P^3 2021

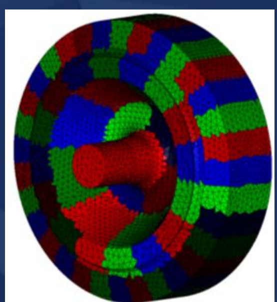
2021 Photocathode Physics for Photoinjectors Workshop

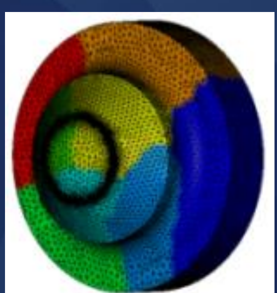
SLAC National Accelerator Laboratory

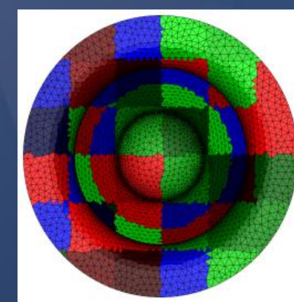
10-12 November 2021

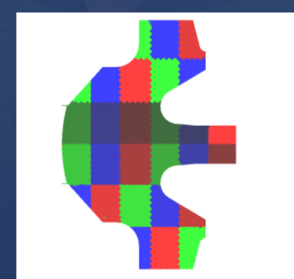
Virtual

Chemical and Geometric Contributions to Intrinsic Emittance for Electron Emission









John Petillo, Aaron Jensen, Serguei Ovtchinnikov

Leidos, Inc.

Kevin Jensen

US Naval Research Laboratory

Work supported by NRL and Leidos

Outline

I. Background and Motivation/Discussion

II. Chemical Contribution to Emittance (Work Function Variation)

III. Artificial (Ordered) Geometric Surface Array Contribution to Emittance

IV. Less Artificial (Non-Ordered) Geometric Surface Array Contribution to Emittance

V. Comparison of Contributions to Emittance

VI. Application: 1 Micron Work Function Patch Size with 10 Micron Feature Size

I. Summary

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Motivation

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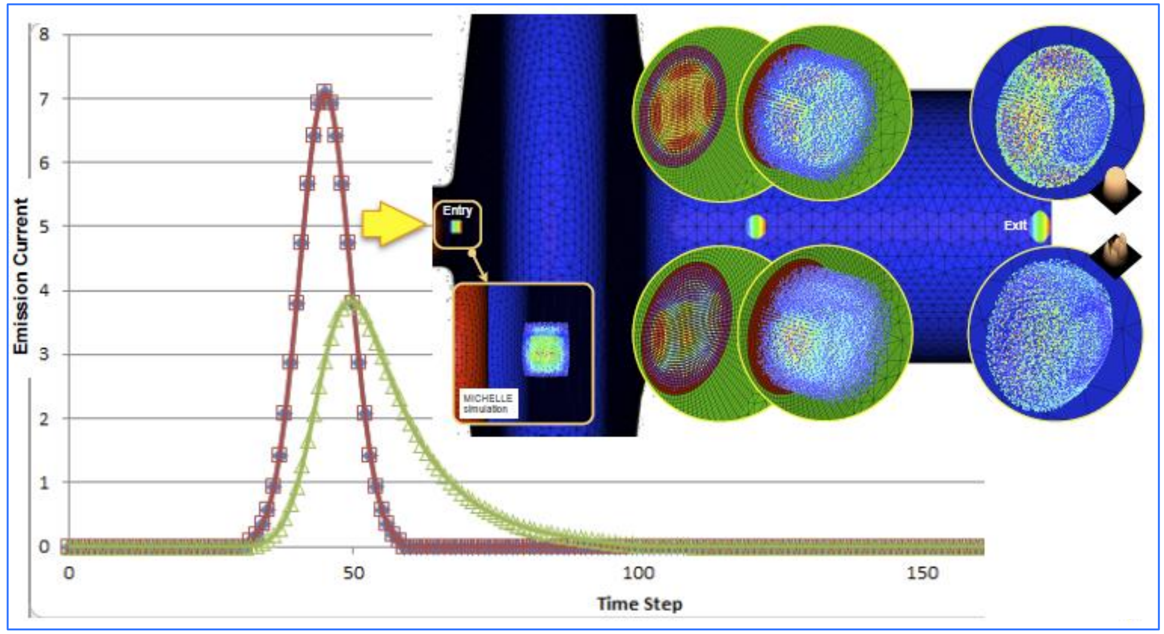
1. Regime of interest:
   - Presentation for regime where space charge effects are not important.
2. Geometric Contribution:
   - Previously reported on a “bumpy” surface formulation that captures the characteristics of surface features on some photoemitters enabling the inclusion of mean transverse energy (MTE) in calculations.
     - Here we use the mathematical surface as a boundary to our mesh generation.
     - Confirmed that simulation reproduces analytical solution for particle distributions and optics.
3. Chemical Contribution
   - In the DARPA INVEST program we showed that the microscopic makeup of the emission surface is the cause of the shape of the Miram curve
     - Miram Curve: Indicates anode current for thermionic emitters as a function of emitter temperature.
     - Curve rolls over as space charge begins to limit the current that makes it out of the potential well that forms.
     - Smooth extended Roll-Over shape is primarily caused by emitter surface chemical makeup
     - Otherwise a relatively sharp transition takes place.
     - Shown to have a significant effect on intrinsic emittance
4. Capturing Emission Distribution
   - Previously have shown that micro/meso-scopic effects lead to specific velocity distributions and emittances.
   - Developed an ability to capture velocity distributions for sample patches and present this distribution to macroscopic-sized regimes.
5. Combination of Effects
   - How does this all play out?

Models in the MICHELLE Code: Historical Slide

Phototemission Model

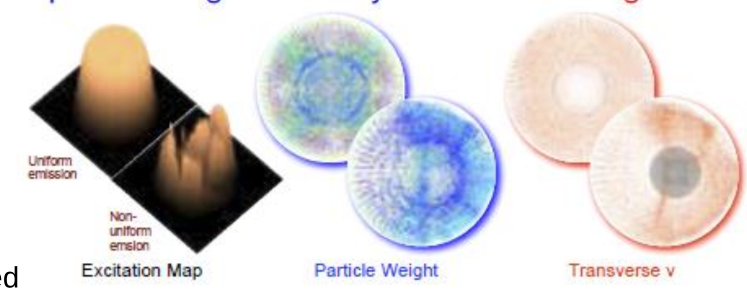
- Delayed Emission model incorporates material properties (m; EG; n & k; R; ; DOS) for metal, semiconductor, and coated material photocathodes
- Geometry / Field enhancement modeled using an impulse approximation to the launch velocity of electrons
- Ability to characterize and model surface roughness
  - Capture emission statistics



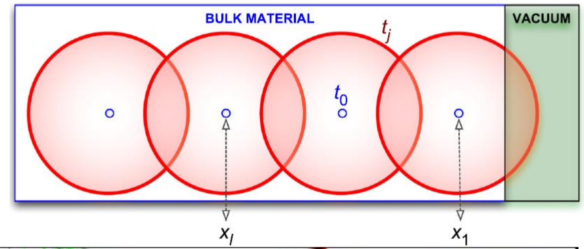
Particle Emission Library

- Have separated out the entire MICHELLE emission model set
- Now exists in a library form
- Callable from
  - Leidos' MICHELLE (C++)
  - Leidos' eBEAM
  - NRL's NEPTUNE
  - AFRL's ICEPIC
  - Fortran 90 (& F77) – codes like LBL's IMPACT-T

Nonuniformity + geometry ↔ transverse
Space Charge + density variation ↔ longitudinal

