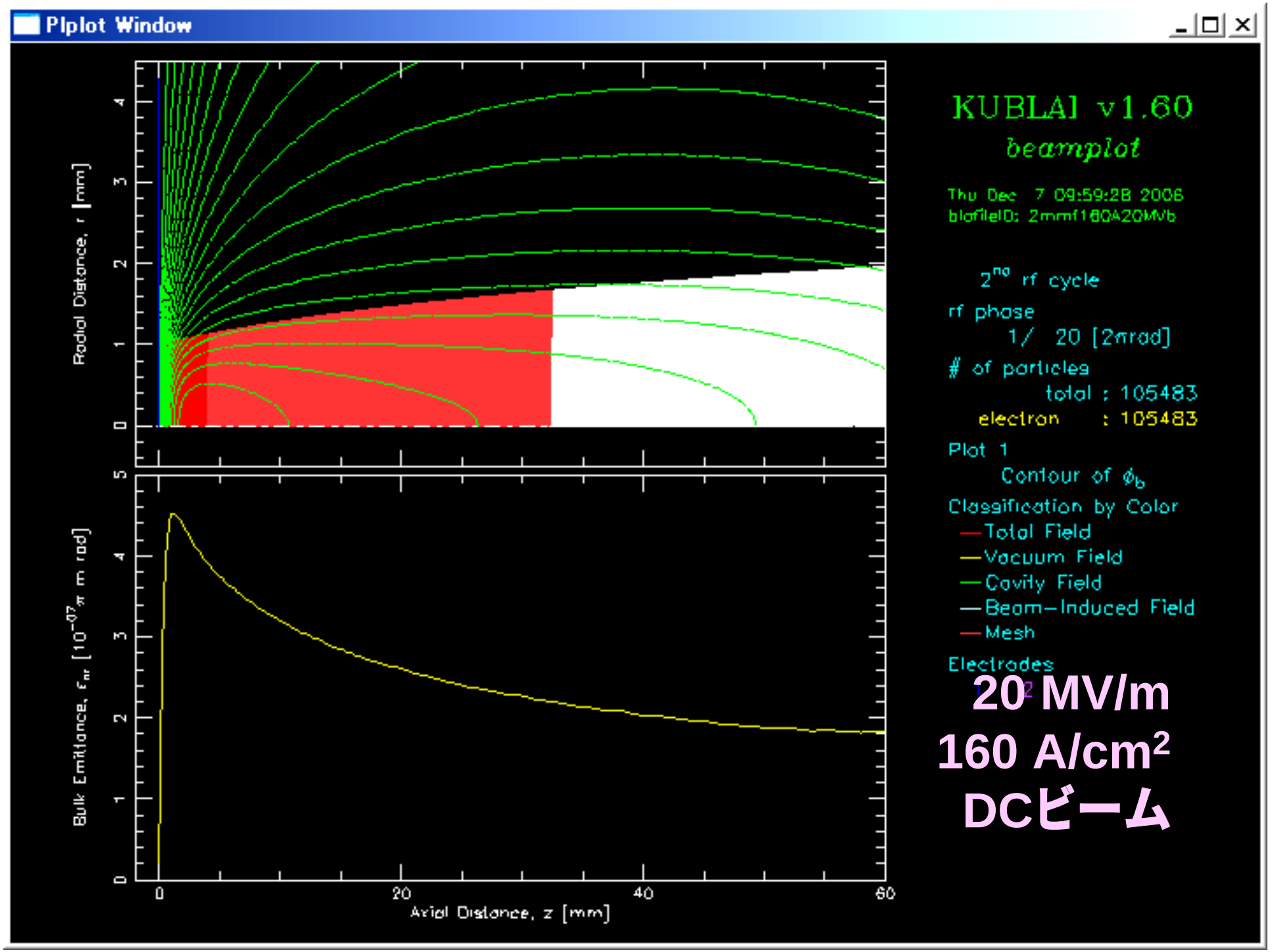
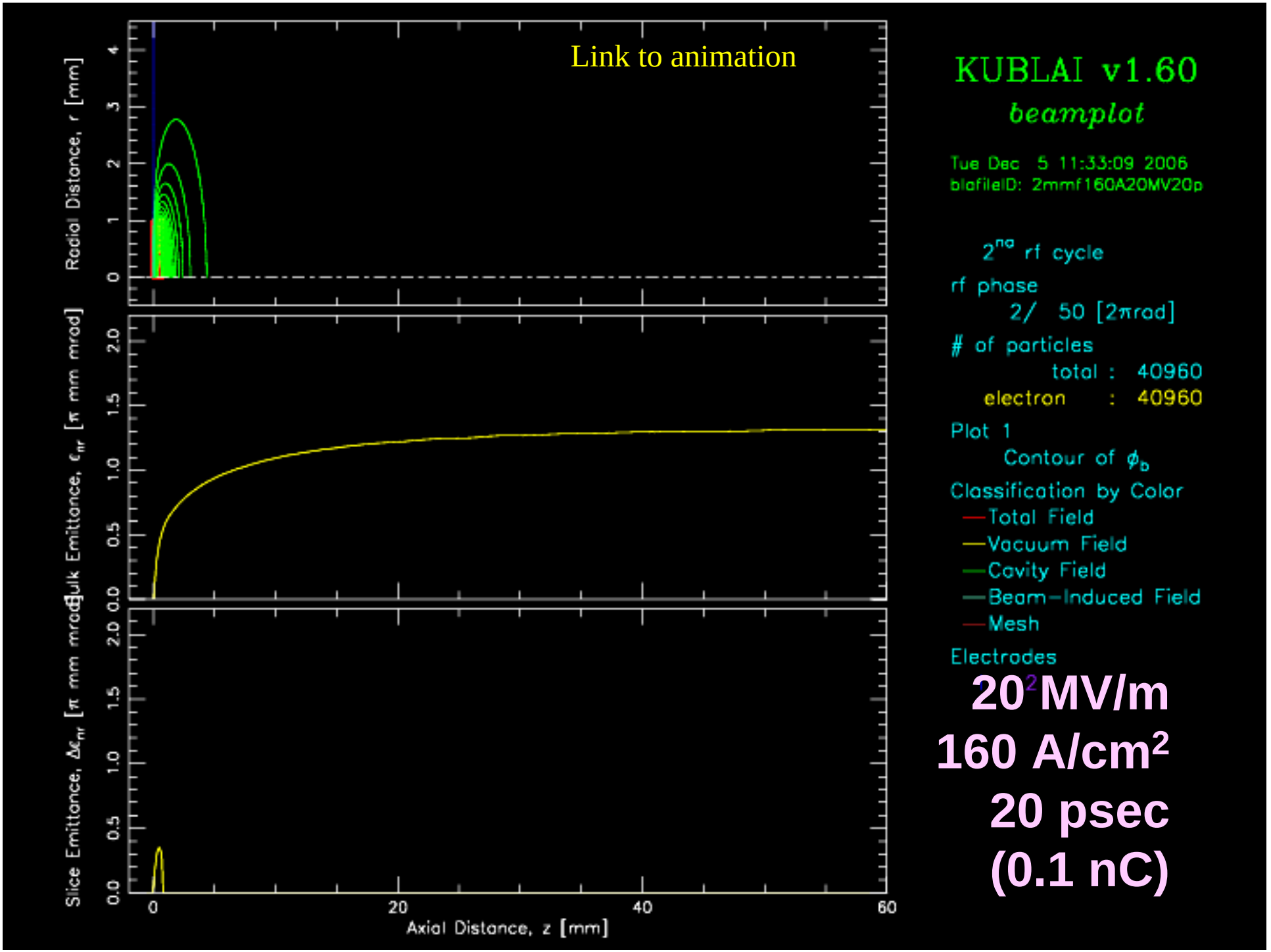
