Thirty Years of Charged Particle Simulation with Opera
Stephen M. Elliott, John Simkin, Elizabeth K. White
History

1970  Rutherford Appleton Laboratory
1972  GFUN
1974  GFUN charged particle tracing
1980  Tosca charged particle tracing
1980  Electron Beam lithography at RAL
1984  Vector Fields
1994  Scala space charge beams
2006  Scala with surface secondary emission
2007  Lossy Dielectrics
2007  Scala with volume secondary emission
2014  Opera magnetron plasma sputtering solver
Simple charged particle tracing from 1992
   Electron motion in magnetron plasma sputtering
   Ion beam sources and accelerators

Space charge beams from 1994
   Ion beam sources
   X-ray tubes
   Magnetron sputter azimuthal electron bunching
   Electron beam guns

Surface secondaries from 2006
   X-ray tubes with backscattered electrons
   Ion beam sources with surface secondaries

Volume secondaries from 2007
   Space charge beam compensation
   Beam charging of lossy dielectrics
   Plasma discharges
   Magnetron sputter erosion and coating
Magnetron Sputter Coater

Unbalanced magnetron electron jet

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Magnetron Sputter Coater

Observation of azimuthal electron bunching in magnetrons

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Observation of azimuthal electron bunching in magnetrons
Ion Accelerator Tube

$H^{+1}$ ions and secondary electrons

Secondaries applied manually

Sep 1998
High Intensity Cesium Sputter (HICS) Source

Accelerator Mass Spectrometer (AMS) for $^{14}$C dating

Mar 2000

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High Intensity Cesium Sputter (HICS) Source

HICS source for AMS

Mar 2000
High Intensity Cesium Sputter (HICS) Source

Cs$^{+1}$ ions, C$^{-1}$ ions, electric equipotentials, and electric field

Mar 2000
High Intensity Cesium Sputter (HICS) Source

Cs\(^{+1}\) ions, C\(^{-1}\) ions, electric equipotentials, and electric field

Mar 2000
Primary e⁻ and secondary H₂O⁺¹ ions
Electron Impact Plasma Ion Source

Electron beam space charge ion trap

Early Thin Film Consulting kinetic plasma simulation method

Jun 2005
Electron emission from virtual cathode
Modeller permits simulation of realistic helical filaments
Primary and backscattered electrons

Sep 2007
Ion Implanter Plasma Ion Beam Source

Plasma free surface ions and surface secondary electrons
**Space Charge Beam Compensation**

*H⁺ ion beam with trapped background gas secondary electrons*
**Space Charge Beam Compensation**

**Downstream plasma boundary**

**Downstream plasma equipotential**

Aug 2008

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Space Charge Beam Compensation

Trapped electrons compensate ion beam space charge

Aug 2008

Uncompensated

With volume secondary electrons
Backscattered thermionic electron beam striking insulator
Insulator electric field influenced by electron bombardment
Z-pinched thermionic electrons in liquid water arc discharge
Arc Plasma Discharges

Secondary ion cloud in liquid water arc discharge
Arc Plasma Discharges

Z-pinched thermionic electrons in vacuum arc discharge
X-Ray Tube Electron Backscatter

Backscattered electrons striking glass tube wall
Glass tube wall current density

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Electron drift in circular magnetron
Electron Cyclotron Resonance (ECR) Ion Source

Ion beam formation from hexapole ECR plasma

Jul 2010
Space charge distribution in hexapole ECR plasma

薄层咨询 改进了的对质子动力学模拟方法
Electron Cyclotron Resonance (ECR) Ion Source

Ion beam current density extracted from ECR source

Thin Film Consulting improved kinetic plasma simulation method

Jul 2010
Anode Aperture Compensated Pierce Gun

Specular reflection

Multi-generation backscattered and secondary electrons

Angular distribution reflection

Sep 2010
Paris Small Tokamak confinement electromagnet concept

Aug 2010
Paris Small Tokamak

Paris Small Tokamak 0.1 T confinement permanent magnet (PM)

Feb 2011
Confinement permanent magnet test, Paris Small Tokamak

Mar 2011
Confinement permanent magnet test, Paris Small Tokamak
Paris Small Tokamak

Paris Small Tokamak 3

Jun 2011

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Secondary electron supported plasma in electrostatic tube

Oct 2011

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Electromagnetic electron confinement in Paris Small Tokamak 3
1.46 Tesla achieved with solenoid, Gizmonics, LLC

Gizmonics, LLC impulse solenoid test system

Feb 2014
Hydrogen Penning plasma with extracted ion and electron beams
**H⁻ Penning Ion Beam Source**

**Extraction of H⁻ ions and parasitic electrons from plasma**

Thin Film Consulting
improved kinetic plasma simulation method

Mar 2012

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H^+ Penning Ion Beam Source

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H^+ ion sputter erosion of Ta cathode

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H⁺ Penning Ion Beam Source

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Ta deposits

H⁺ ion sputtered Ta deposition on anode

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H- Penning Ion Beam Source

Secondary gas electrons

Thin Film Consulting improved kinetic plasma simulation method

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Magnetron Sputter Coater

Magnetic steel support

Glass substrate

Magnetron cathode

ITO Target

Colorado Concept Coatings in-line coater

May 2010

Colorado Concept Coatings

Thin Film Consulting
**Magnetron Sputter Coater**

Thin Film Consulting improved kinetic plasma simulation method

**Colorado Concept Coatings first magnetron erosion simulation**

May 2010
Magnetron Sputter Coater

Plasma electron time-of-flight above target
**Magnetron Sputter Coater**

- Error:
  - 0.54% of utilization
  - 2.04% analytical

Simulation

Utilization = 25.90%

Experiment

Utilization = 26.44%

Simulated target erosion

- Scala Plasma solver

Mar 2013

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$H^+$ Penning Diode

Thin Film Consulting v3 kinetic plasma simulation method

Quasineutral plasma

Sheath

Presheath

Penning diode, current research

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Primary cathode electron energy, eV
Secondary gas electron energy (no reflections), eV

Confidential
**H⁺ Penning Diode**

**Thin Film Consulting v3 kinetic plasma simulation method**

**H⁺ ion energy (no reflections), eV**

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