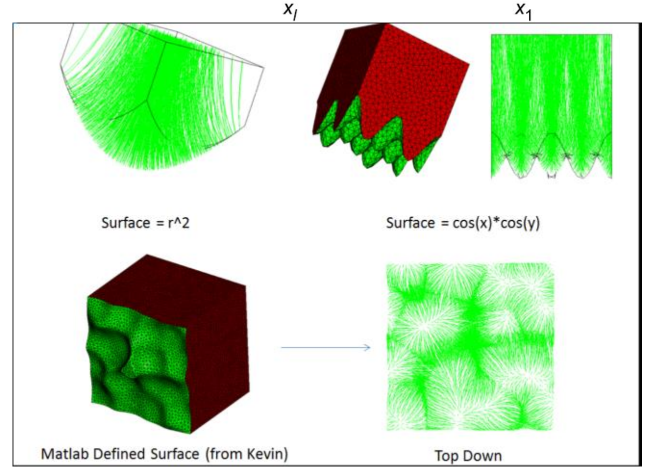


Particle Emission & Surface Roughness: Historical Slide

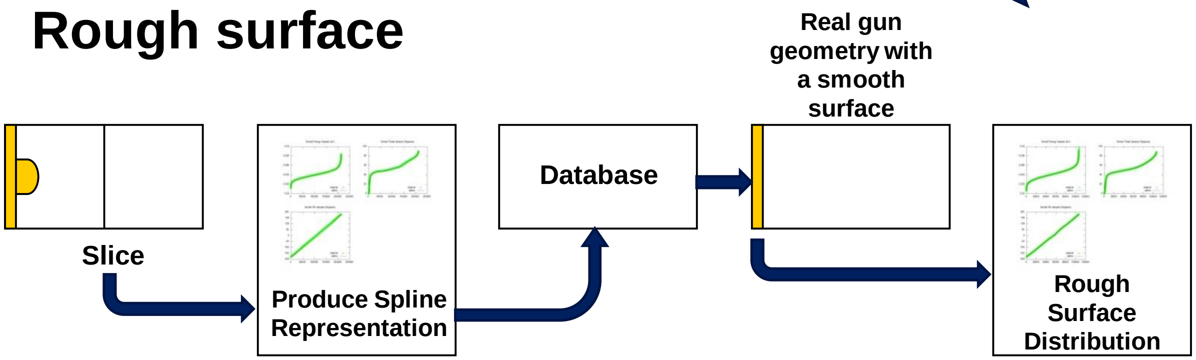


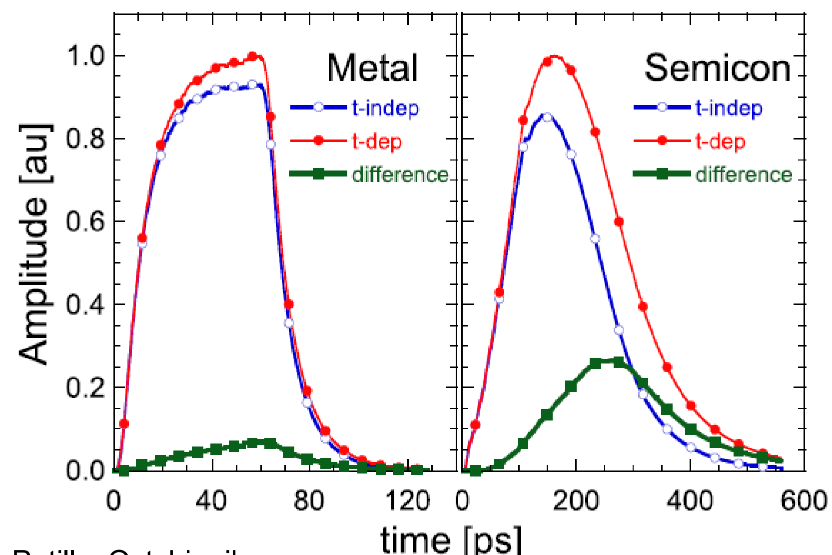
Particle Emission Models:

- New delay model (laser penetrates deep into the material)
- Rough surface model - analytic
  - Produces distributions allowing MICHELLE to re-emit from a macroscopically flat surface and capture these dynamics
  - Method works with SD & TD
- All the above properties affect the intrinsic emittance and the formation of beam halos & tails



