

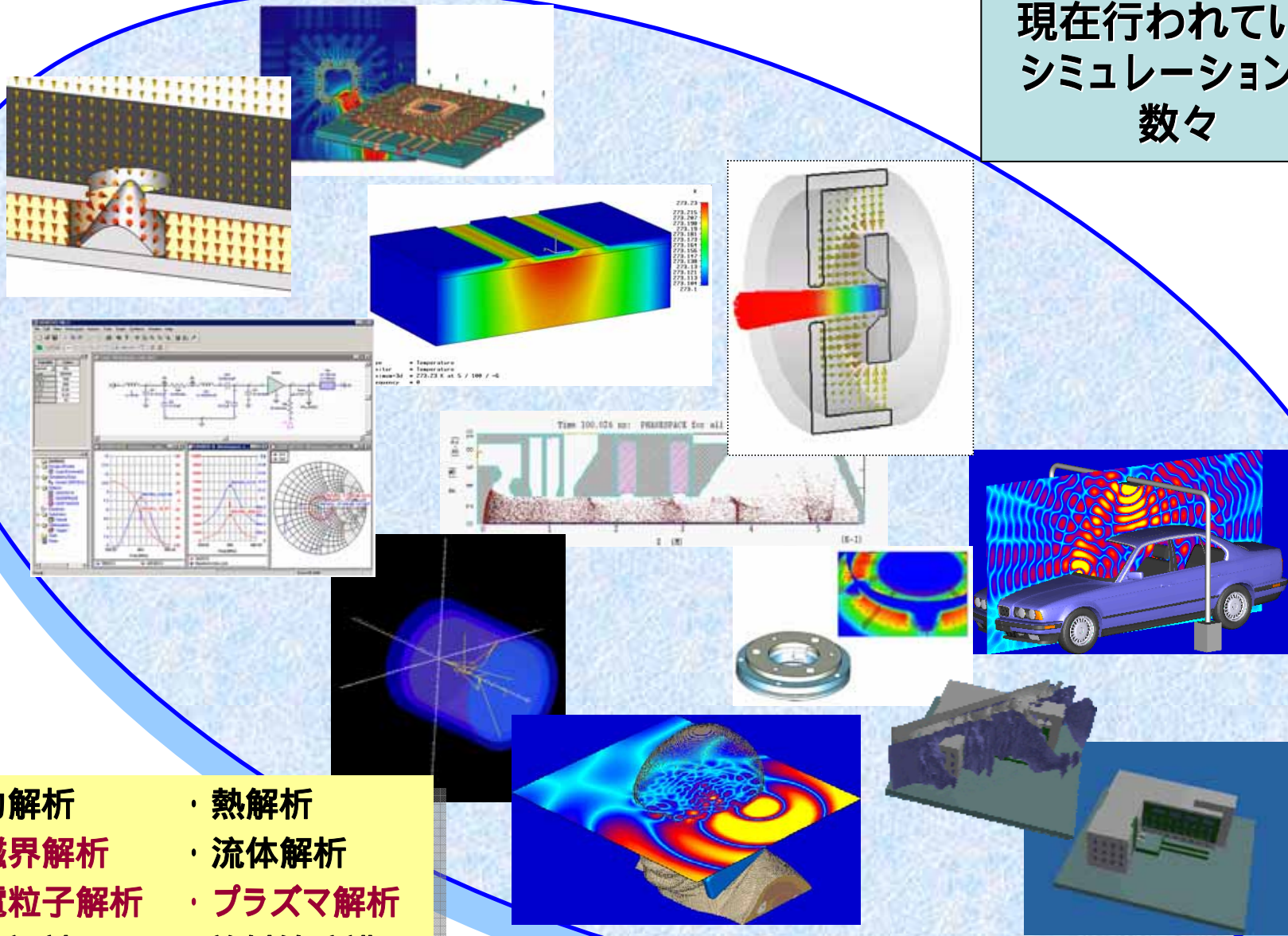
電磁界・荷電粒子・プラズマ解析 ソフトウェアの現状

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川崎市麻生区栗木2-7-6
菅野浩一



Hardware, Software and Professional services

現在行われている
シミュレーションの
数々



- ・ 応力解析
- ・ 電磁界解析
- ・ 荷電粒子解析
- ・ 回路設計
- ・ 分子動力学
- ・ 熱解析
- ・ 流体解析
- ・ プラズマ解析
- ・ 放射線防護
- ・ その他



1. 電磁界・荷電粒子・プラズマ解析
2. 現在のコードで設定できる荷電粒子発生モデル
3. 電磁界・荷電粒子・プラズマ解析ソフトウェアと
解析例紹介

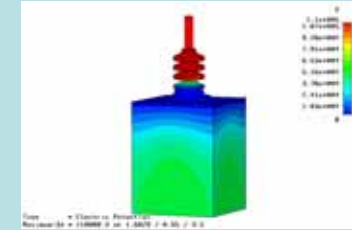
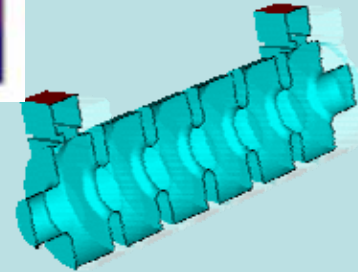
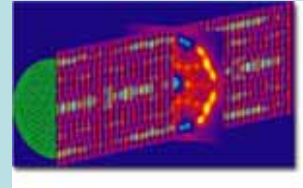
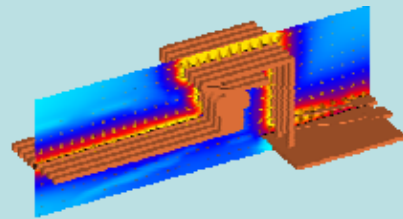


シミュレーション、その前に...

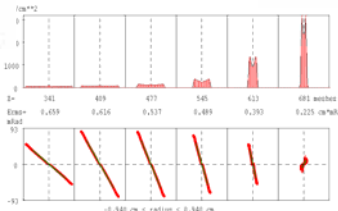
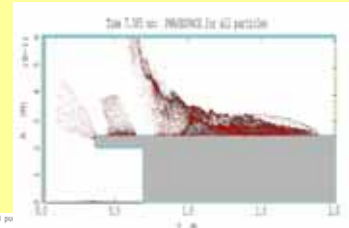
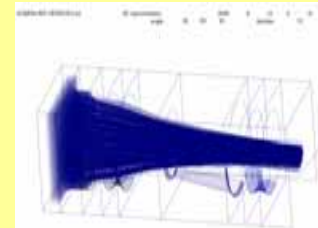
- 使用目的、開発目的に見合っているか
 - 📌 目標、💰 予算、🕒 スケジュール、👤 マンパワー
 - 🖥️ コンピュータ環境
- メッシュサイズは十分細かいか
 - 特に電子源に対して
- 計算が収束しているか
- 比較条件が一致しているか
- 粒子数は十分か
 - セルとの関係も大切
- ...

1. 電磁界・荷電粒子・プラズマ解析

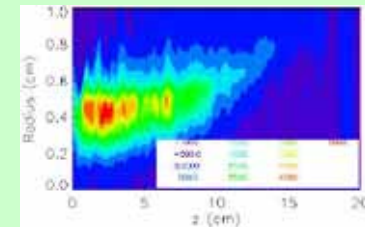
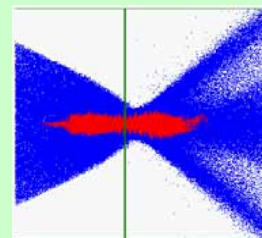
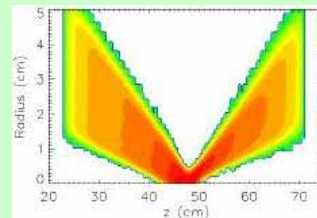
- 電磁界解析:



- 荷電粒子解析:



- プラズマ解析:



2. 現在のコードで設定できる荷電粒子発生モデル

- 固定放出
- 空間電荷制限放出
- 熱電子放出
- 電界電子放出
- 光電子放出
- 二次電子放出
- プラズマからのイオン引き出し
- 後方散乱、イオン化...

空間電荷制限放出、熱電子放出

Richardson-Dushmanの式

$$J_s = AT^2 e^{-\frac{e\Phi}{kT}}$$

陰極の電子放出性能に依存

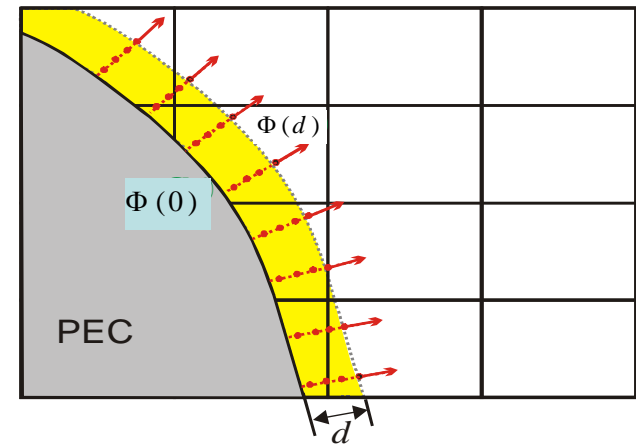


放出電流

Child-Langmuirの式

$$J_s = \frac{4}{9} \epsilon \sqrt{2 \frac{q}{m}} \frac{(\Phi(d) - \Phi(0))^{3/2}}{d^2}$$