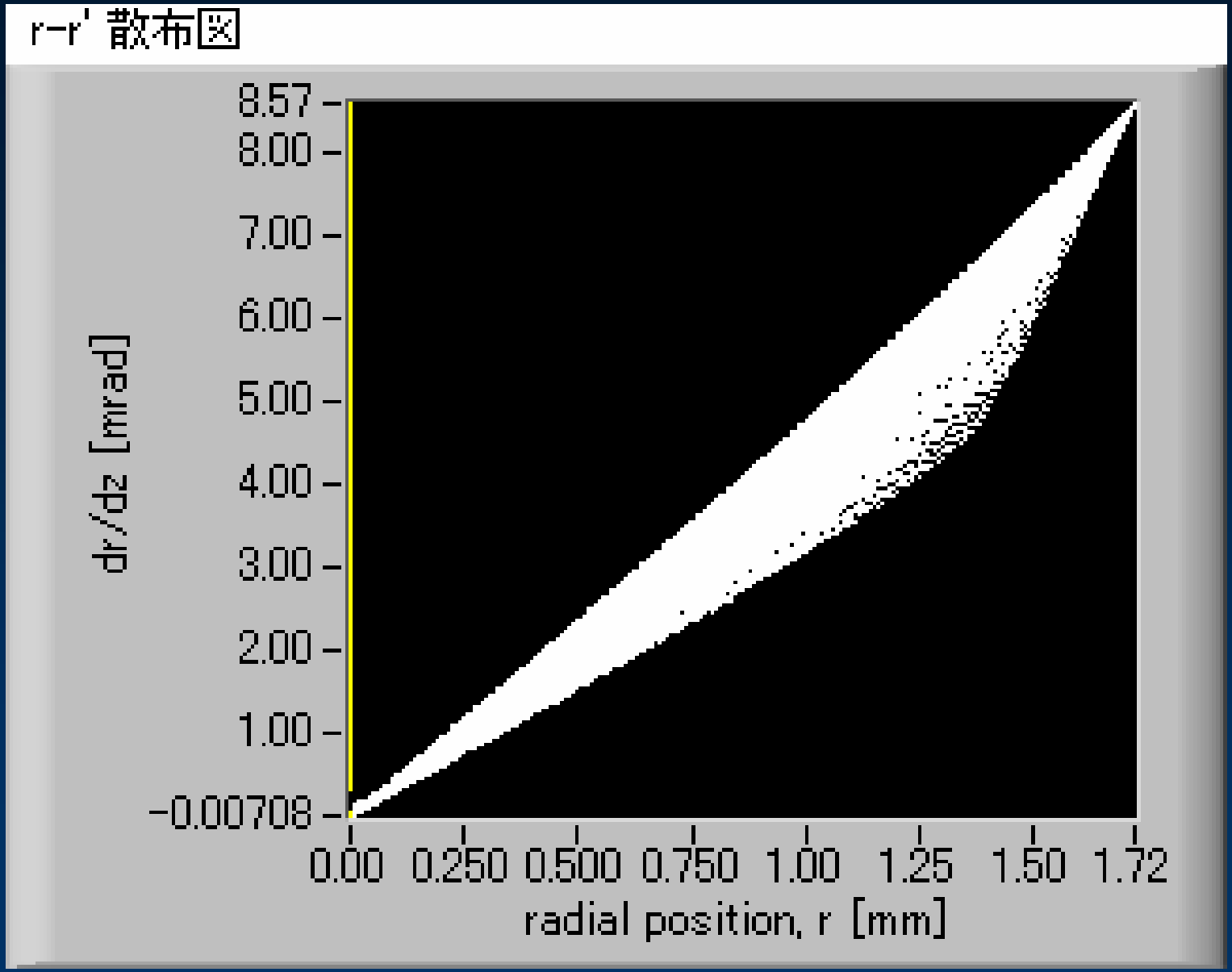
4. パルスビームへの鏡像の影響