Rough surface

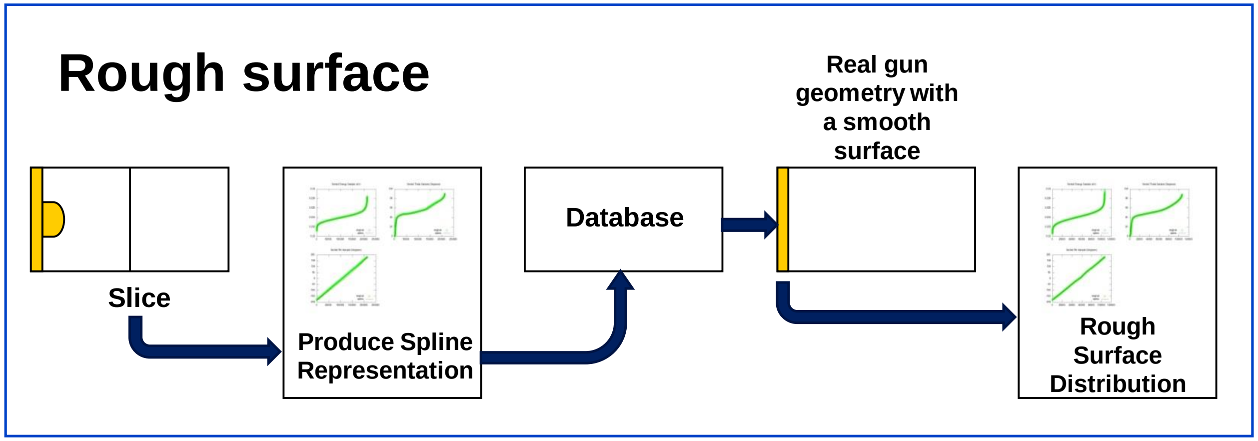


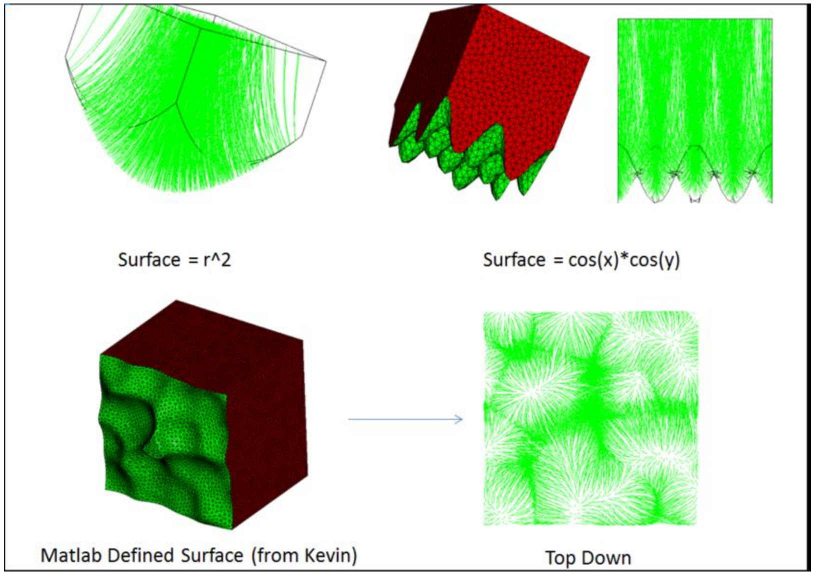


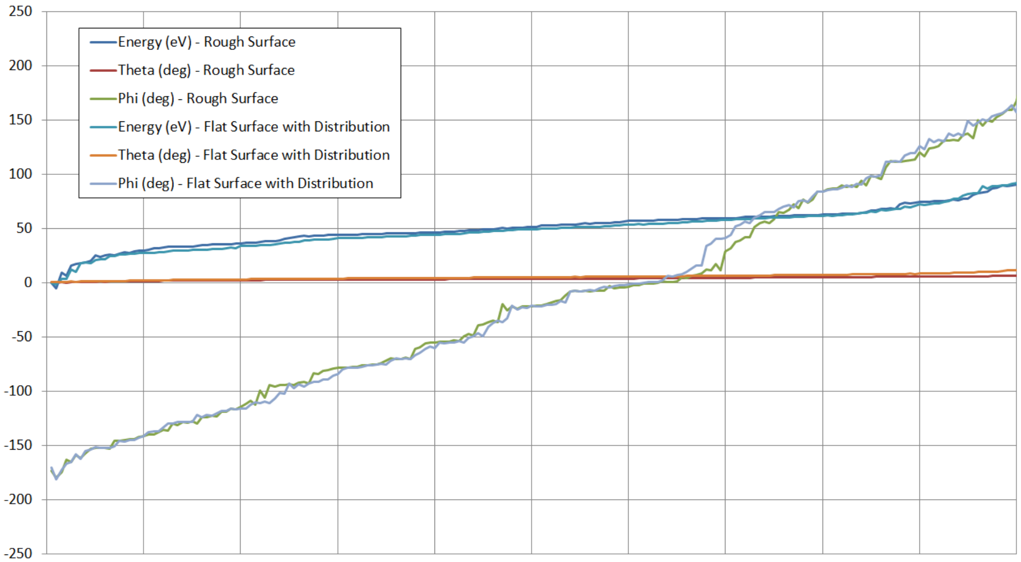
“Modeling emission lag after photoexcitation”, Jensen, Petillo, Ovtchinnikov, Panagos, Moody, & Lambrakos, J. of Applied Physics 122, 164501 (2017);

Particle Emission & Surface Roughness: Historical Slide

- Methodology used to capture emitted velocity and angular distribution
- Allows beam distribution calculated in a micro/meso-scopic simulation to be sampled and launched in a large scale macroscopic simulation







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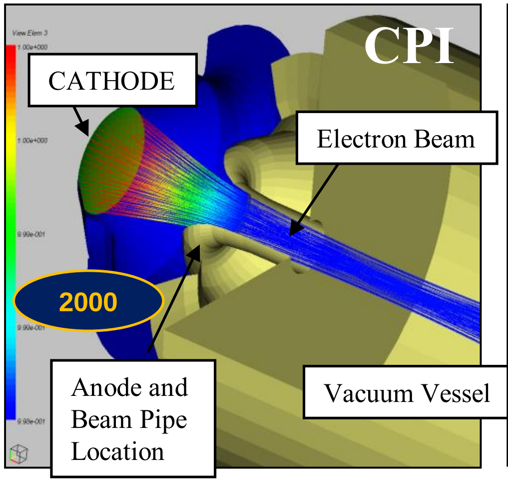
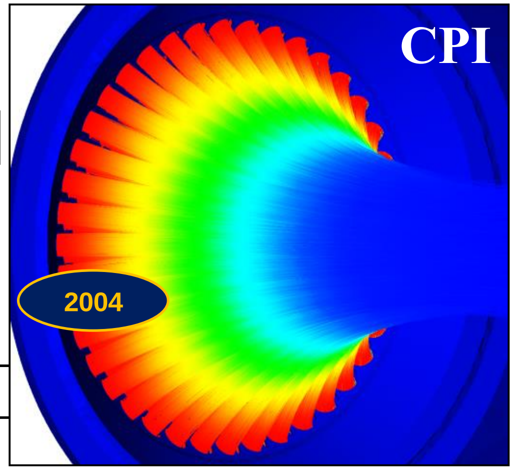
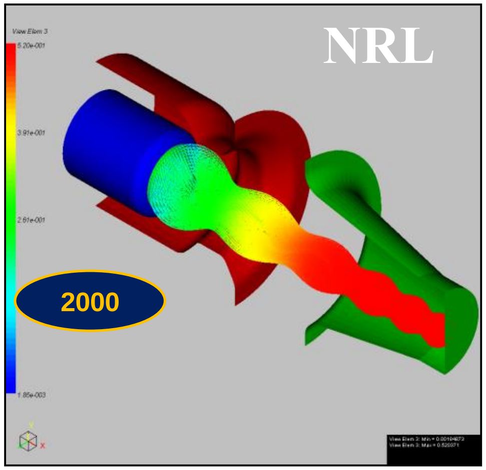
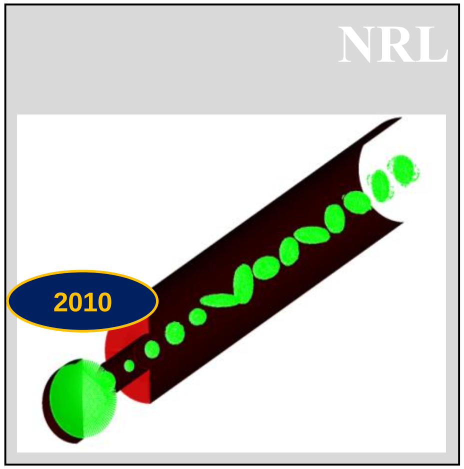
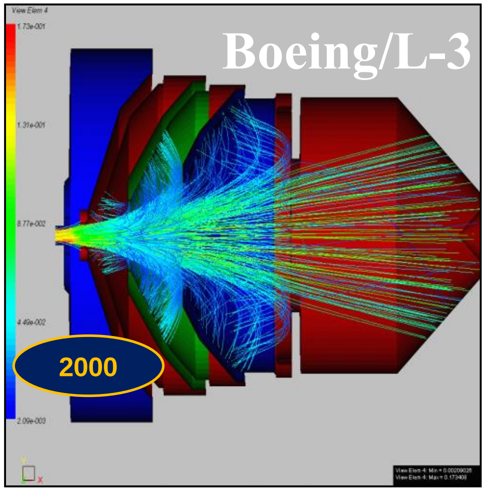
Traditional Voyager/MICHELLE Problem Classes