放出面近傍の電場に依存



仮想陰極

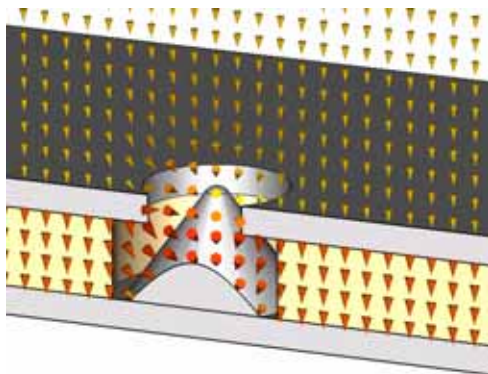
引き出し電圧

電界電子放出

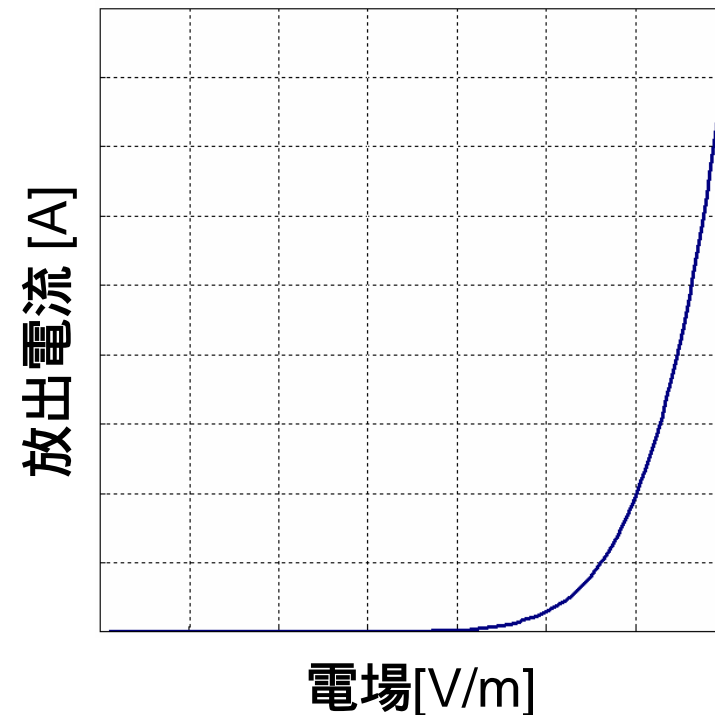
Fowler-Nordheimの式

$$J_s = AE^2 e^{-\frac{B}{E}}$$

- 10^9 - 10^{10} V/m以上の高電界によって電子が発生
- フィールドエミッターアレイ、ニードル陰極、CNT陰極など



電界放出型三極管コールド
カソードATC-CCシリーズ



3. 電磁界・荷電粒子・プラズマ解析コード と解析例紹介



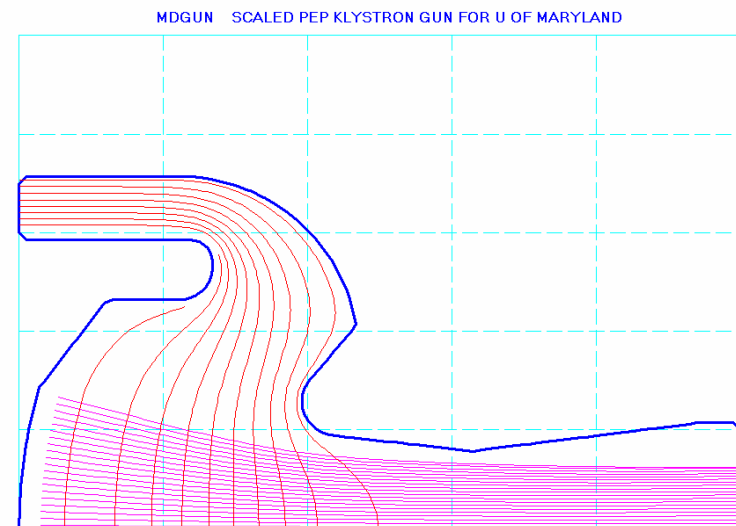
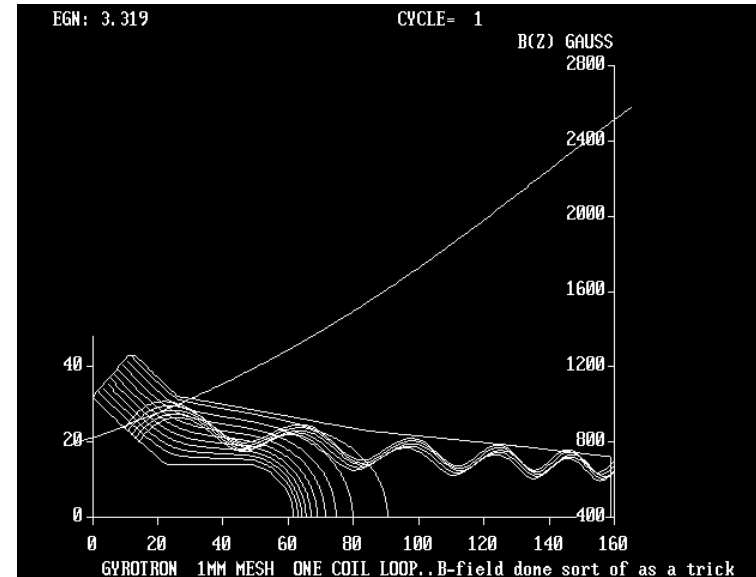
電磁界・荷電粒子・プラズマ解析コード

- **EGUN:** 電子銃、電界放出解析
- **IGUN/nIGUN:** プラズマイオン源解析
- **PARTICLE STUDIO:** 3次元荷電粒子解析
- **MAGIC:** 電磁界・荷電粒子運動解析
- **LSP:** 大規模プラズマ解析



EGUN

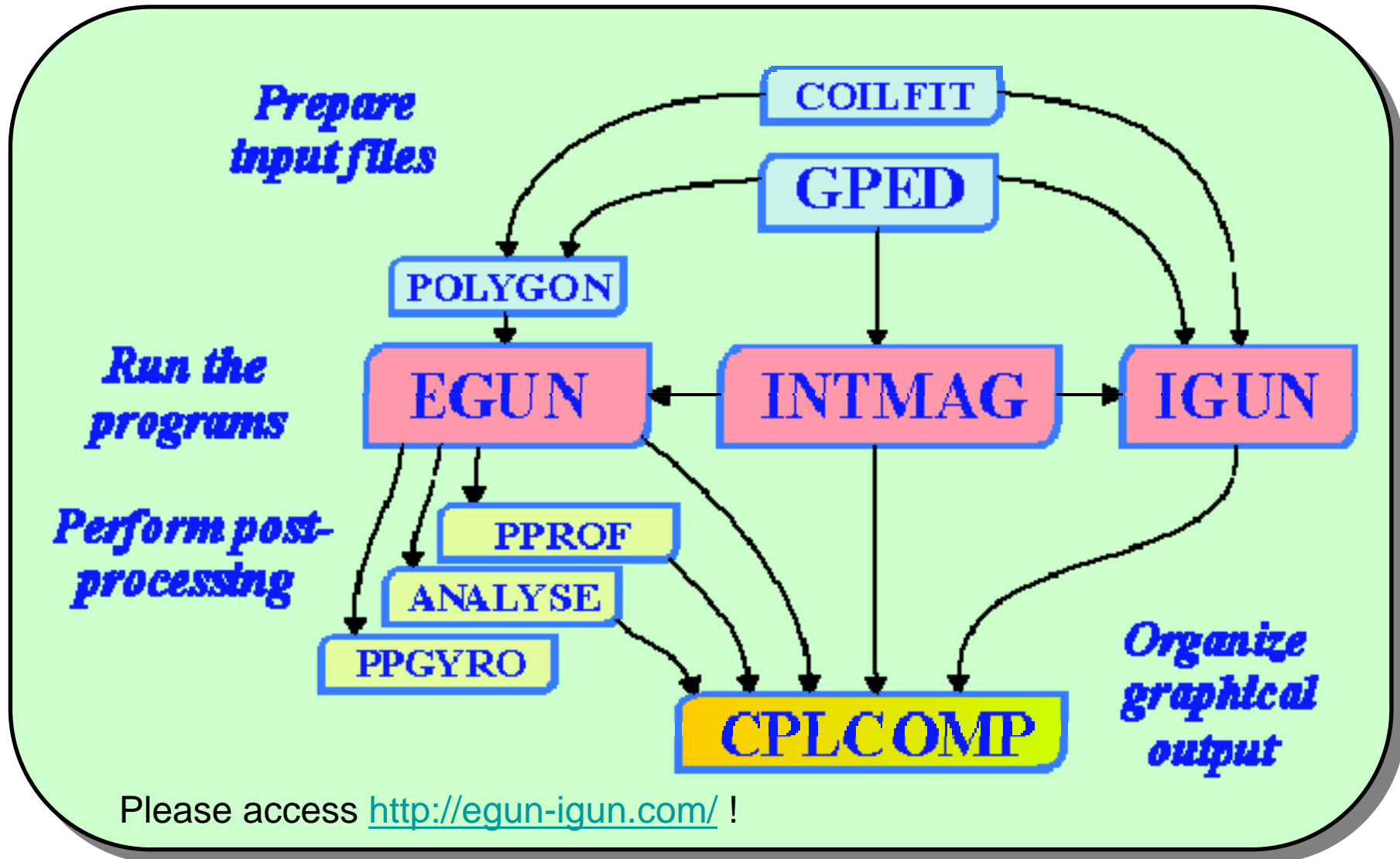
- 電子銃、イオン源に特化したコード
- Fowler-Nordheimの式に対応した電界電子放出の計算
- 副分割が可能で陰極部の電場の依存が強い電界電子放出陰極や微小陰極の計算も可能



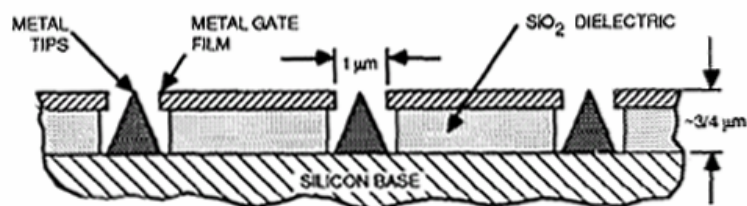
Hardware, Software and Professional services



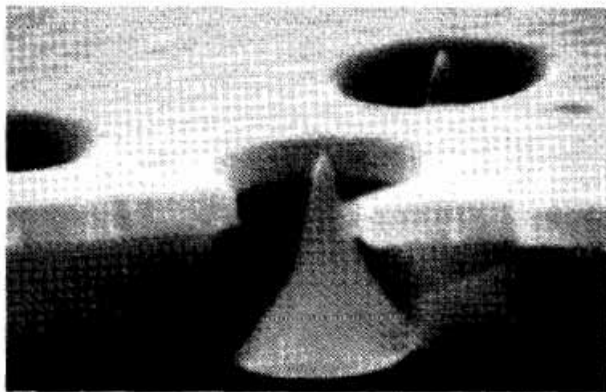
EGUN family



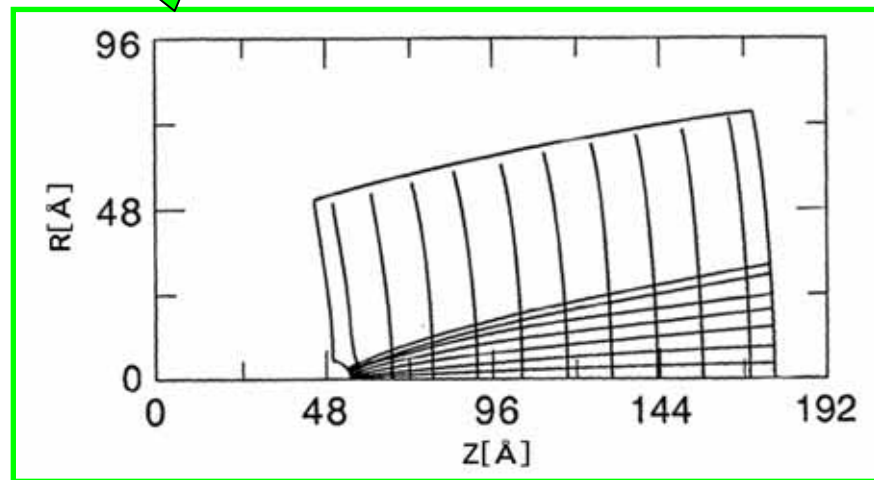
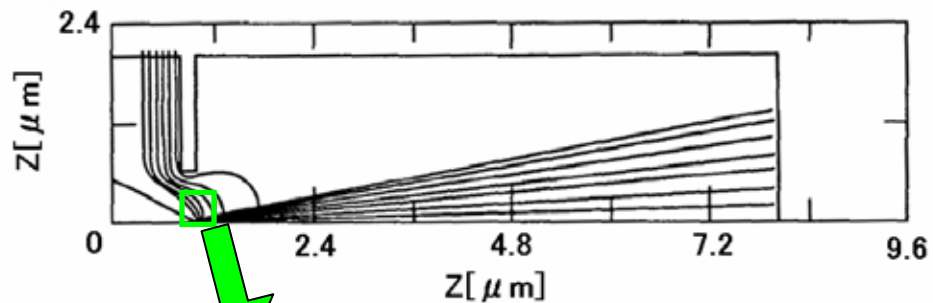
Spindt型フィールドエミッター