Plplot Window
Radial Distance, r [mm]
Norm RMS Emittance, $\varepsilon_{n,i}$[10^{-07} m rad]
Axial Distance, z [mm]
0
20
40
60
KUAD2 v2.30
dartplot
Sun Nov 26 15:12:24 2006
drtfileID, 2mmf160420MV
20th iteration
Error
ϕ_b – 0.00[%]
$H_{b,\theta}$ – 0.00[%]
$A_{b,\theta}$ – 0.00[%]
I_{inj} – 0.00[%]
Plot 1
Contour of ϕ_b
Classification by Color
electron
Injection Current
5.027[A]
Electrodes
1 2
20 MV/m
160 A/cm²
DCビーム

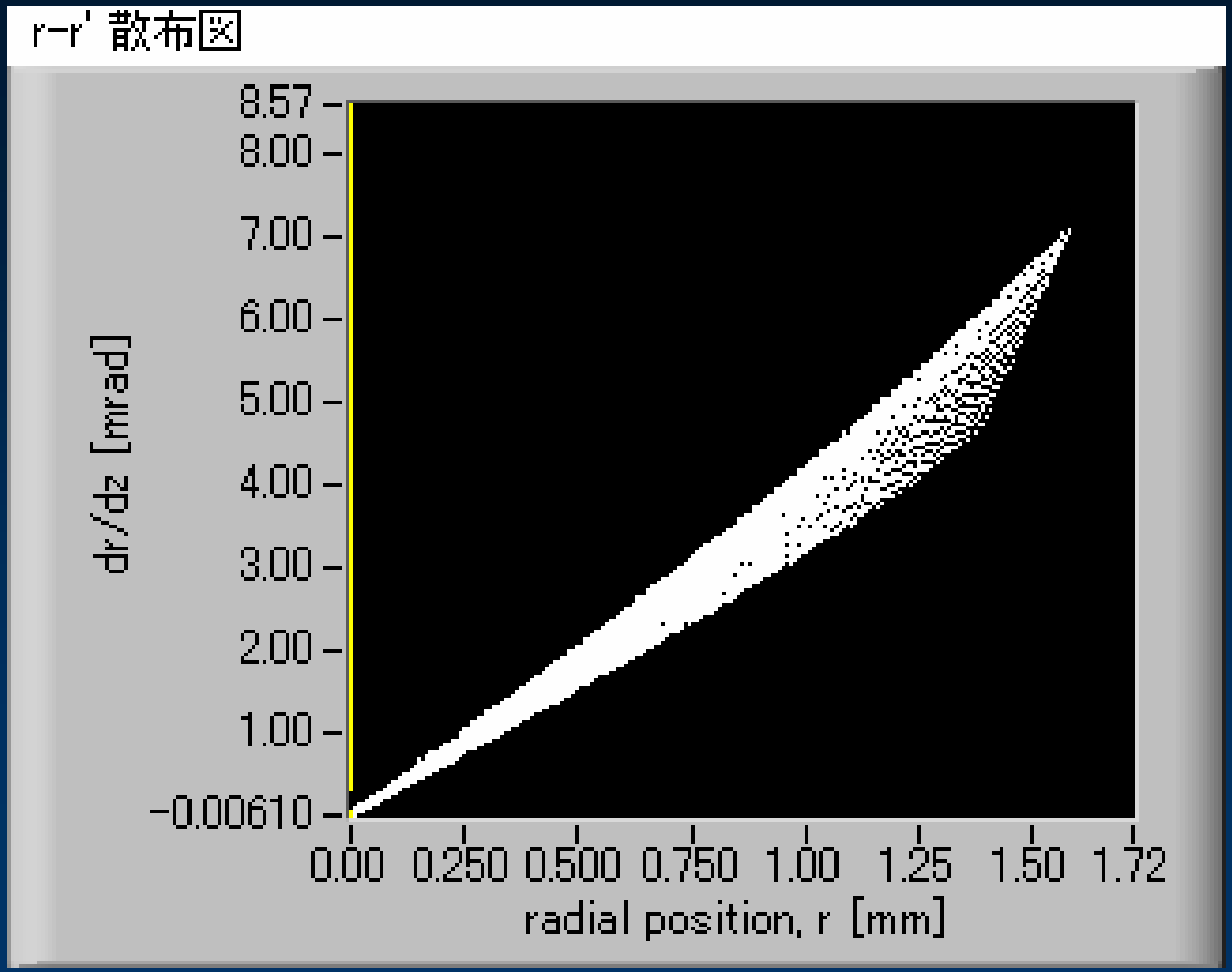

Plplot Window
Radial Distance, r [mm]
Bulk Emittance, ε_n [10^{-07} m rad]
Axial Distance, z [mm]
0
20
40
60
KUBLAI v1.60
beamplot
Thu Dec 7 09:59:28 2006
biofile10: 2mmf160A20MVb
2nd rf cycle
rf phase
1/ 20 [2πrad]
# of particles
total : 105483
electron : 105483
Plot 1
Contour of ϕ_b
Classification by Color
Total Field
Vacuum Field
Cavity Field
Beam-Induced Field
Mesh
Electrodes
20 MV/m
160 A/cm²
DCビーム


Link to animation
KUBLAI v1.60
beamplot
Tue Dec 5 11:33:09 2006
biofileID: 2mmf160A20MV20p
2nd rf cycle
rf phase
2/ 50 [2πrad]
# of particles
total : 40960
electron : 40960
Plot 1
Contour of φb
Classification by Color
Total Field
Vacuum Field
Cavity Field
Beam-Induced Field
Mesh
Electrodes
20²MV/m
160 A/cm²
20 psec
(0.1 nC)
Radial Distance, r [mm]
Bulk Emittance, εnr [π mm mrad]
Slice Emittance, Δεnr [π mm mrad]
Axial Distance, z [mm]

全粒子　@ z = 50 mm

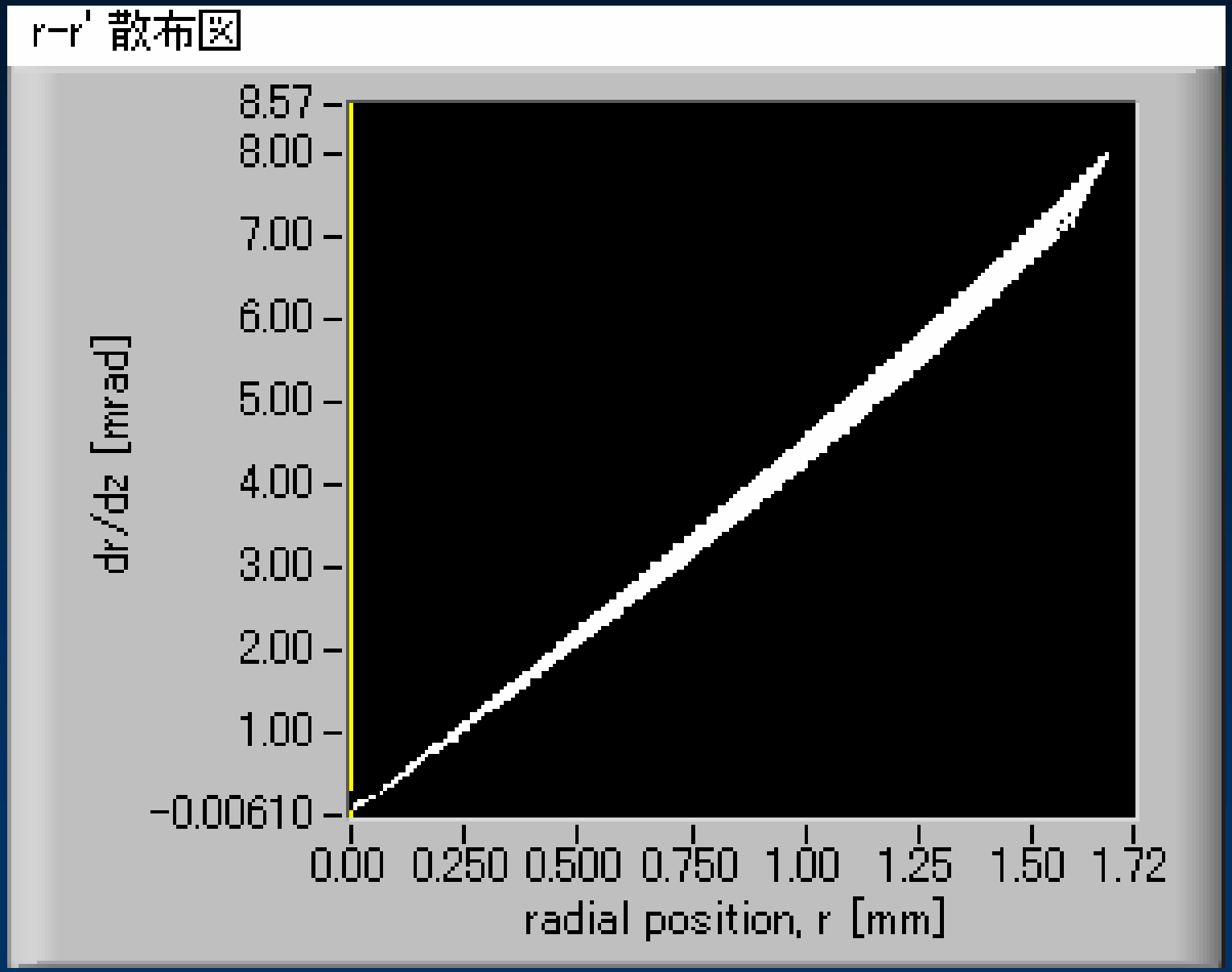

r-r' 散布図
8.57
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
-0.00708
dr/dz [mrad]
0.00
0.250
0.500
0.750
1.00
1.25
1.50
1.72
radial position, r [mm]