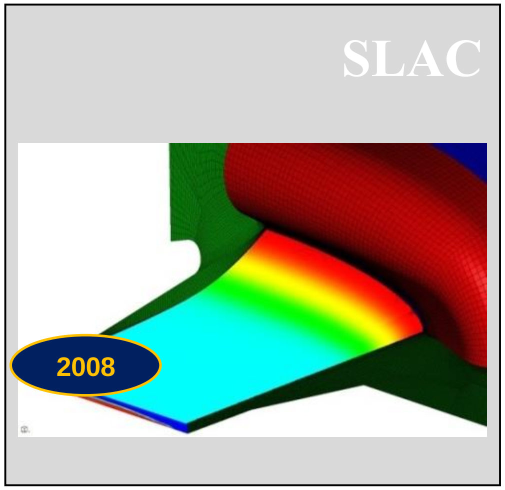


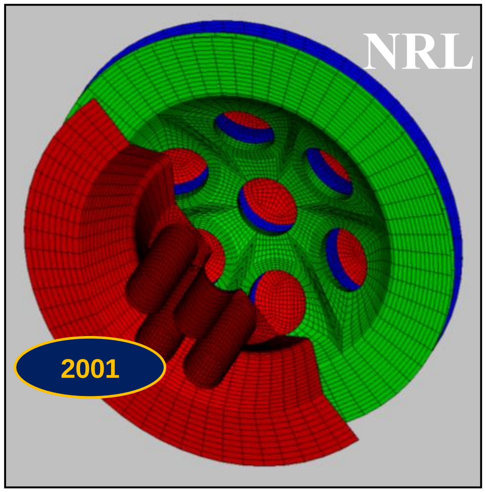


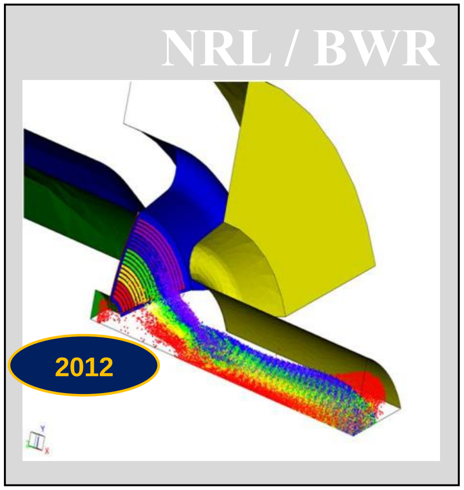




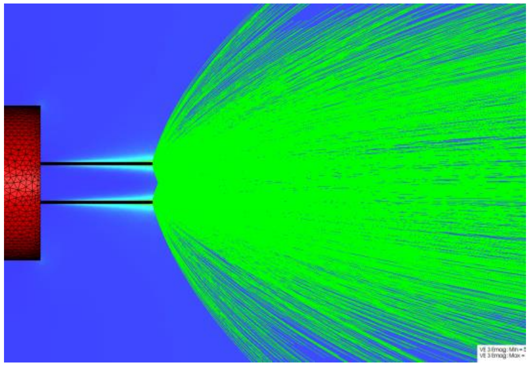


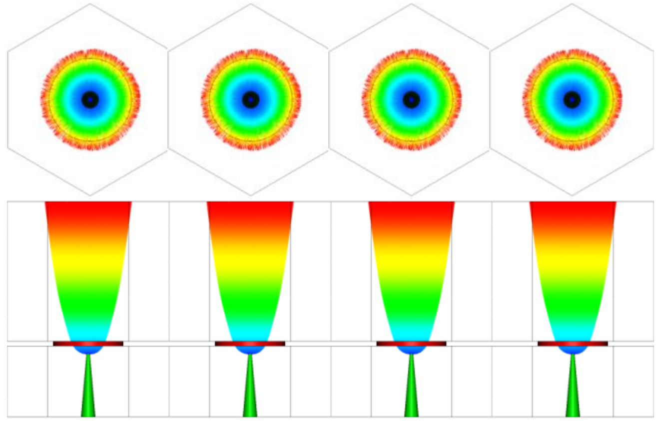


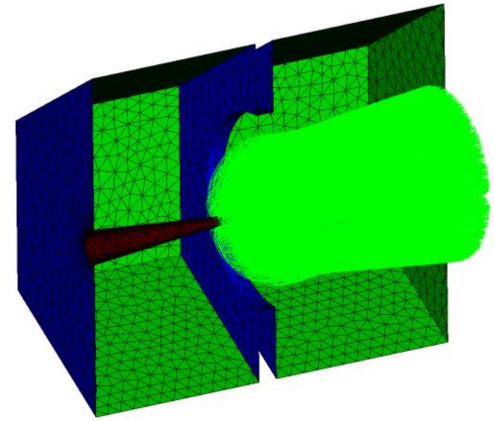


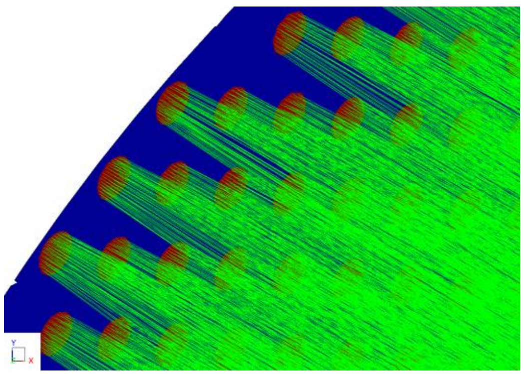


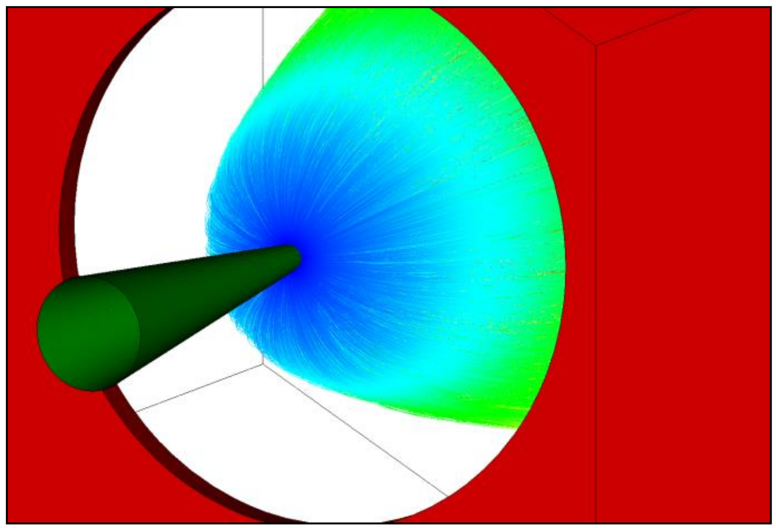
MICHELLE VE Problem Classes: Field Emission Arrays

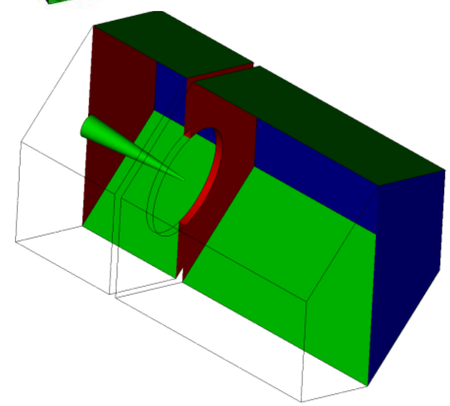


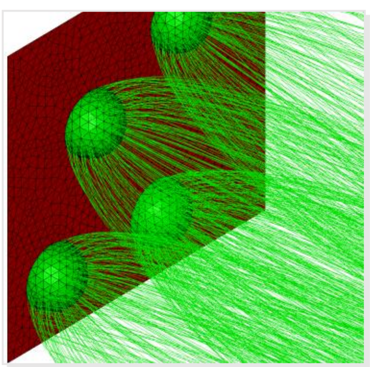


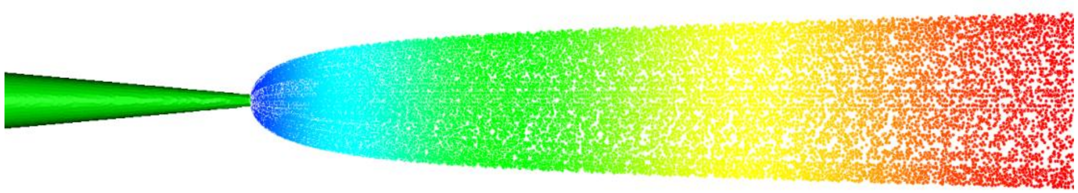


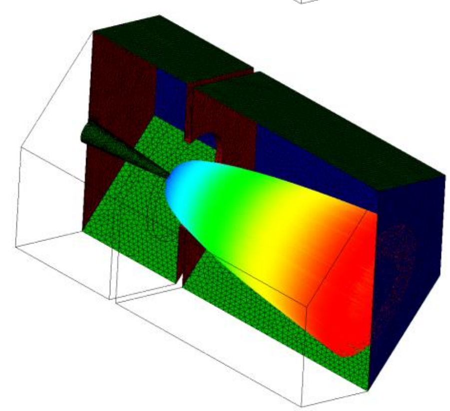












MICHELLE/Voyager

❑ Applications

- Charged Particle Beam Optics for VE, HPM, DE, Accelerator components (FELs)
- Electron guns, beam sources, transport, electron collectors
- Beams in RF cavities: RF photocathodes, IOTs ➔ including beam loading