概要図



電子顕微鏡写真



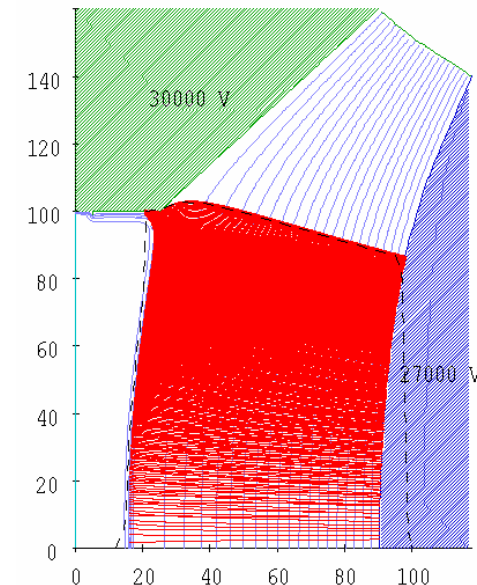
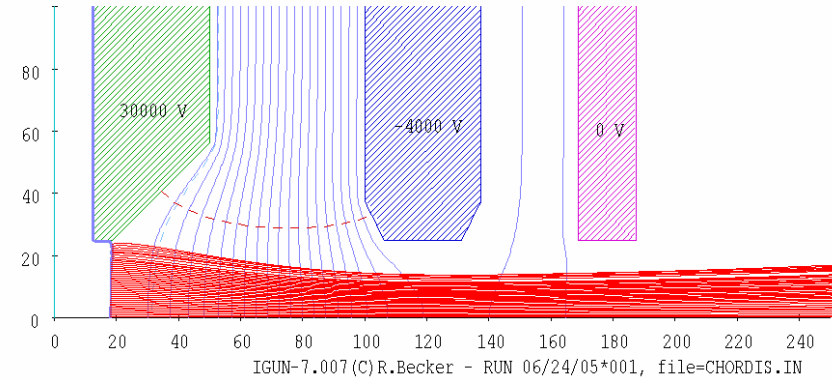
計算結果

W.B.Herrmannsfeldt, et. al., "High-resolution simulating of field emission", SLAC-PUB-5217

IGUN

- プラズマイオン源用コード
- プラズマ室のポテンシャル分布をシンプルな一次元シースモデルに基づいて取り扱い安定に計算
 - 電子エネルギー : ボルツマン分布
 - イオンエネルギー : const.

Up=30022.5, Te=5.0 eV, Ui=5.0 eV, mass=-1.0, Ti=0 eV, Usput=0 V
1.81E-2 A, crossover at R= 13.8, Z=130 mesh units, Debye=0.191 mesh units
CHORDIS ion source

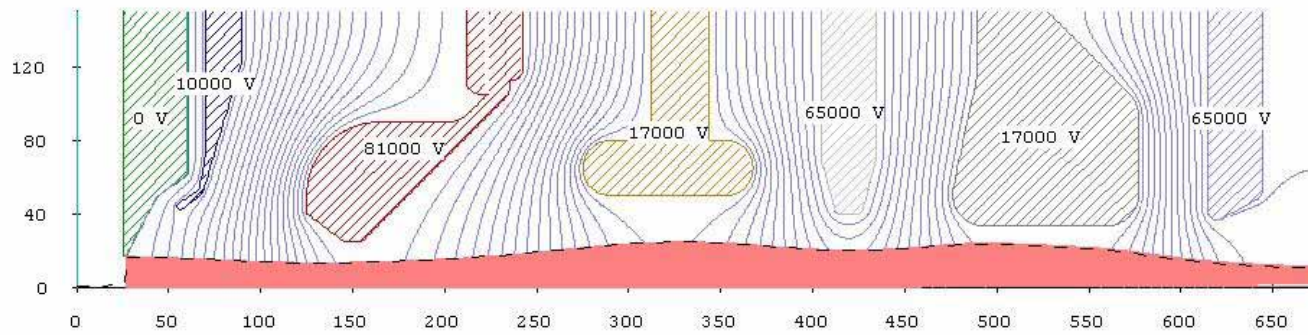


負イオン源用設計解析 nIGUN

- プラズマからの**負イオン**引き出しに不可欠な高速イオン・熱イオンの効果を考慮する世界で唯一のプログラム
- 正電荷を持つあらゆる数の高速イオンや熱イオンを考慮できる自己矛盾がない理論を導入
- 加速電場によるプラズマの分解をプロットすることも可能

6.92E-2 Å, crossover at R= 10.4, Z=675, Debye =2.77E-2 mesh units

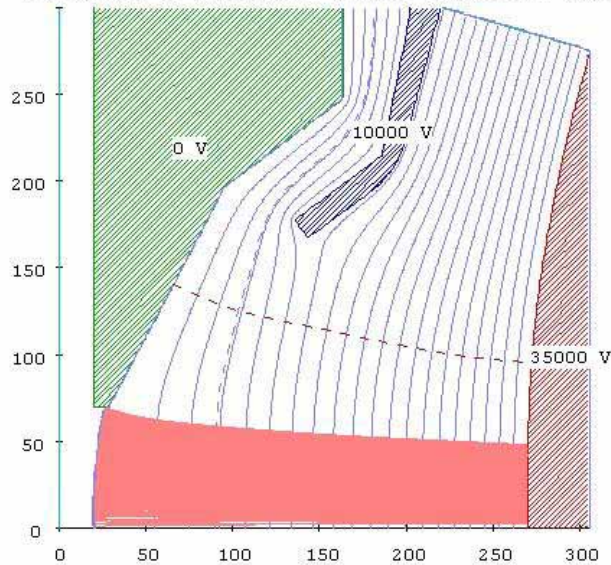
TOTAL.IN (sum of EXT_106c.IN and 106_4847.IN)



nIGUN-1.005(C)R.Becker - RUN 05/23/05*001, file=snstotal.in

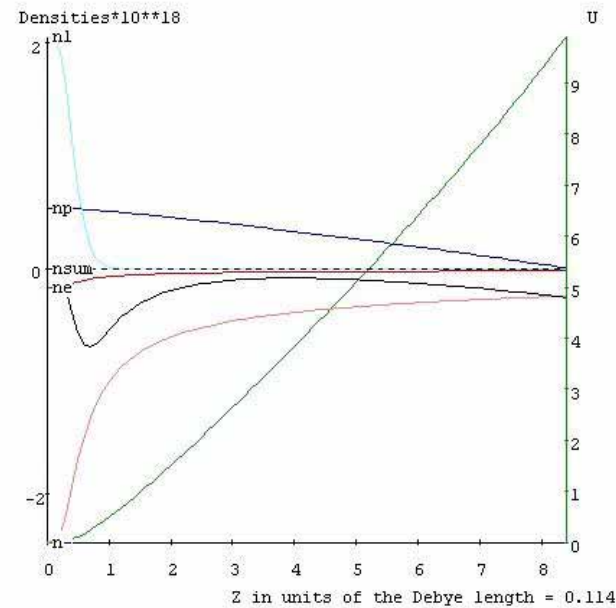
6.29E-4 Å, crossover at R= 61.0, Z=66, Debye =0.114 mesh units

Plasma part of SNSTOTAL.IN (sum of EXT_106c.IN and 106_4847.IN)



nIGUN-1.005(C)R.Becker - RUN 06/02/05*001, file=SNSPLAST.IN

Particle densities and potentials across the sheath



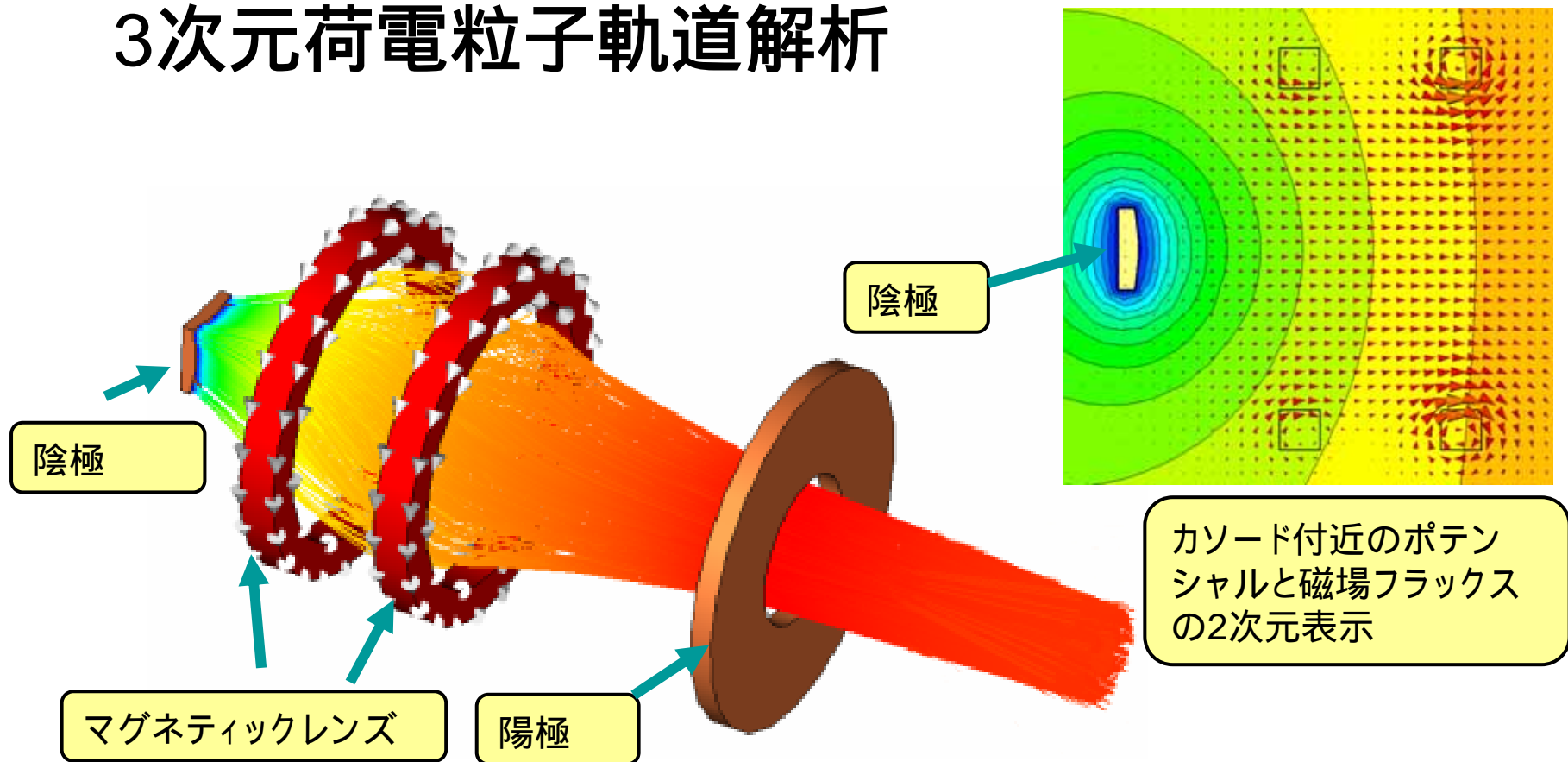
SNSイオン源とLEBT(Low-Energy Beam Transport)