#1 / 8　(先頭)　@ z = 50 mm


r-r' 散布図
8.57
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
-0.00610
dr/dz [mrad]
0.00
0.250
0.500
0.750
1.00
1.25
1.50
1.72
radial position, r [mm]

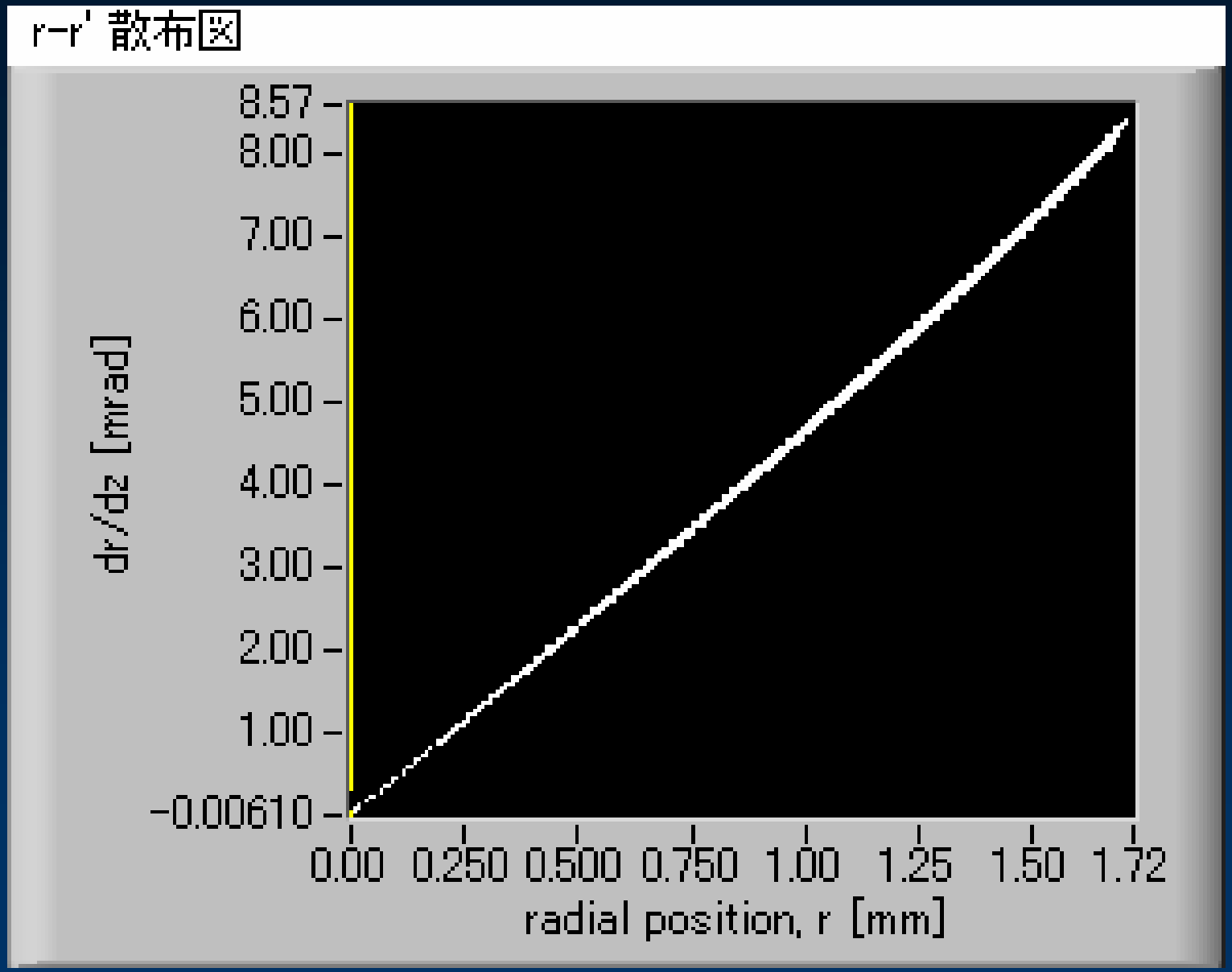
#2 / 8

@ z = 50 mm


r-r' 散布図
8.57
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
-0.00610
dr/dz [mrad]
0.00
0.250
0.500
0.750
1.00
1.25
1.50
1.72
radial position, r [mm]