❑ Algorithms

- Solvers
  - Steady-State ES PIC - “Gun” algorithm
  - Time-Domain ES PIC
- 2D & 3D Finite Element Electrostatic/Magnetostatic (self) Particle-in-Cell
  - Linear, quadratic, cubic bases
- Domain-decomposed Unstructured, Structured, & Hybrid mesh capable
  - Elements: Tetrahedra, hexahedra, prisms, pyramids, quads, triangles
- Circuit model: e.g., IOT RF cavity including beam loading
- Many physics-based emission models (Jensen/Dionne)

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Voyager/MICHELLE Version 7

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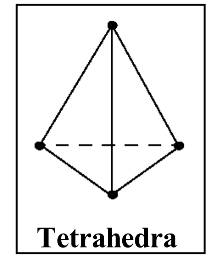
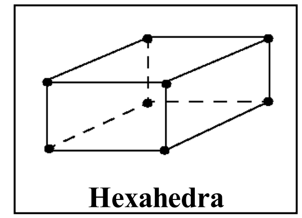
Gun (source), Collector and Transport Charged Particle Optics Modeling Code





Finite Element Approach – linear, quadratic, cubic

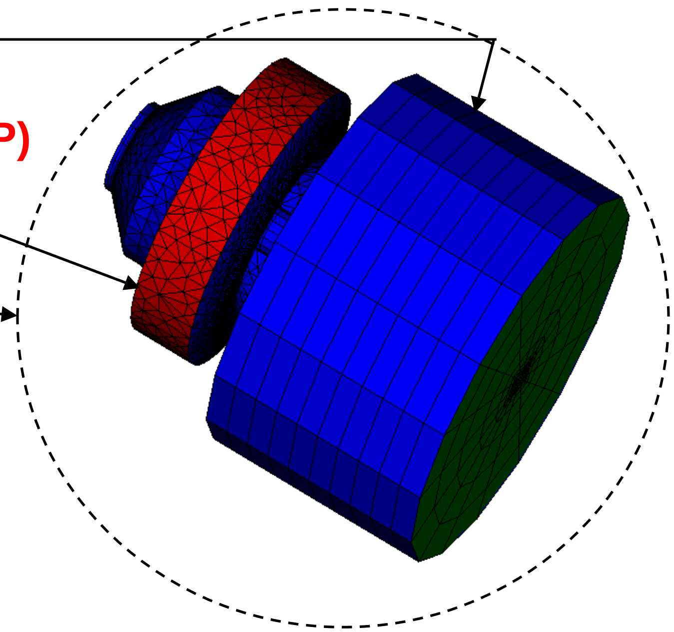
Two Electrostatic Particle-In-Cell (ES-PIC) methods

- SS: Equilibrium Steady-State PIC ("gun model")
- TD: Time Domain ES PIC

Grid System Supported - conformal

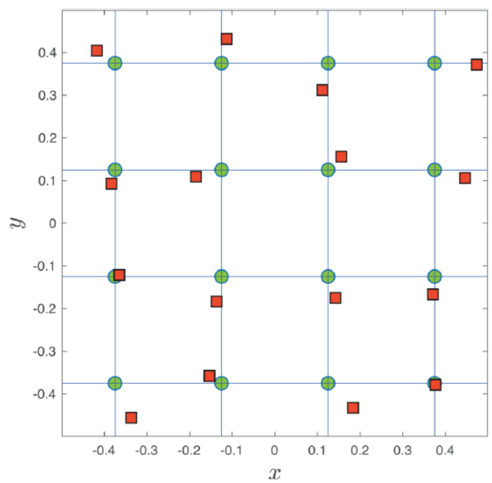
Within Voyager GUI with ICEM-CFD mesher

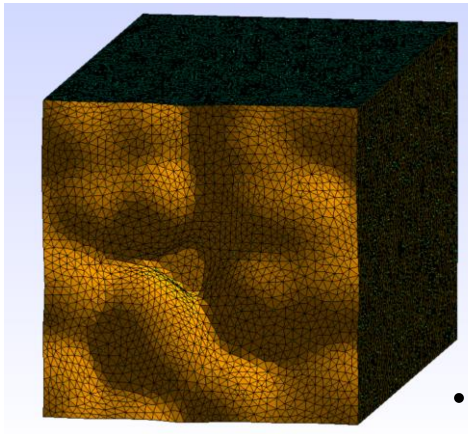
- Supports most high-end CAD modelers **(primitives: CUBIT, CAPSTONE, Gmsh, A-MP)**
  - we use SolidWorks
- Structured Mesh **(ICEM, Gmsh)**
  - 3D Multi-block, Hexahedral
- Unstructured Mesh **(ICEM, CUBIT, CAPSTONE, Gmsh, A-MP)**
  - 2D - Triangle, Quadrilateral
  - 3D - Tetrahedral, Hexahedral, Prism, Pyramid
- Hybrid Mesh
  - Single run Structured mesh and Unstructured mesh
  - Benefits: Compact data storage of a structured mesh for computational efficiency and improved particle tracking



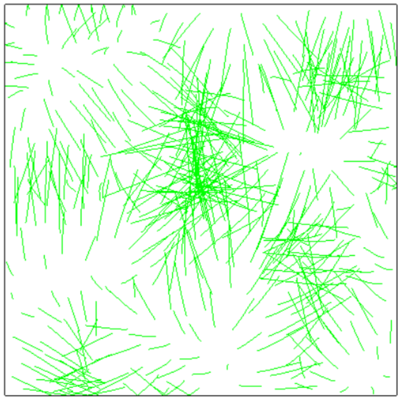
Fully integrated into *Analyst-MP* *(A-MP)*, Cadence/AWR's full-featured EM modeling environment

Mathematical Approximation of Geometrical Surface Features



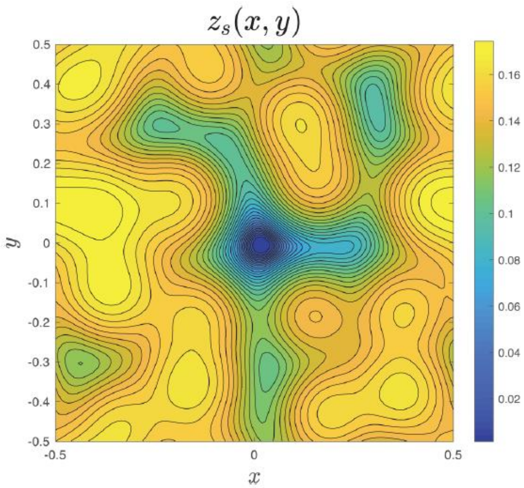


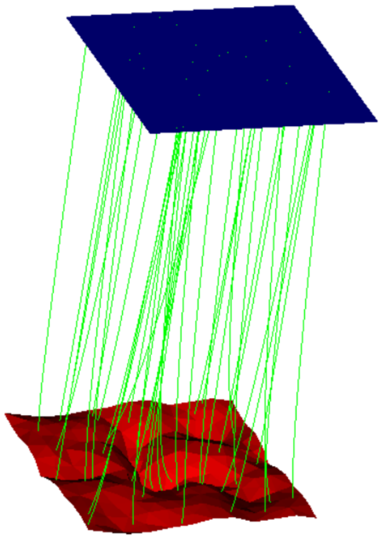
- Top down view of trajectories
- Macroparticle count reduced for emphasis