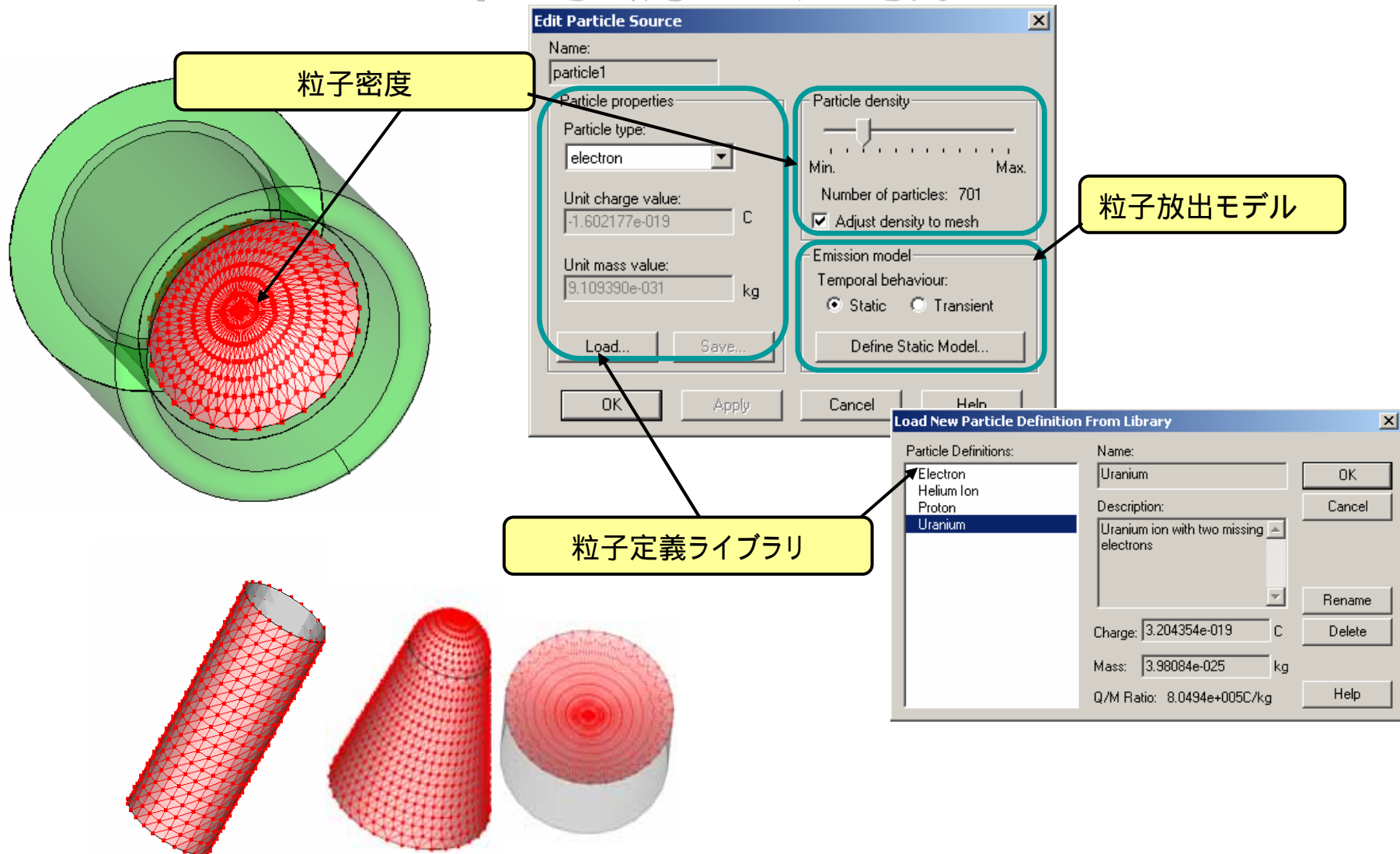
Hardware, Software and Professional services

PARTICLE STUDIO CST GmbH (独)

- MAFIAに代わる、使いやすいGUI完備の3次元荷電粒子軌道解析



PARTICLE STUDIOにおける 粒子源の定義

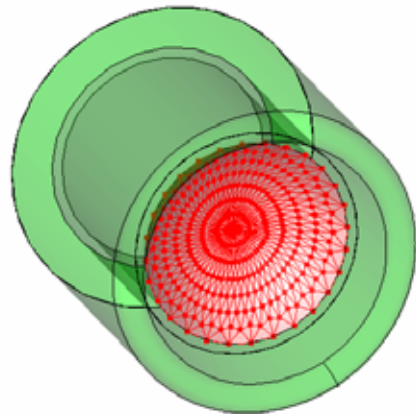
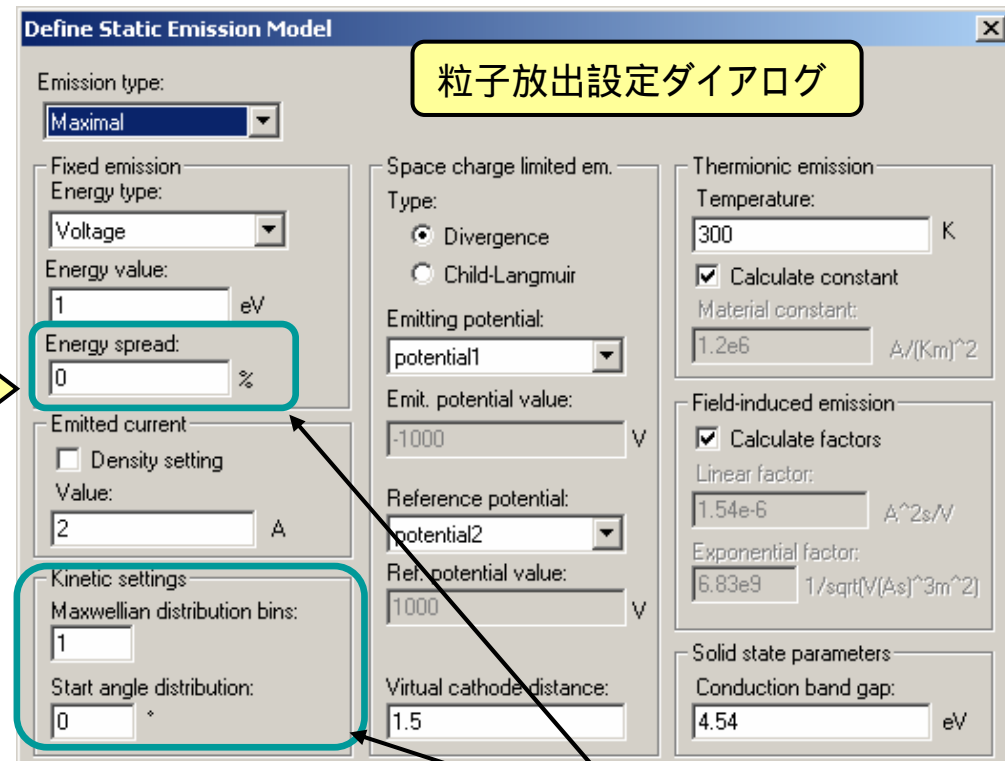
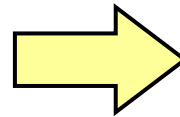
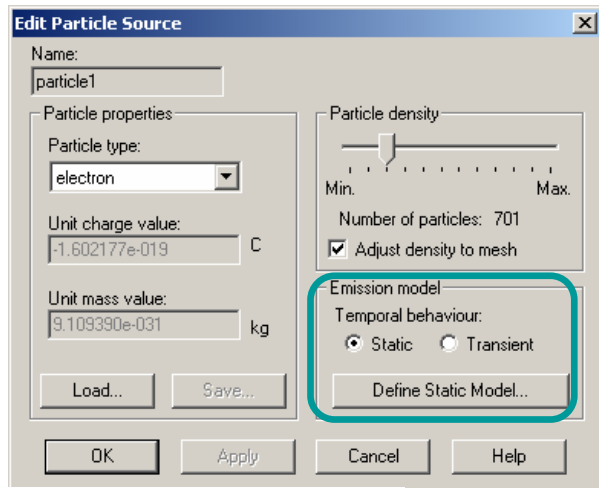


粒子密度

粒子放出モデル

粒子定義ライブラリ

粒子密度

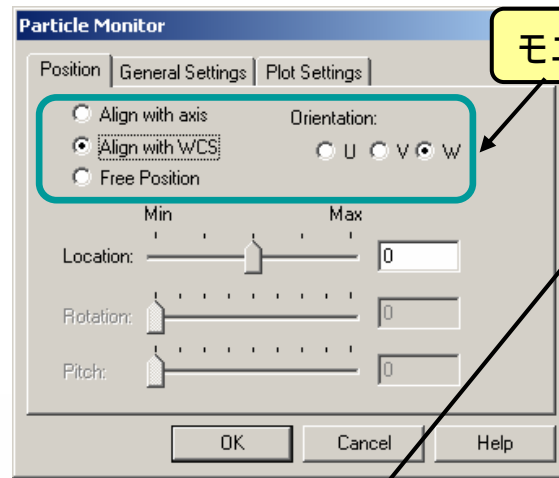


1. 固定放出 (電流とエネルギー)
2. 空間電荷制限放出 (Childの法則)
3. 熱電子放出 (Richardson-Dushmanの式)
4. 電界電子放出 (Fowler-Nordheimの式)

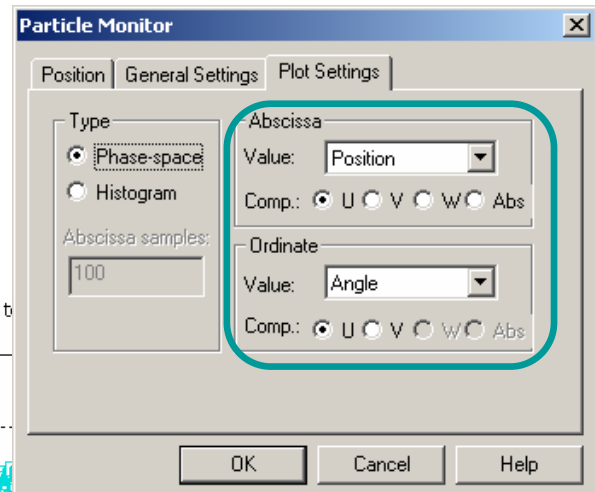
- エネルギー広がり
- Maxwell-Boltzmann速度分布

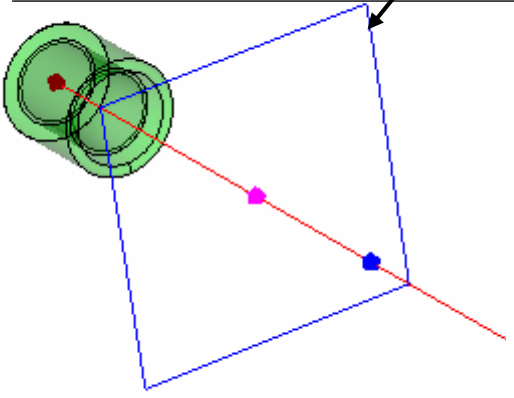
ポストプロセス

粒子モニター:

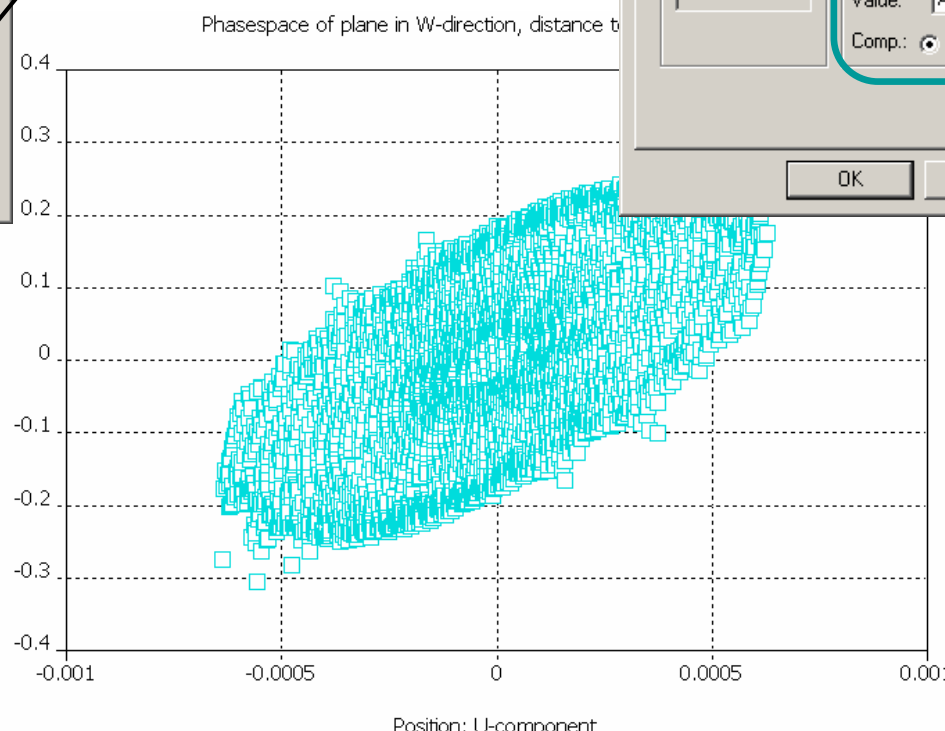


モニタリング平面の定義



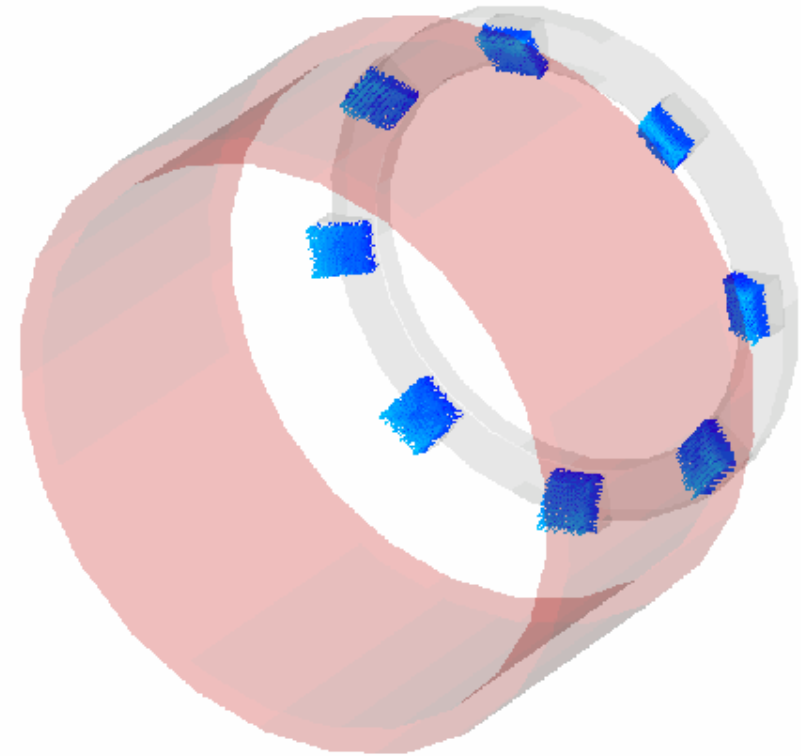
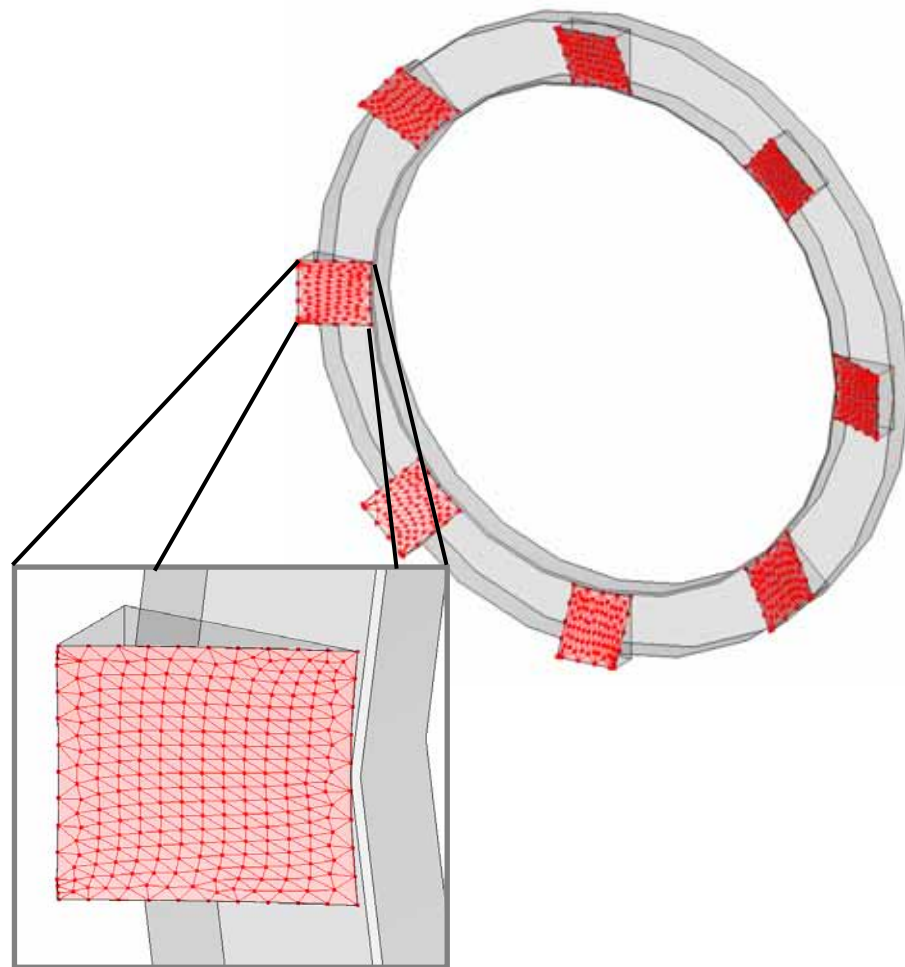


任意のモニタリング面を選択可能



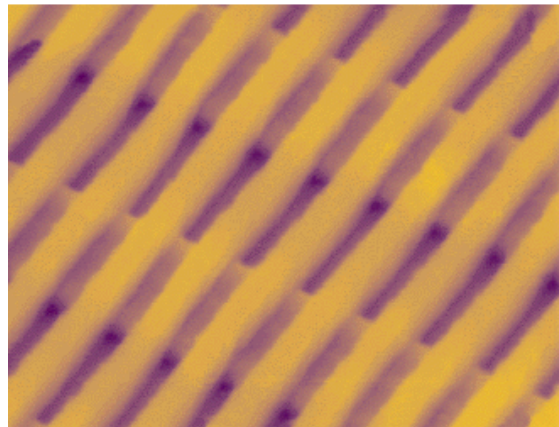
Phasespace of plane in W-direction, distance to

マルチビーム電子銃

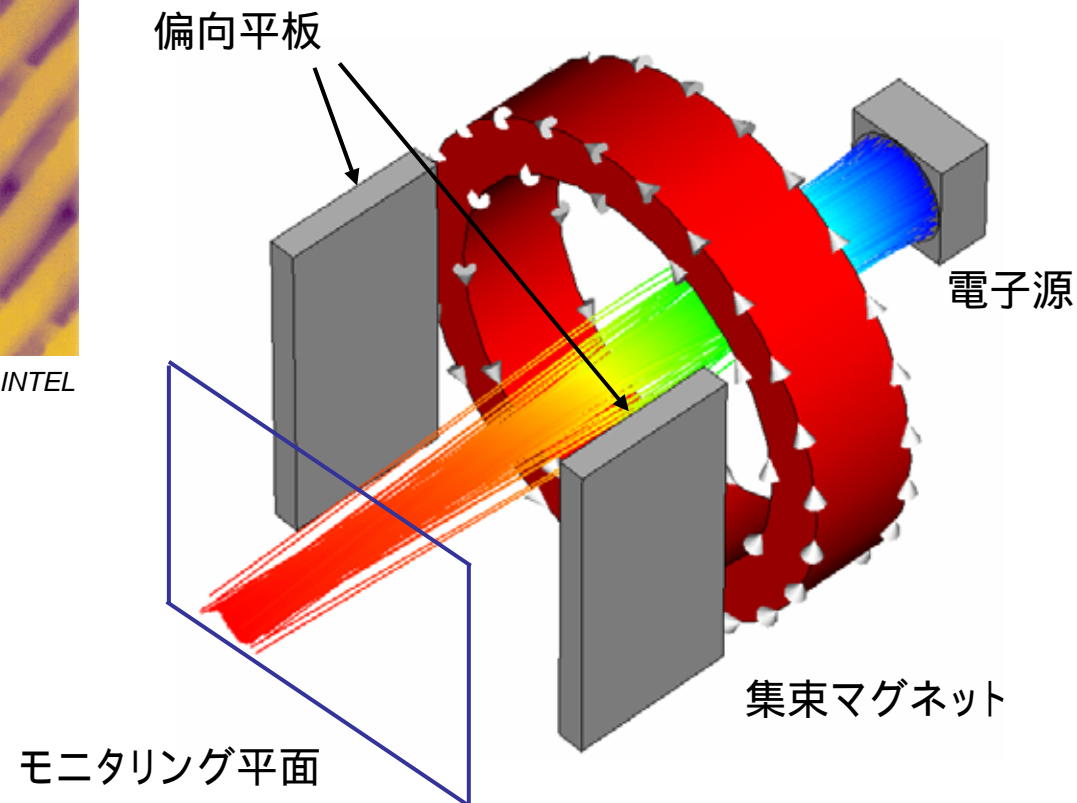


チップ製造用リソグラフィ電子ビーム

チップ上に直接マスクパターンを作るための電子ビームの使用
半導体マスク

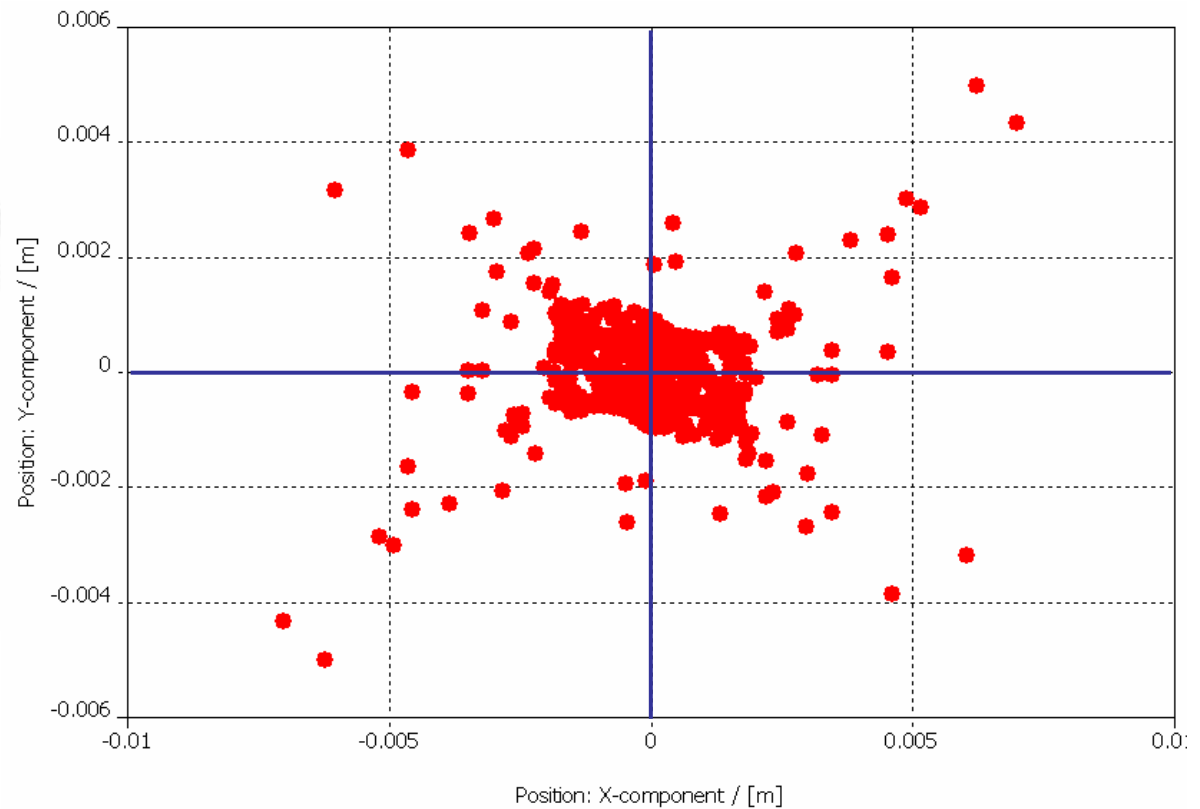
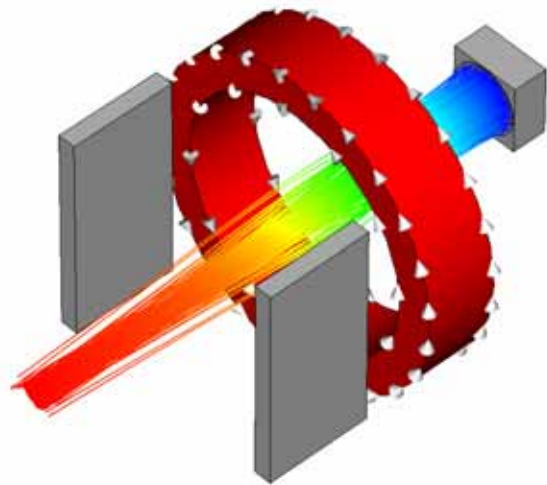