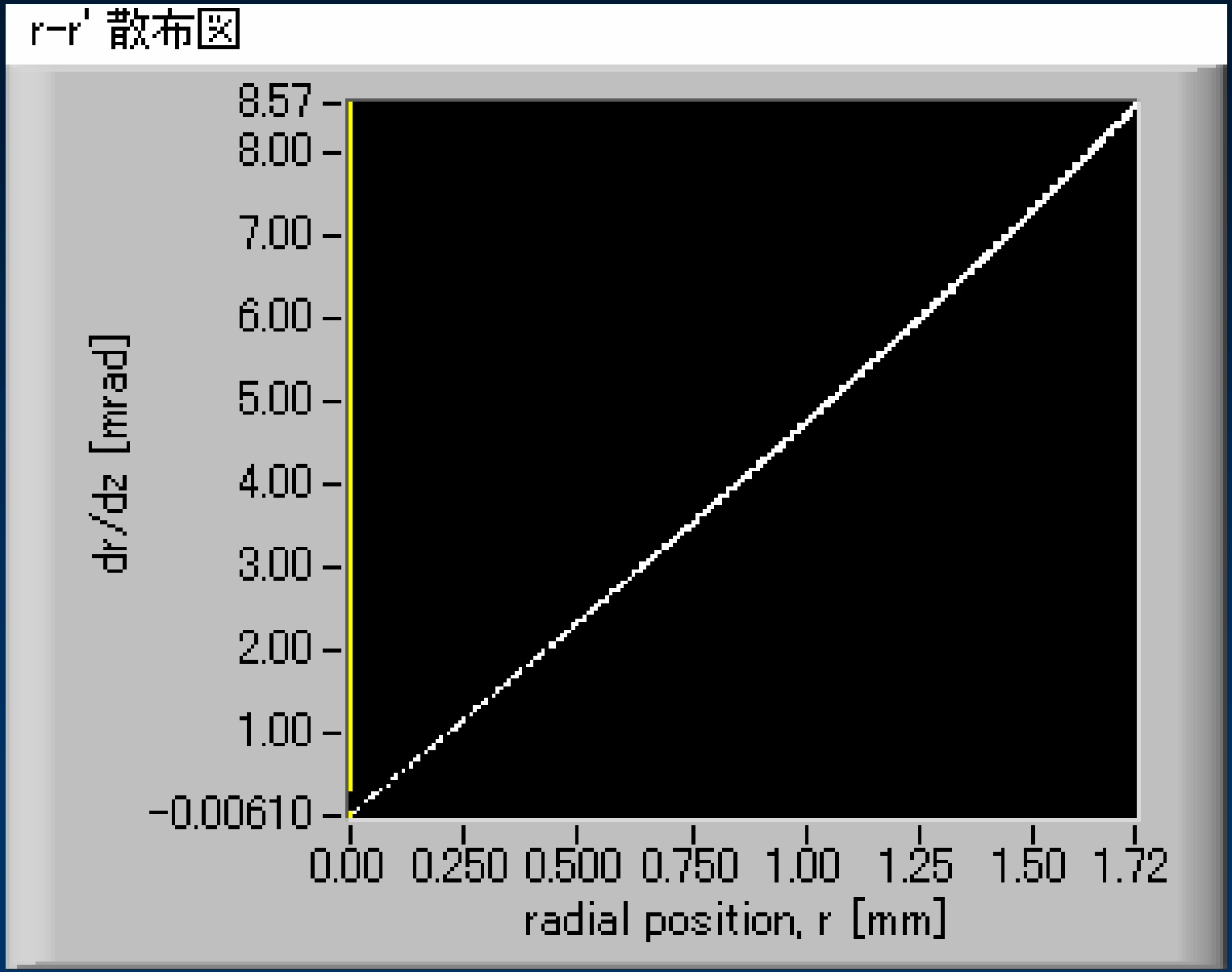
#3 / 8

@ z = 50 mm


r-r' 散布図
8.57
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
-0.00610
dr/dz [mrad]
0.00
0.250
0.500
0.750
1.00
1.25
1.50
1.72
radial position, r [mm]

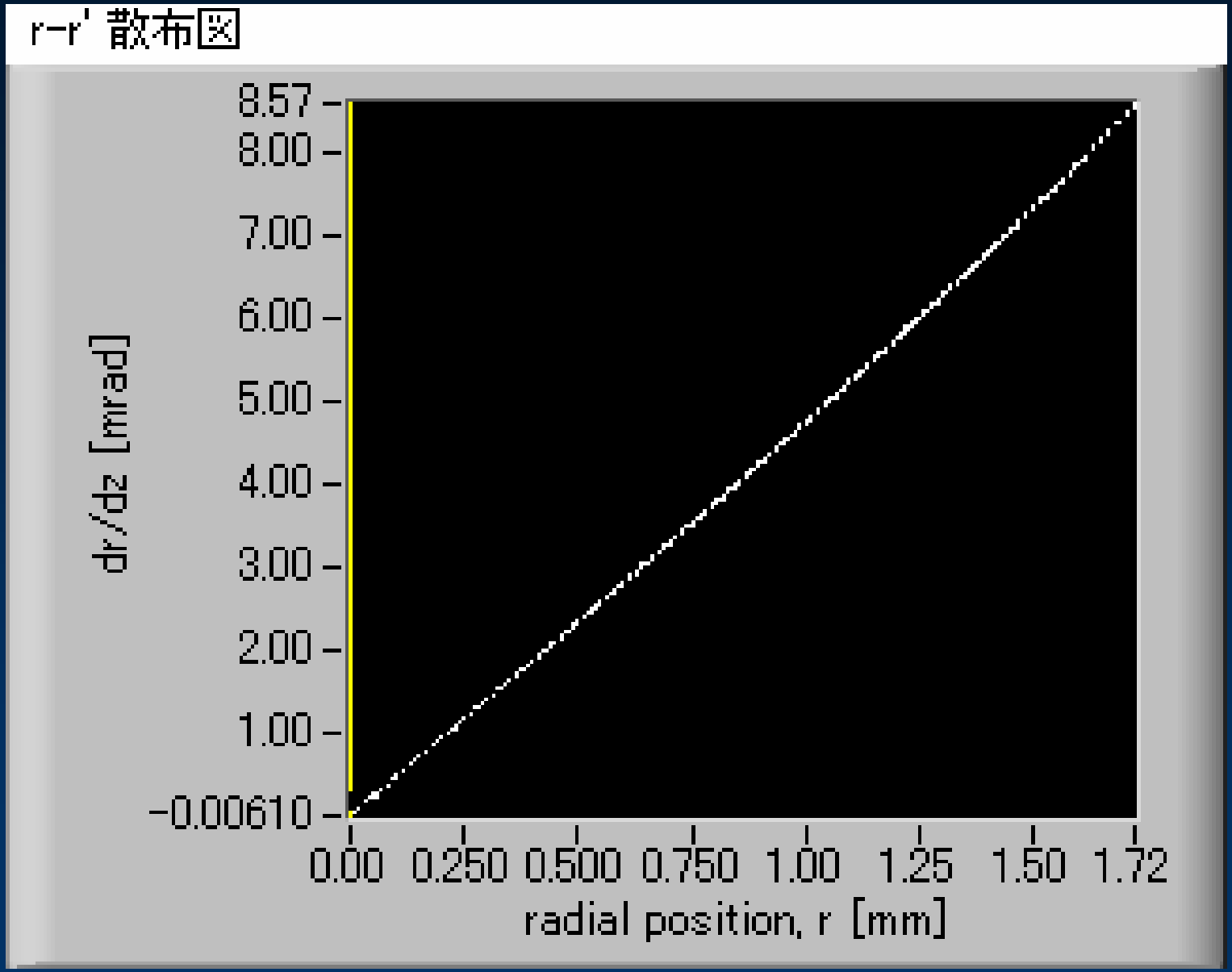
#4 / 8

@ z = 50 mm


r-r' 散布図
8.57
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
-0.00610
dr/dz [mrad]
0.00
0.250
0.500
0.750
1.00
1.25
1.50
1.72
radial position, r [mm]