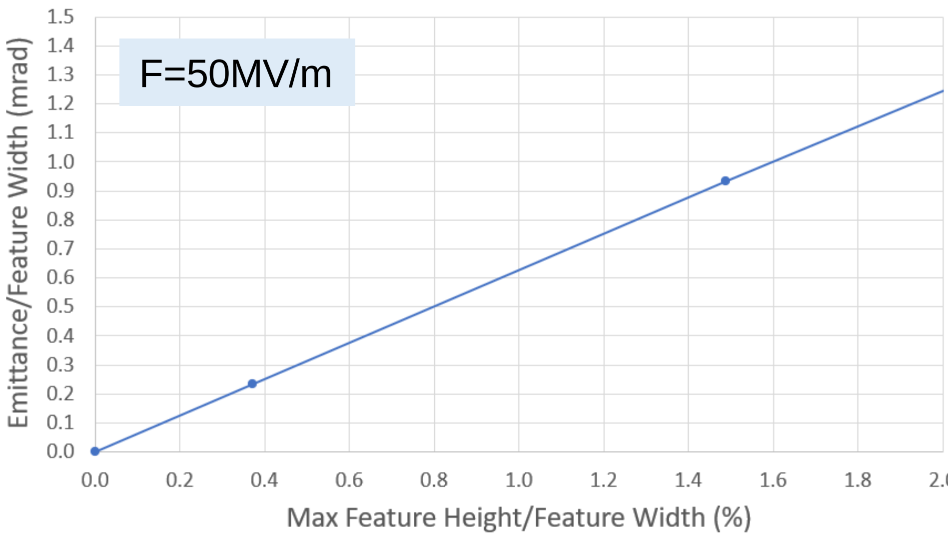


- Scale amplitude of rough surface
- Emittance ~4x higher than simple hemisphere
  - Even when normalized against max height feature

RMS Feature Height: 0.0346
Max Feature Height: 0.186
Feature Width: 0.25



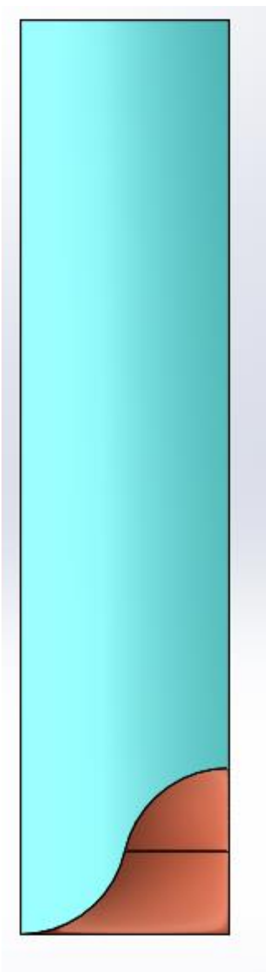


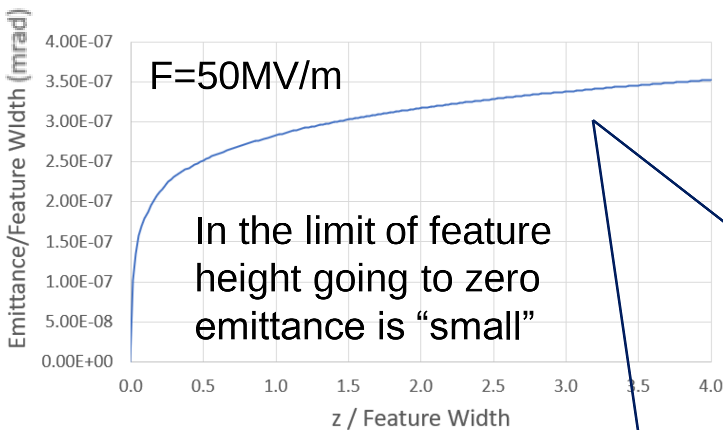


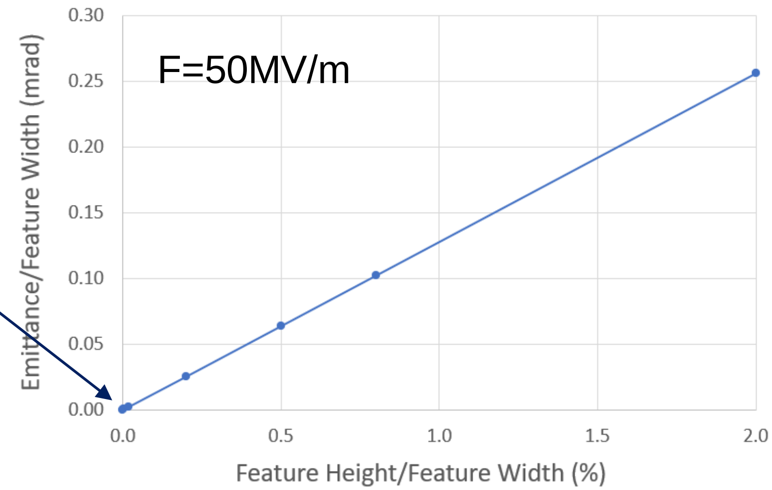
K.L. Jensen, M. McDonald, O. Chubenko, J.R. Harris, D.A. Shiffler, N.A. Moody, J.J. Petillo, and A.J. Jensen, “Thermal-field and photoemission from meso- and micro-scale features: Effects of screening and roughness on characterization and simulation”, J. Appl. Phys. **125(23)**, 234303 / 1-25 (2019). 10.1063/1.5097149

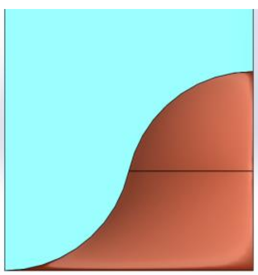
Infinite Array of Simple Hemispheric Geometrical Surface Features