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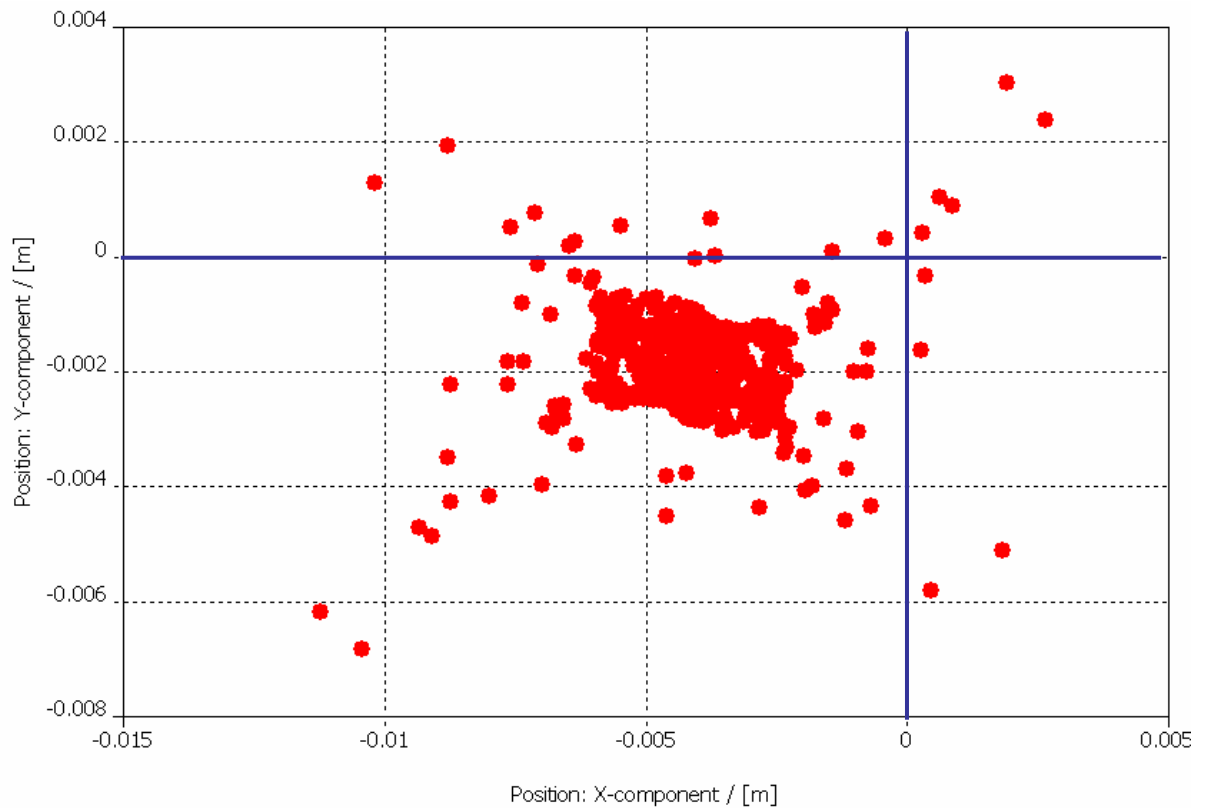
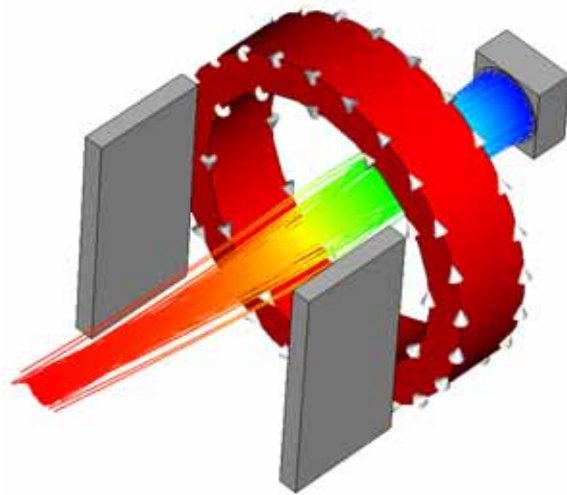
リソグラフィビーームの偏向

偏向電圧: 0V



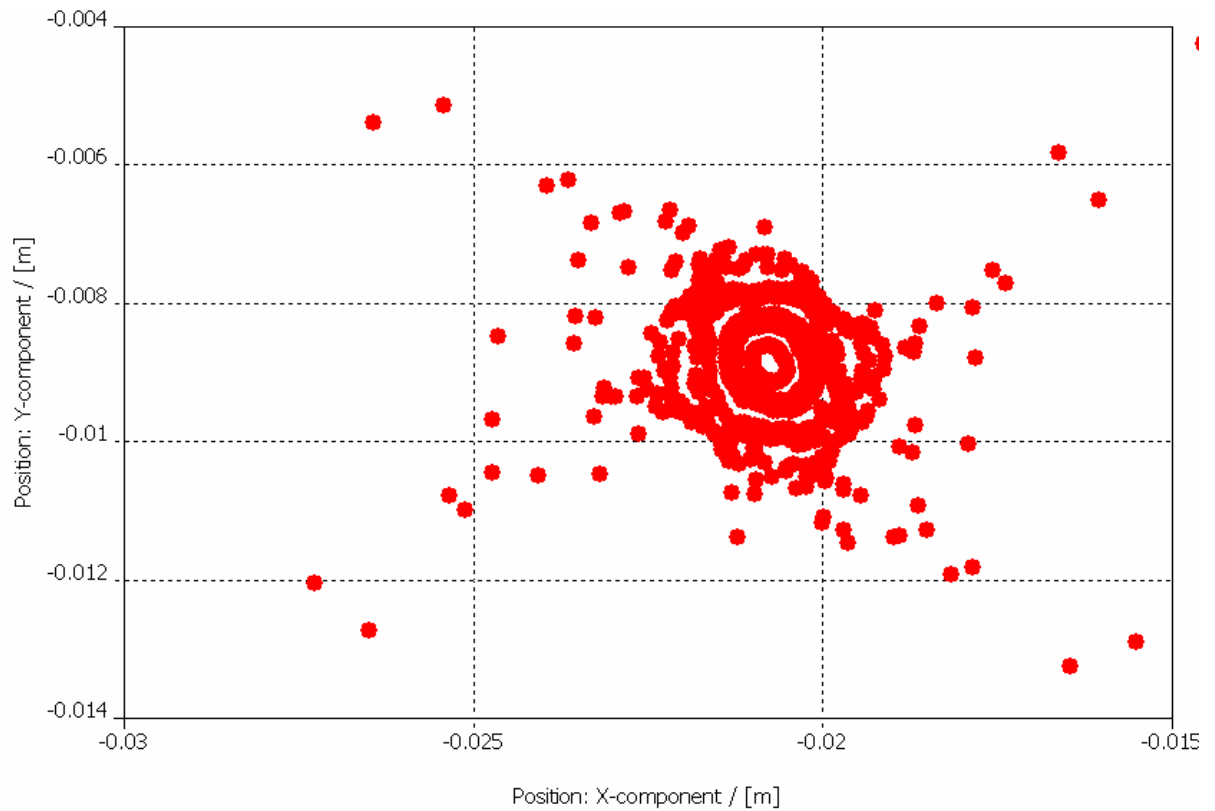
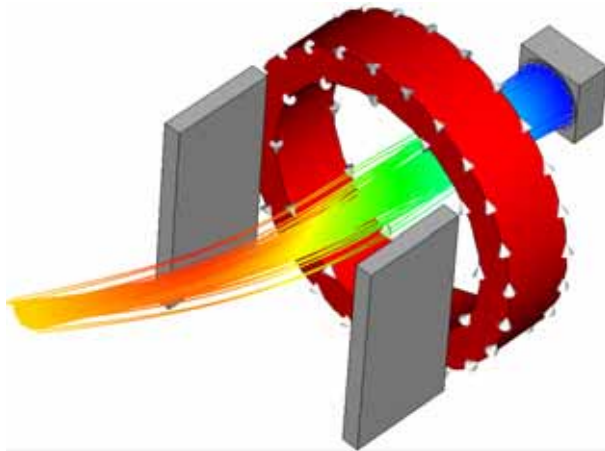
リソグラフィビーームの偏向