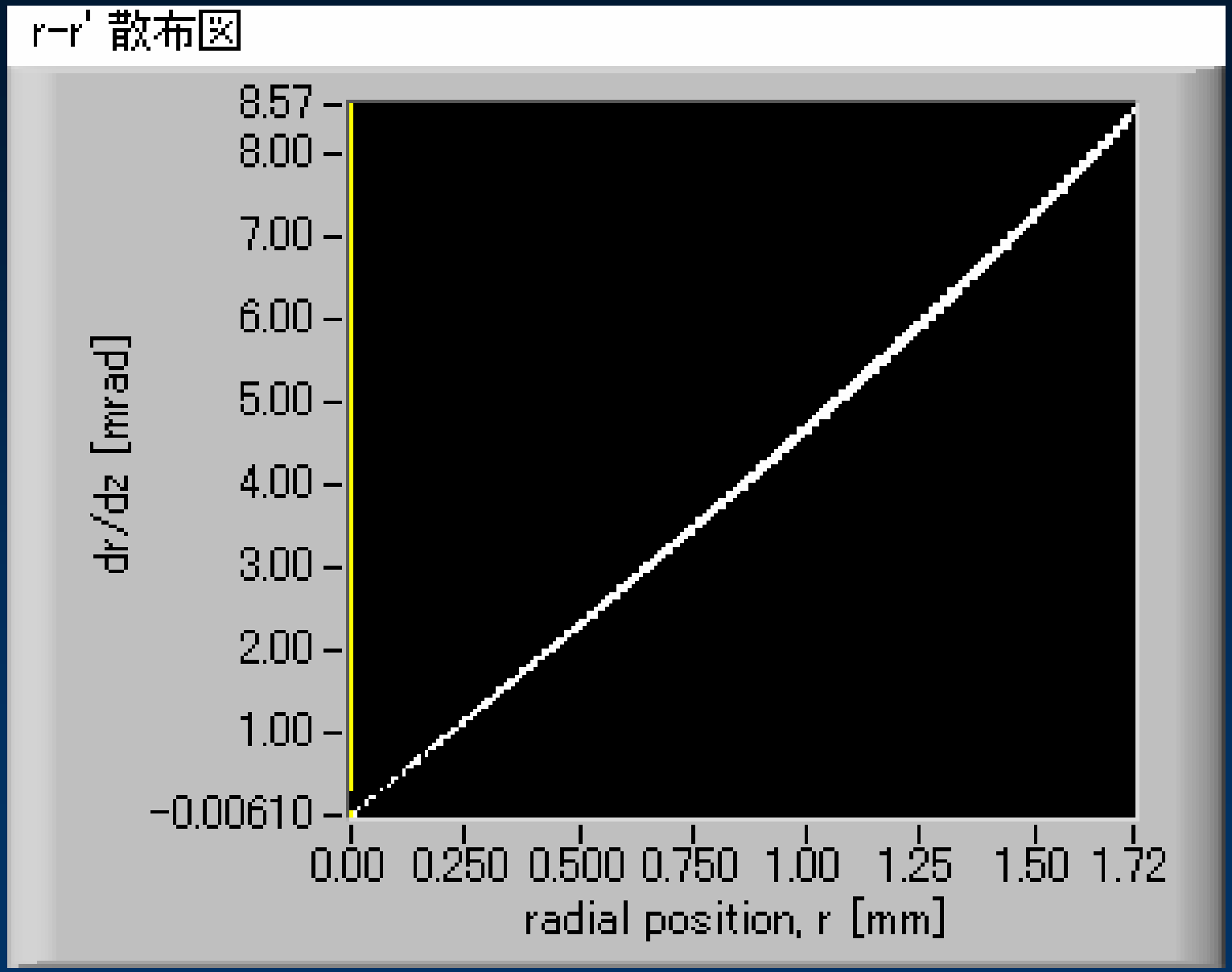
#5 / 8

@ z = 50 mm


r-r' 散布図
8.57
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
-0.00610
dr/dz [mrad]
0.00
0.250
0.500
0.750
1.00
1.25
1.50
1.72
radial position, r [mm]