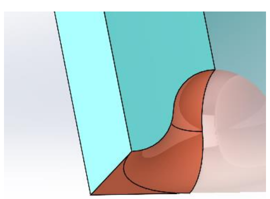
Hemispheric feature emittance



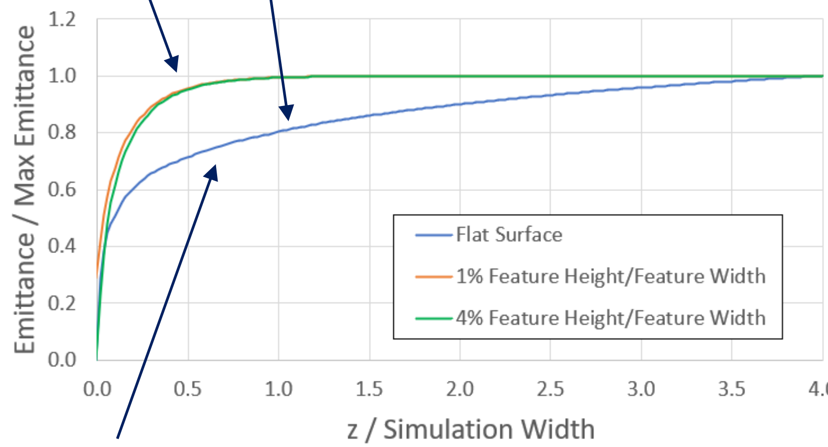


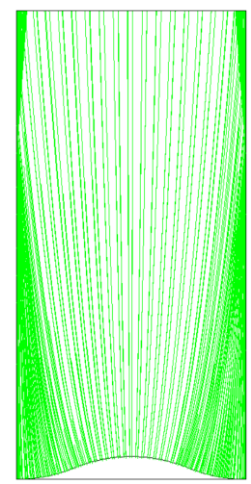






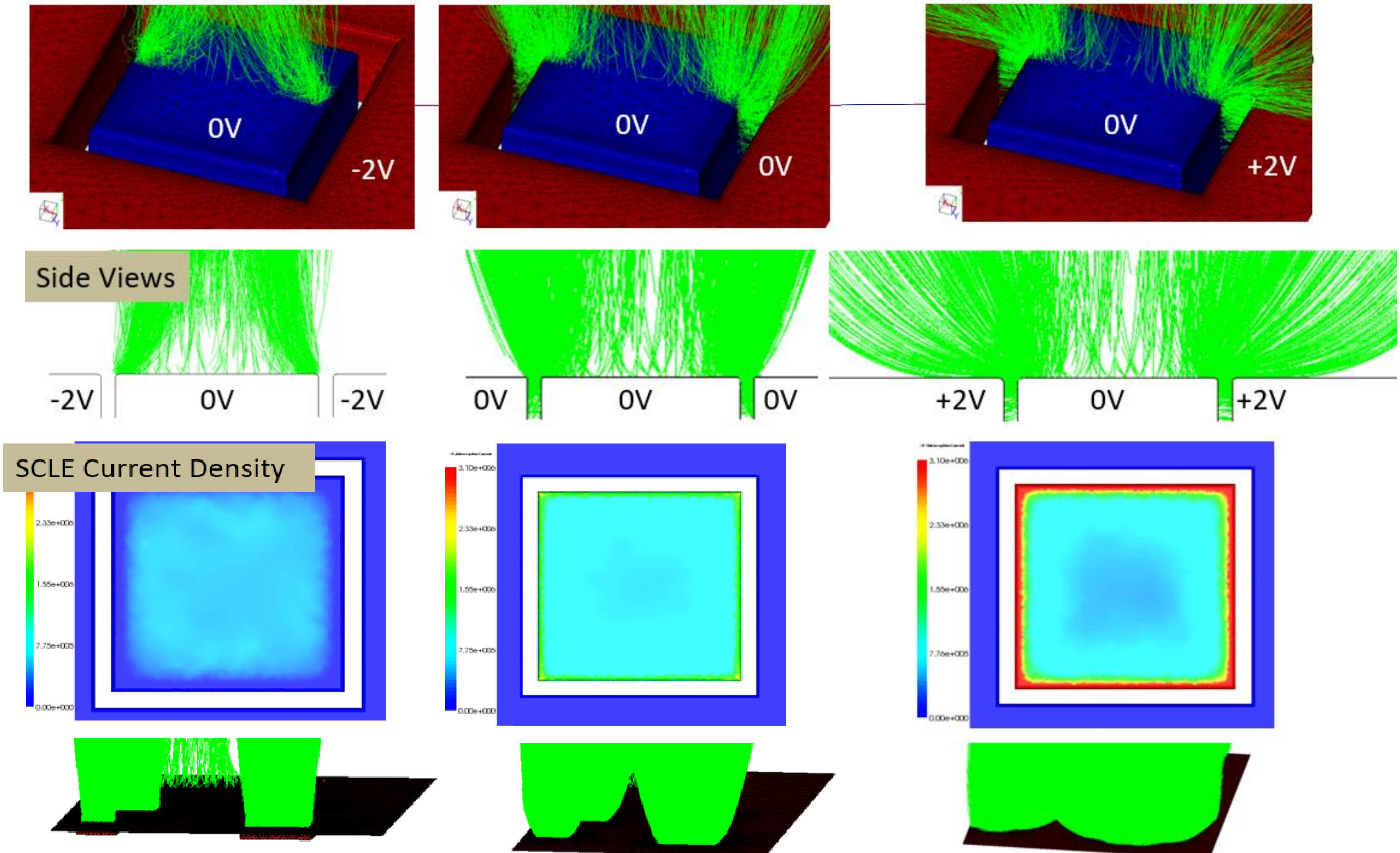
Emittance dominated cases come up quickly





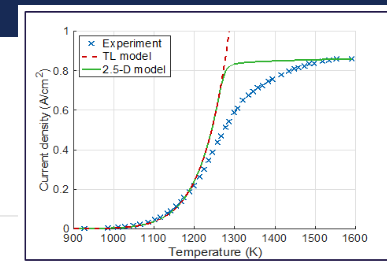
For a flat surface noise dominates and emittance grows slowly

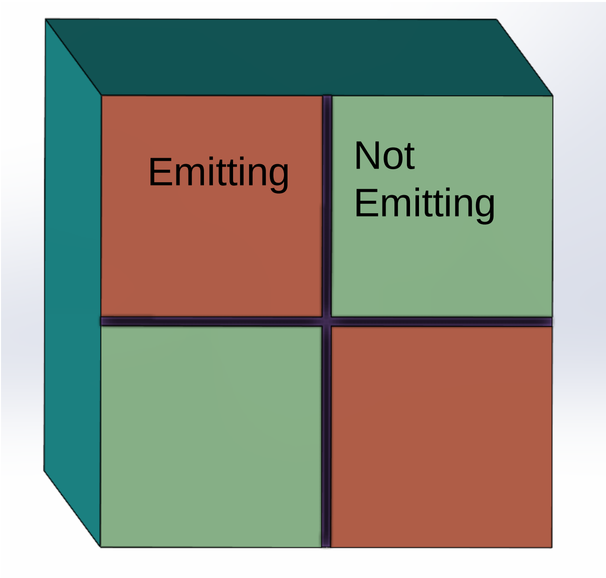
Space Charge and Patch Fields Modify Emission Characteristics for Thermionic



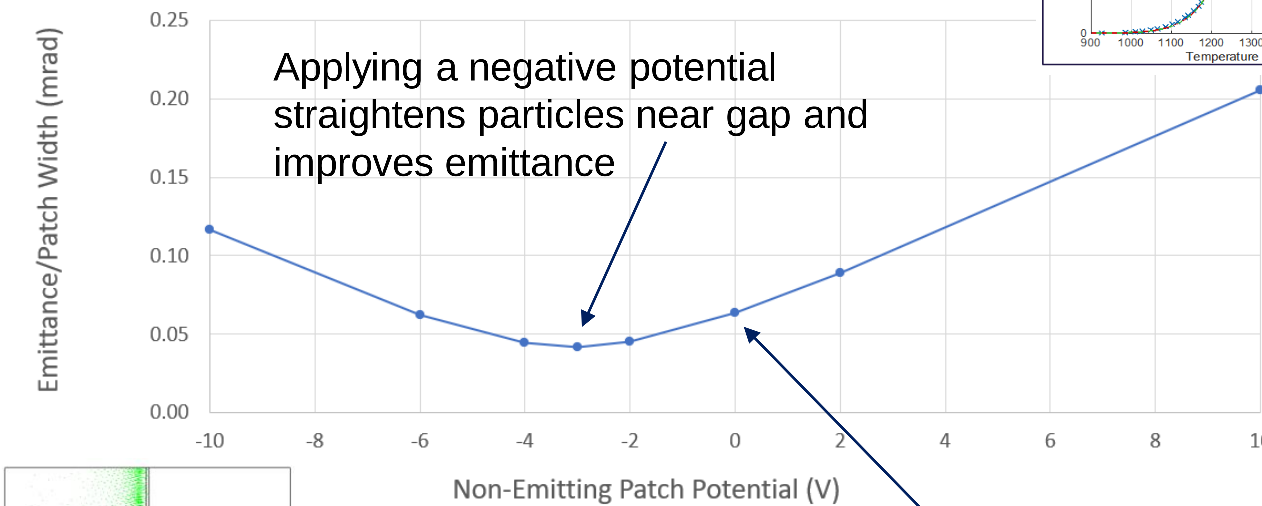
Chemical Roughness: Variation in Work Function / Effective Potential)