偏向電圧: 2kV



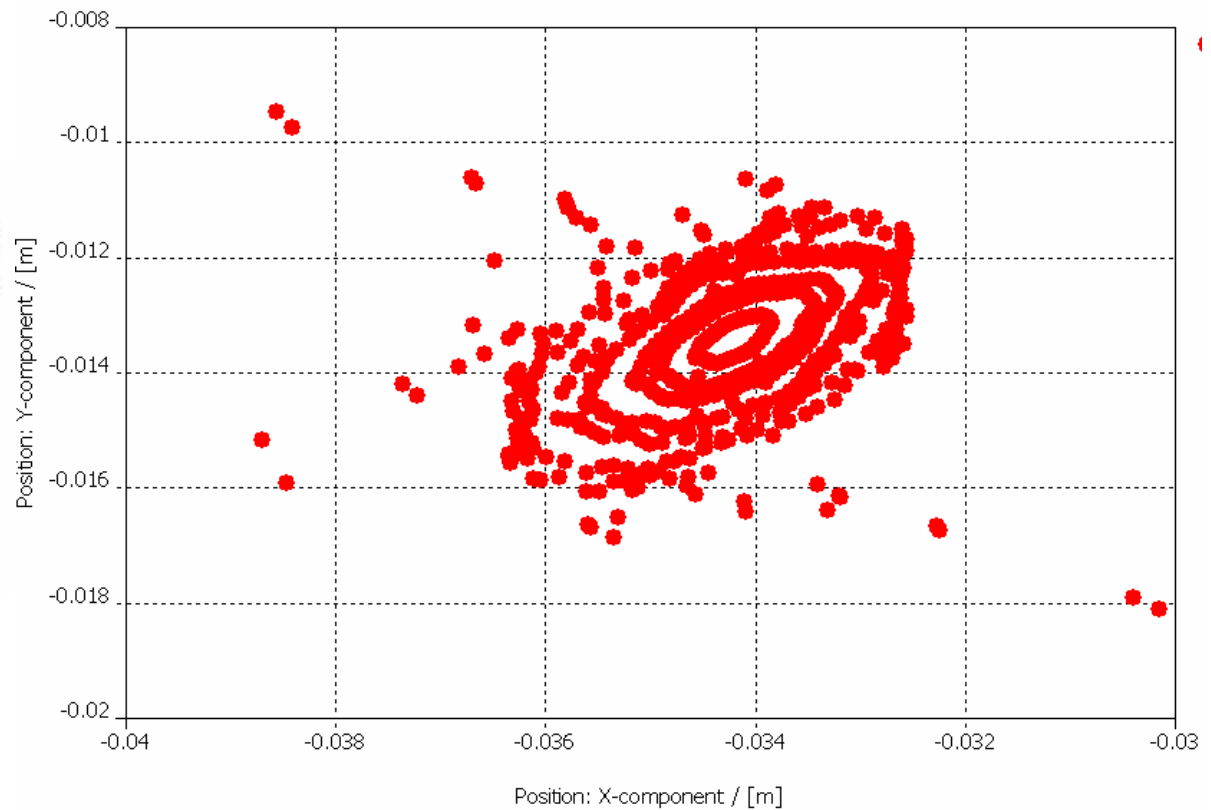
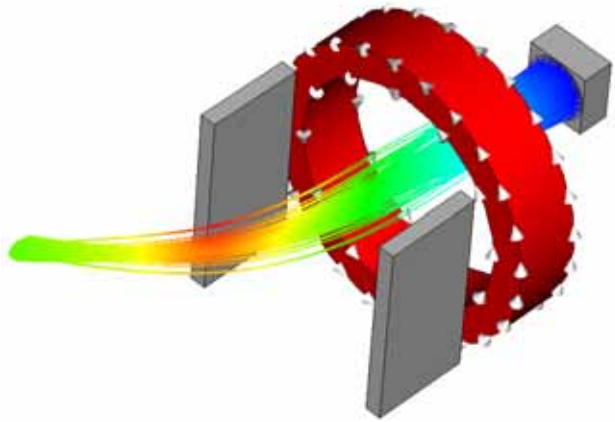
リソグラフィビーームの偏向

偏向電圧: 10kV

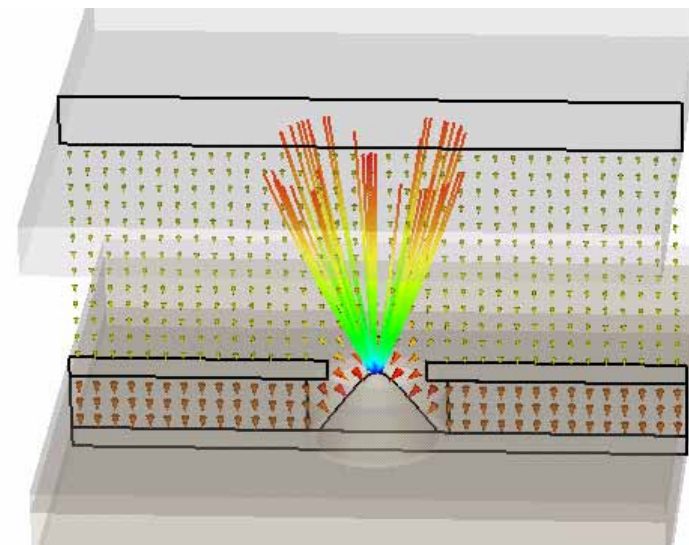
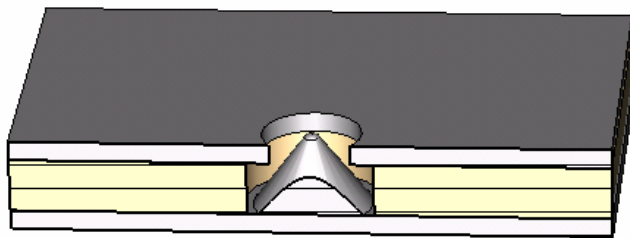
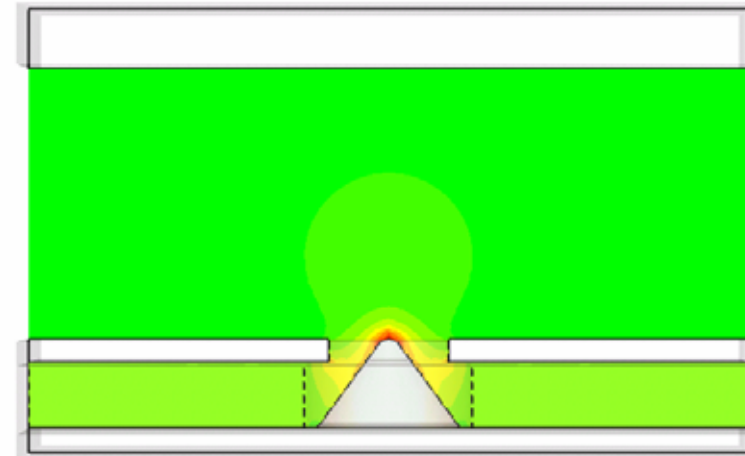
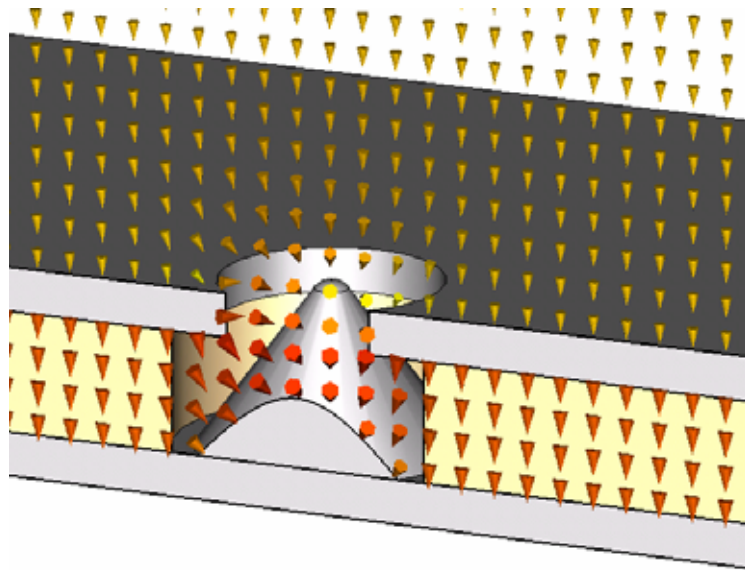


リソグラフィビーームの偏向

偏向電圧: 16kV



フィールドエミッター



MAGICにおける粒子源の定義

16. EMISSION PROCESSES

This chapter covers the following commands:

- [EMISSION \[options\]](#)
- [EMISSION BEAM](#)
- [EMISSION EXPLOSIVE](#)
- [EMISSION GYRO](#)
- [EMISSION HIGH_FIELD](#)
- [EMISSION PHOTOELECTRIC](#)
- [EMISSION SECONDARY](#)
- [EMISSION THERMIONIC](#)
- [EMIT](#)
- [PHOTON](#)
- [IONIZATION](#)

You can use these commands to describe the emission of charged particles from the surfaces of an object.

Most of the parameters required for the emission models are specified using default values. You can change any of these values using the [EMISSION \[options\]](#) command. You can use the rest of the EMISSION commands to create customized models of the following emission processes:

BEAM	— an arbitrary, prescribed beam.
EXPLOSIVE	— field-extraction from a surface plasma.
GYRO	— a prescribed beam for gyro devices.
HIGH_FIELD	— high-field (Fowler-Nordheim) emission.
PHOTOELECTRIC	— photoelectric emission.
SECONDARY	— secondary emission.
THERMIONIC	— thermionic emission.

The first three are "artificial" emission processes (as opposed to fundamental processes that involve the work function). In [BEAM](#) emission, the beam properties are assumed to be known a priori and are simply prescribed, without regard for the underlying fundamental processes. For example, it can be used to model a beam that enters a cavity, without including the processes that create the beam in the first place. In [EXPLOSIVE](#) emission, one or more species is extracted from an assumed surface plasma, a phenomenon typically encountered in pulsed-power applications. The underlying processes of high-field emission and joule heating, which produce the plasma, are considered only phenomenologically. The surface plasma is assumed, but not actually modeled with particles. Instead, particles are created with charge sufficient to cause the normal electric field at the surface to vanish. This zero, or near-zero, surface field is a distinguishing feature of [EXPLOSIVE](#) emission. [GYRO](#) emission is really a special case of [BEAM](#) emission in which the controls have been adapted specifically for gyro (rotating beamlet) applications.

The last four represent fundamental emission processes, in which energy is supplied to overcome a work function. In [HIGH_FIELD](#) emission, the energy is supplied by the ambient electric field and results in quantum-mechanical tunneling. The electron yield thus varies with the electric field on the surface according to the Fowler-Nordheim equation. In [PHOTOELECTRIC](#) emission, the energy to overcome the work function is supplied by an incident photon. The energy spectrum of the emitted electrons depends on the incident photon spectrum, and a transport code is typically used to compute the electron energy spectrum, which is required input for this emission model. The spatial distribution of the photon flux is specified with a [PHOTON](#) command, used only in conjunction with [PHOTOELECTRIC](#) emission. In [SECONDARY](#) emission, the energy to overcome the work function is supplied by energetic charged particles that are incident upon a conducting surface. The electron yield varies with the material and the angle and energy of the incident particle. In [THERMIONIC](#) emission, the energy to overcome the work function is thermal, and the electron yield varies with the surface temperature, according to the Richardson-Dushman equation.

Once an emission model has been created, you can enable emission on a particular object by using the EMIT command. In 3D simulations, the EMIT command can be used only with volume objects ([VOLUME](#), Ch. 10) and not from points, lines, or areas. In 2D simulations, the EMIT command can be used only with area objects ([AREA](#), Ch. 10). In both cases, the spatial objects must be perfectly conducting ([CONDUCTOR](#), Ch. 14).

The following table presents some general guidelines on the selection of emission algorithms. Alternatives are best used only with a good understanding of the

Cont'd

The screenshot shows a window titled "MAGIC Help" with a menu bar containing icons for "非表示" (Hide), "戻る" (Back), "印刷" (Print), and "オプション(O)" (Options). Below the menu bar are three tabs: "目次(C)" (Table of Contents), "キーワード(N)" (Keywords), and "検索(S)" (Search). The left pane shows a tree view of the help content, with "EMISSION PHOTOELECTRIC" selected under "16. Emission Processes". The right pane displays the documentation for the "EMISSION PHOTOELECTRIC Command".

EMISSION PHOTOELECTRIC Command

Function: Specifies a photoelectric emission process.

Syntax:

```
EMISSION PHOTOELECTRIC photon_source f(e) yield photon_energy [options] ;
```

Arguments:

- photon_source — name of photon source, defined in [PHOTON](#) command.
- f(e) — electron energy function (electron/kev), defined in [FUNCTION](#) command (type DATA only).
- yield — conversion yield (electrons/photon).
- photon_energy — average photon energy (keV).
- options — see [EMISSION \[options\]](#) command.

Defaults:

None, except for the option defaults. The EMISSION PHOTOELECTRIC command must be entered for this model to be used.