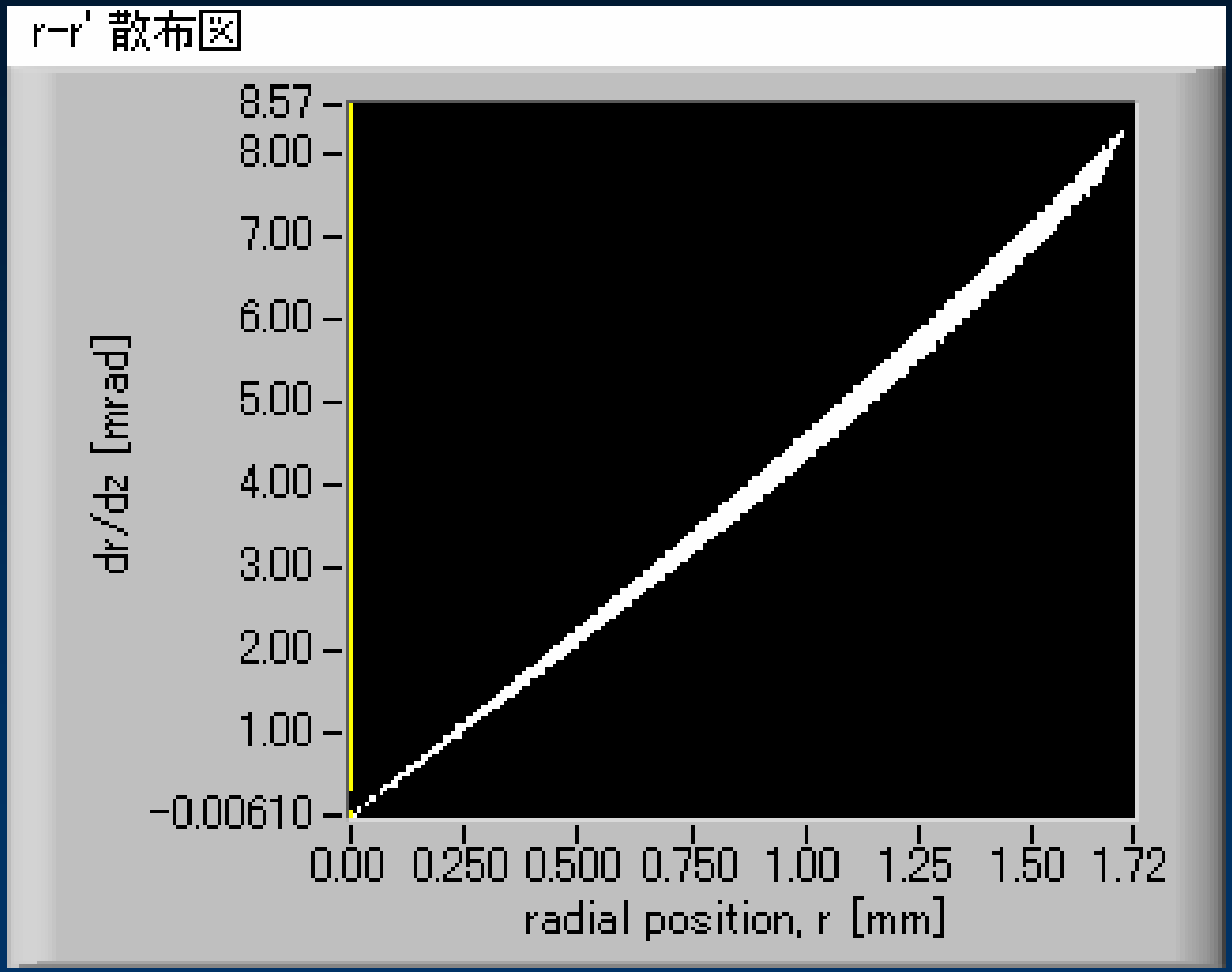
#6 / 8

@ z = 50 mm

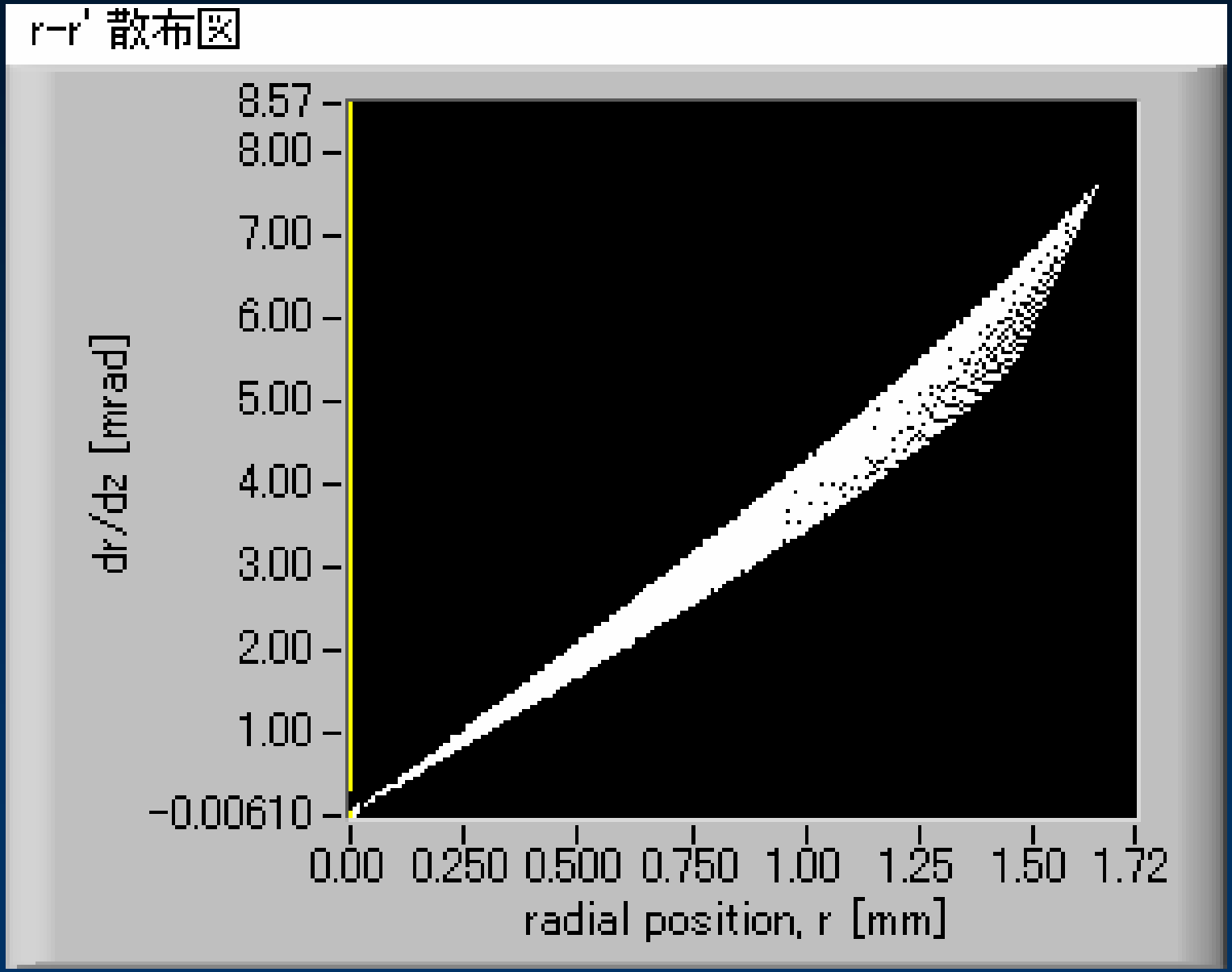

r-r' 散布図
8.57
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
-0.00610
dr/dz [mrad]
0.00
0.250
0.500
0.750
1.00
1.25
1.50
1.72
radial position, r [mm]