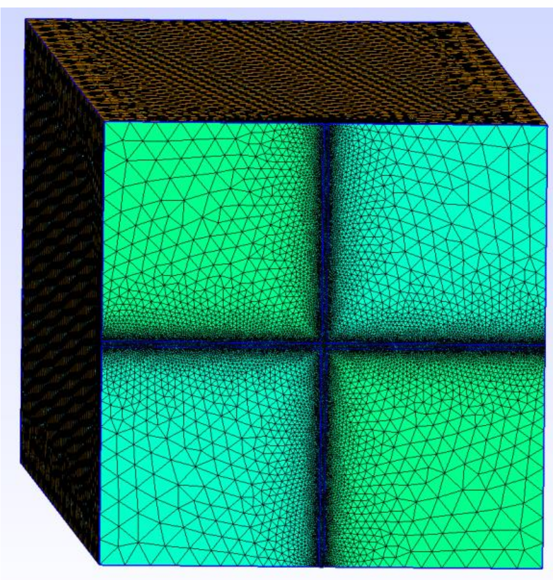
In thermionic emission, intrinsic emittance and detail of emitted distributions are affected by work function variations. Effective variations in surface potentials have a microscopic beam optics effect – leading to MTE

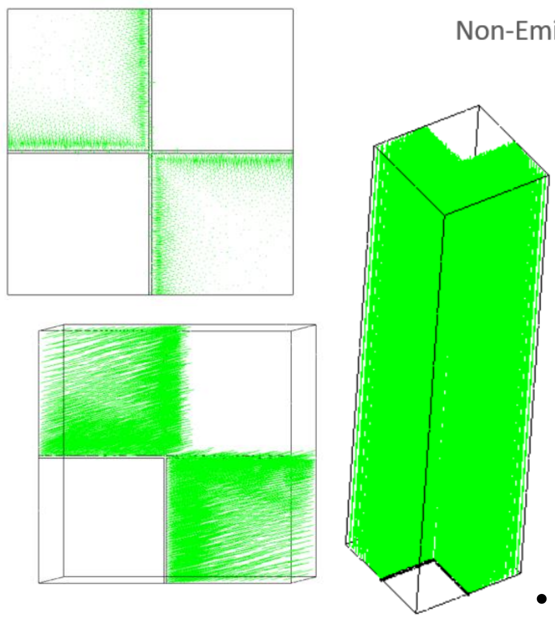


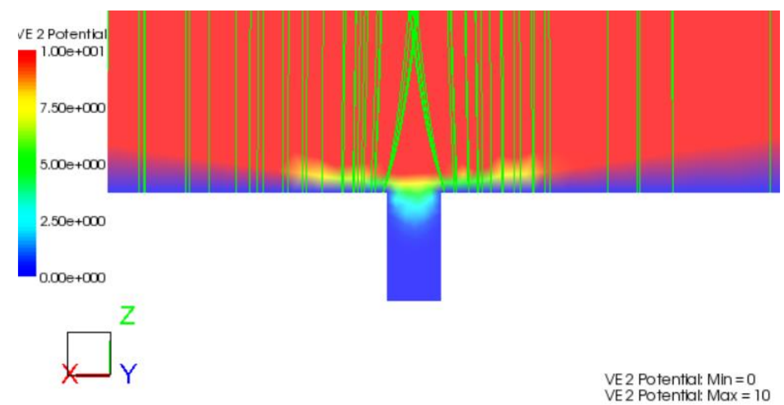


F=50MV/m









- Gap between patches increases emittance
- Voltage differences increase emittance

Application: 10 micron Patch
1 micron Feature

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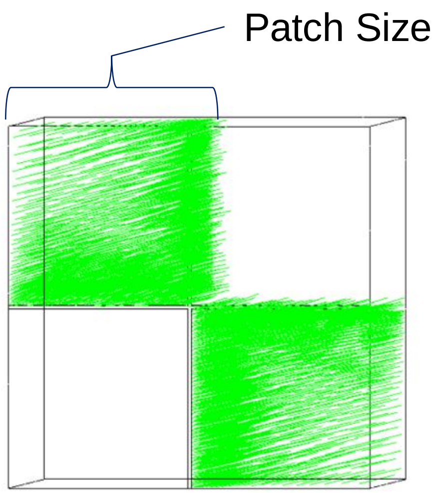
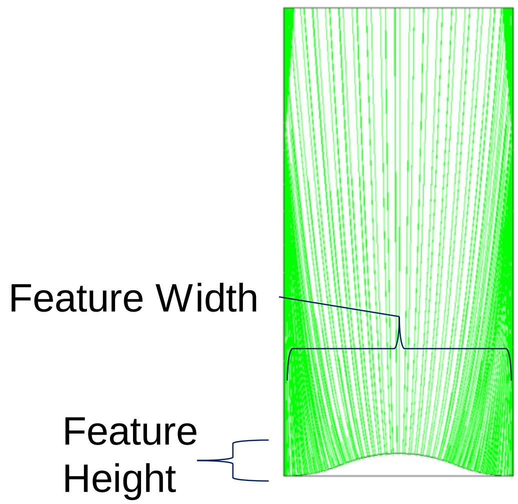
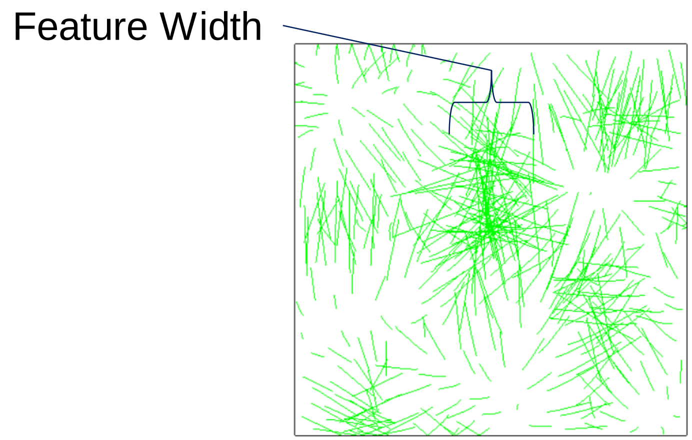


Patch Emission



Rough Emission



Rough Emission

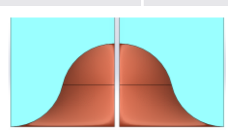
For a 10um Patch

Patch Potential (V)	Emittance (mm*mrad)
-10	1.17E-03
-6	6.23E-04
-4	4.45E-04
-3	4.20E-04
-2	4.51E-04
0	6.34E-04
2	**8.90E-04**
10	2.06E-03

For a 1um Feature

1um Width Feature Height (um)	Emittance (mm*mrad)
0.0	0.0
0.1 (10%)	1.280E-03
0.2	2.560E-03
0.3	3.840E-03
0.4	5.120E-03
0.5	**6.400E-03**
0.6	7.680E-03
0.7	8.960E-03

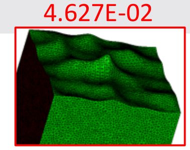
7%



For a 1um Feature

1um Width Feature Height (um)	Emittance (mm*mrad)
0.0	0.0
0.1 (10%)	**6.610E-03**
0.2	1.322E-02
0.3	1.983E-02
0.4	2.644E-02
0.5	3.305E-02
0.6	3.966E-02
0.7	4.627E-02

1.8%



U.S. NAVAL RESEARCH LABORATORY

Summary

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I. **Multiple sources of emittance leading to MTE when no space charge is present**

II. **Chemical Contribution to Emittance (Work Function Variation)**
- Significant but perhaps not the largest source of intrinsic emittance

III. **Artificial (Ordered) Geometric Surface Array Contribution to Emittance**
- Underestimates the emittance due to rough surface features

IV. **Less Artificial (Non-Ordered) Geometric Surface Array Contribution to Emittance**
- Model expected to better estimate the intrinsic emittance

V. **Comparison of Contributions to Emittance (1 um feature vs. 10 um WF patch)**
- Jensen rough surface model indicates an order of magnitude increase in emittance over a 2 V work function patch emittance

VI. **Next step: Include the effects of space charge**