Description:

The photoelectric emission process is described by the equations,

$$\frac{d^5 q}{dA dt dE \sin \theta d\theta} = \frac{1}{\pi} \eta s(t) f(E) \cos \theta$$

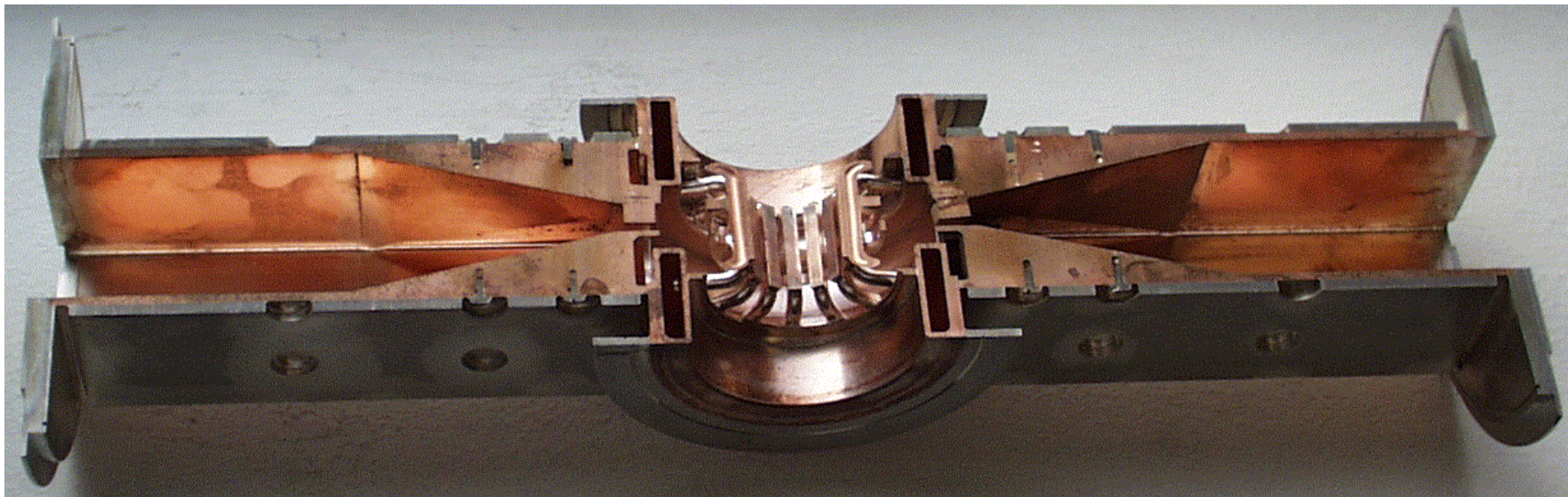
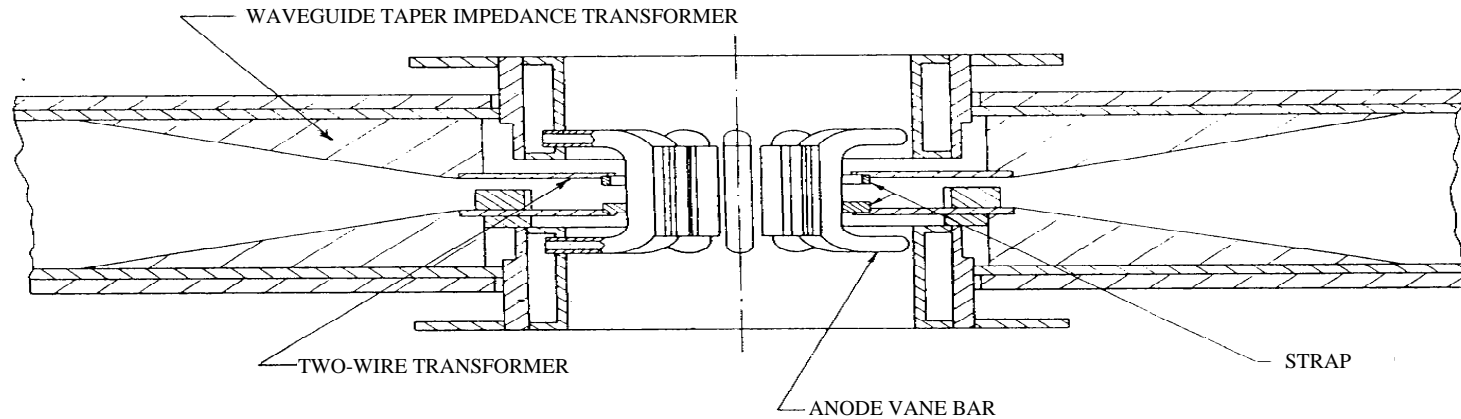
where

$$\eta = -41.87 \eta' \chi(r) / \varepsilon .$$

The definitions of these quantities is listed below:

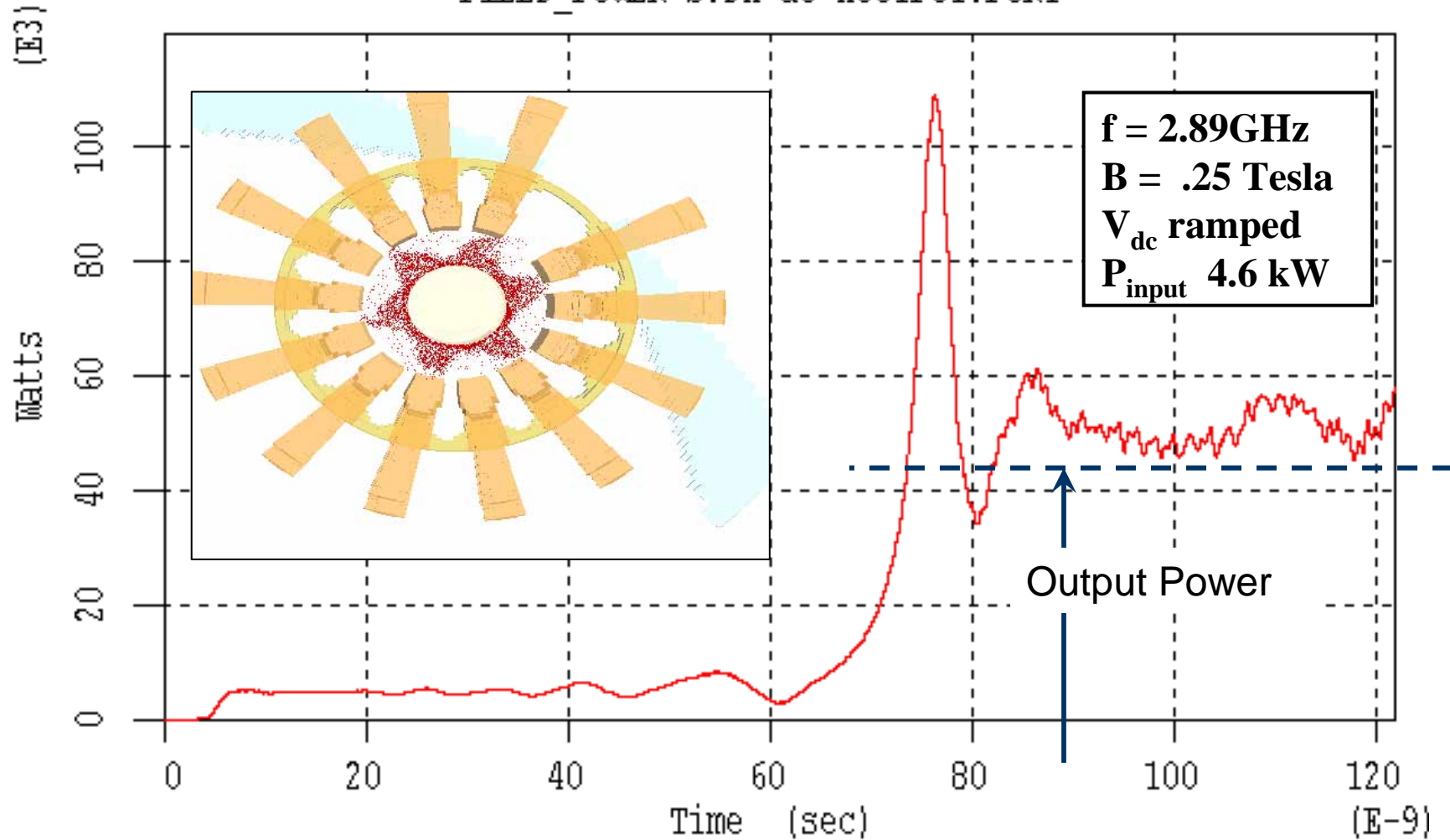
- E — represents the electron energy (keV).

Using MAGIC3D to model the Baby Amplitron L4717



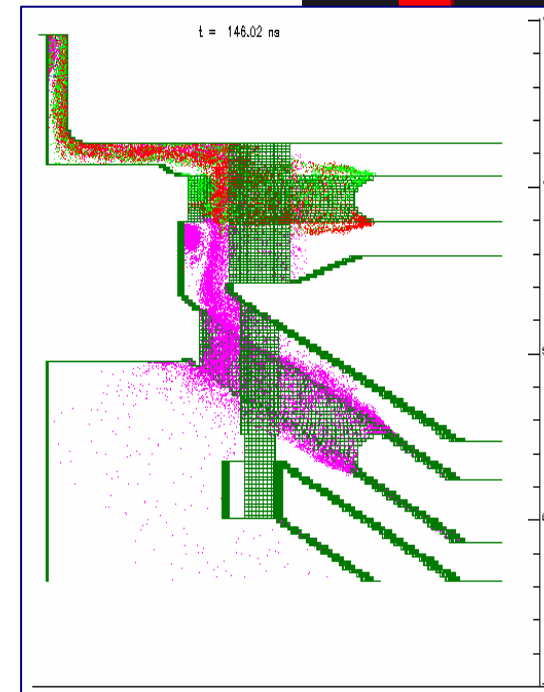
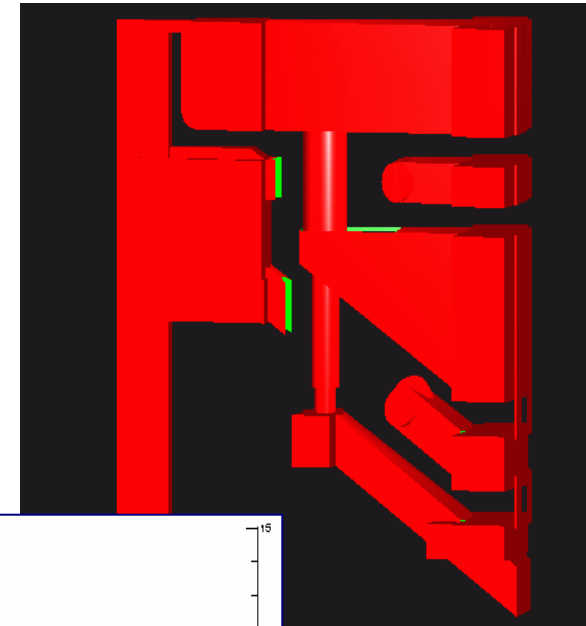
Hot Test: Output Power

FIELD_POWER S.DA at XOUTPUT.PORT



LSP ATK-Mission Systems (米)

- PIC(Particle-in-cell)による大規模電磁気プラズマ用3次元電磁界解析コード
- 多様な電磁界・荷電粒子の解析が可能
 - 電界放出
 - トランсмッションライン境界
 - 誘電体
 - 分散的な磁気材料
 - 二次電子放出
 - 中性粒子のイオン化
 - 表面加熱と表面からの中性粒子の脱離
 - ...



まとめ

- 荷電粒子放出に関する理論モデルの多くは考慮されている
- ただし、メッシュを十分に細かくするなどの適切な処置は必須
- 副分割などの対応は市販のコードでも装備 (FEAも計算可能)
- コード開発に時間を割いた場合のコストも要検討 (あるものは利用してしまおう！)
- 最終的には、他分野、また設計や教育にも広く使われる (社会貢献!!)

Fin.



Hardware, Software and Professional services