#7 / 8

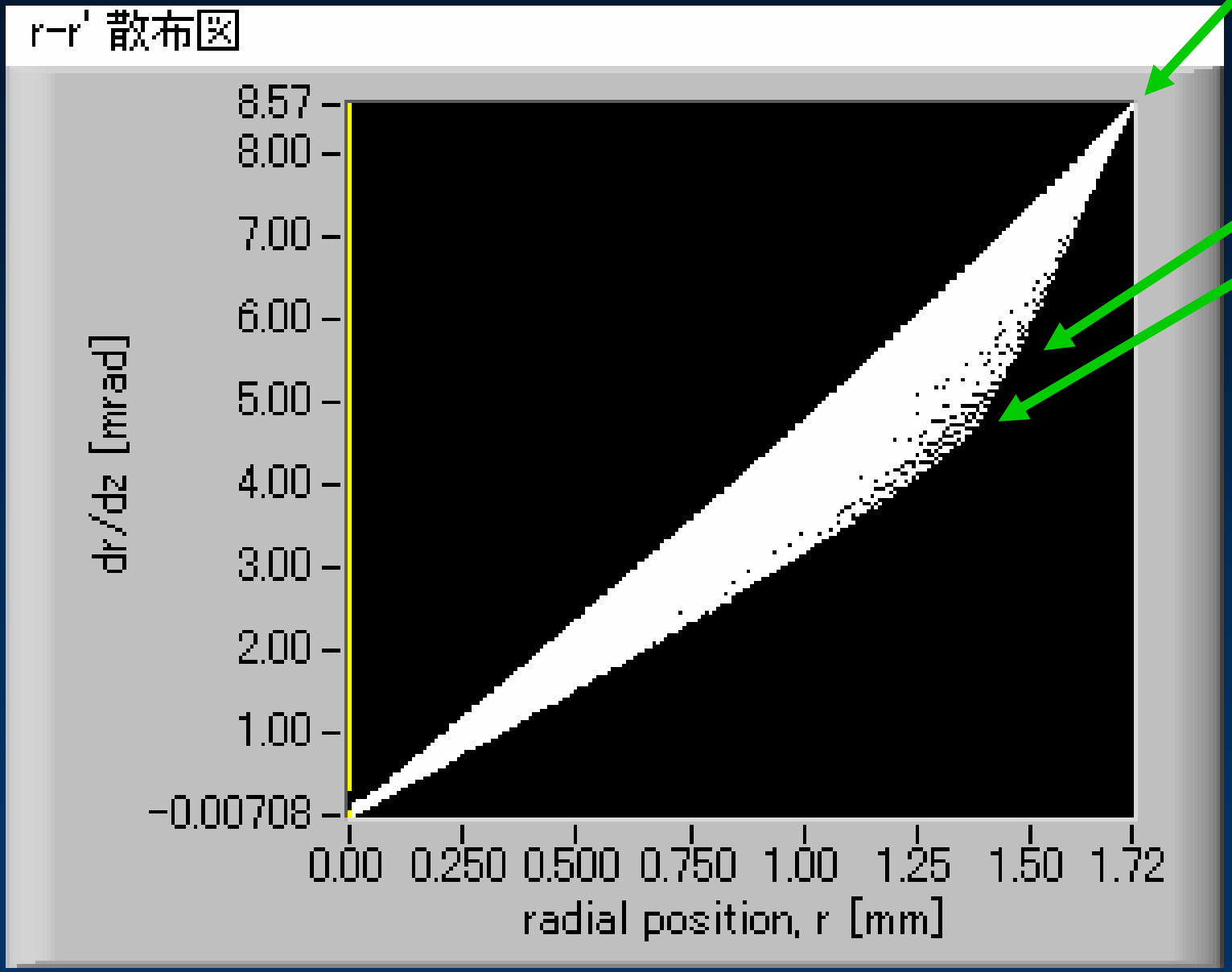
@ z = 50 mm


r-r' 散布図
8.57
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
-0.00610
dr/dz [mrad]
0.00
0.250
0.500
0.750
1.00
1.25
1.50
1.72
radial position, r [mm]

#8 / 8 （最後尾） @ z = 50 mm


r-r' 散布図
8.57
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
-0.00610
dr/dz [mrad]
0.00
0.250
0.500
0.750
1.00
1.25
1.50
1.72
radial position, r [mm]

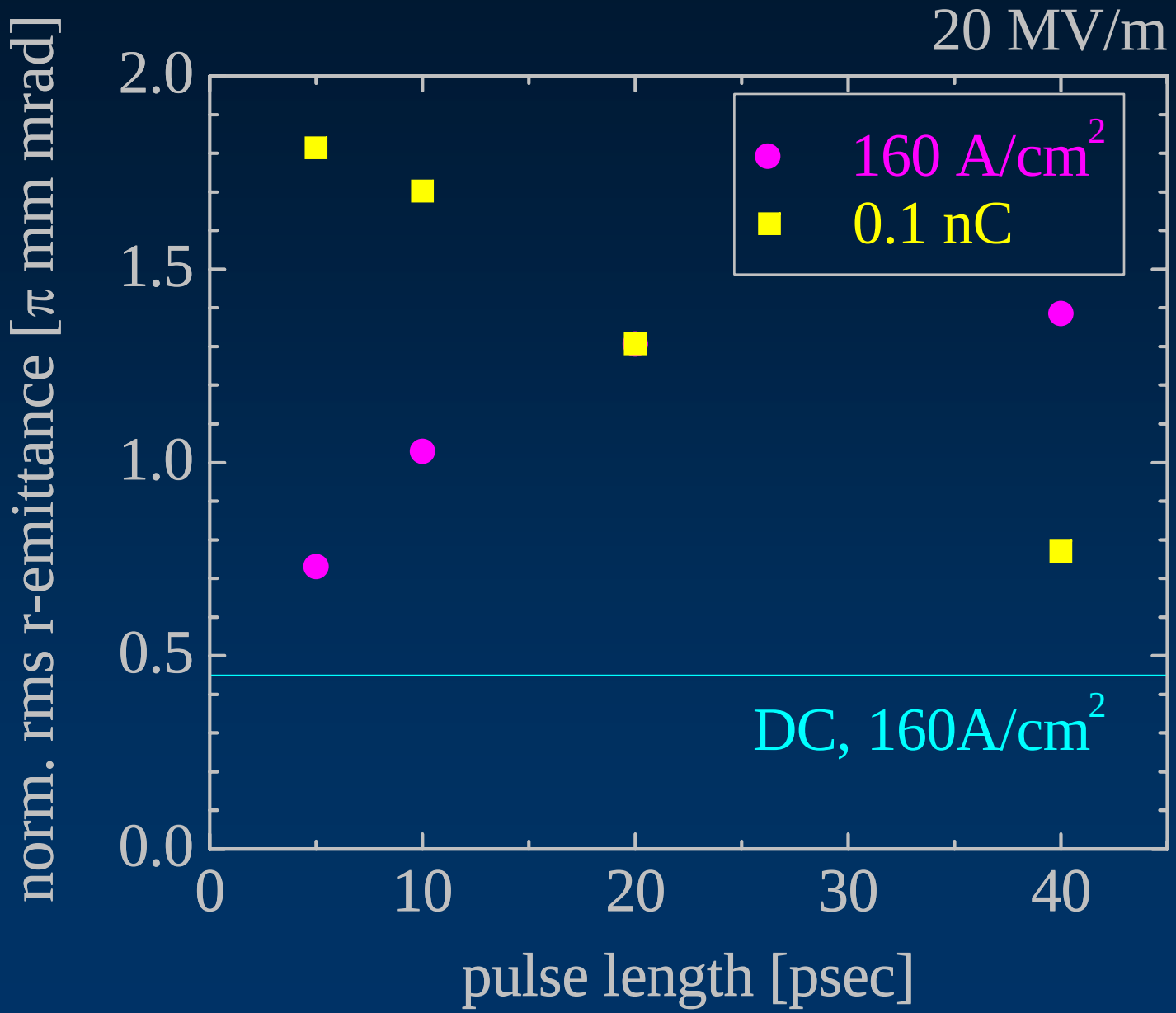
全粒子　@ z = 50 mm


r-r' 散布図
8.57
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
-0.00708
dr/dz [mrad]
0.00
0.250
0.500
0.750
1.00
1.25
1.50
1.72
radial position, r [mm]
中
後
先

パルスの先頭と最後尾が受ける鏡像の効果は異なる

カソードを離れた後の空間電荷効果の影響の方が大きい

norm. rms r-emittance @ z = 50 mm



ま と め

- ✓ 陰極近傍（z<1mm：2mmϕの場合）でエミッタンスが急増.

  （エミッタンス@z=1mm）∝（電流密度）/（電界）

- ✓ 同時に，横方向の電流密度分布が一様ではなくなる.

  z<1でのエミッタンスを一時的に打ち消すこともある.

- ✓ $\varepsilon_{\mathrm{total}}^2 = \varepsilon_{\mathrm{th}}^2 + \varepsilon_{\mathrm{SC}}^2$ は見事に成り立つ.

- ✓ パルスだと，DCに比べて最大で約3倍，エミッタンス増

  （電流密度160A/cm^2，電界20MV/mで）