Breakdowns of Superconducting RF Cavities due to Discharge and Plasmas

Myriam Qureshi

Abstract. One of the main limitations in current day superconducting and copper RF cavities is field emission. Many studies have been done to gain a better understanding of the mechanisms that take place during field emission. One study used a DC apparatus to induce field emission on niobium and copper cathodes. The experiment consisted of applying a high voltage to a gap between two electrodes, which varied the electric field values between 20 MV/m and 200 MV/m. The voltage used and field obtained are comparable to what is used in the actual cavity; the experiment uses as much as 14,500 volts and generates an electric field of 150 MV/m. As a compliment to this experiment a plasma simulation has been used to model the effects of field enhancement due to plasma and voltage breakdown events. Simulations were carried out using dc and ac conditions by applying a voltage between two parallel plates. The simulation is a particle-in-cell code called Oopic (Object Oriented Particle-in-Cell code). The main objective is to simulate the voltage breakdown from its early stages of field emission up to the flash.

I Background on Field Emission and Voltage Breakdown

Although many concepts of the theory of field emission are understood, there is much controversy. Little is known about the stages that occur in between the field emission and the voltage breakdown. The basic principle of field emission can be explained as a quantum mechanical tunneling process. When the surface electric field exceeds threshold levels, the electrons trapped in the metal by the work function begin to tunnel out in to the vacuum. What

happens to these charged particles after they tunnel out of the surface? If there were any gases trapped on the surface and released by some mechanism, the electrons would ionize the neutral particles in the gas. Collision between electrons and gas atoms is one way that an ion cloud may form. Knobloch has shown that for sufficient current and sufficient gas pressure there will be a local field enhancement due to a positively charged ion-cloud [1]. The ions also return to the emission site causing more heating and more gas release. Eventually the process can avalanche and the local gas cloud can discharge, which is the most likely cause of the voltage breakdown. The whole process is similar to a lightning arc discharge. But there are many features of this model that need to be flushed out and better understood. Where does the gas come from, what leads to the avalanche? Knobloch and Padamsee [2] have shown that the melted parts of the emitter and the gas evolution from the surface are due to the field emission current heating. Ionization by these electrons lead to a cloud of gas located right over the emitter. The high voltage present between the surface and the ion-cloud, affect the stability of the growth of the emission current. This leads to a spark between the ion cloud and the emitter, which in turn destroys the emitter and produces several craters. If the conditions surrounding these events can be discovered, they can be executed inside the RF cavity and destroy the particulates, that cause the field emission, during the explosion.   If we can model the electric field near the emitter and induce a spark using Oopic, then hopefully we can understand what conditions are needed to enhance the electric field and improve the efficiency of RF cavities.

Previous experiments performed on dc high voltages with niobium and copper cathodes have shown that in most cases field emission occurs before the voltage breakdown. Simulations show that gas build up that causes ion accumulation near the emitter produces a large field enhancement and a discharge. This being the case, plasma and discharge may be the links to understanding the explosion.

The evidence of the explosion is found on the cavity walls in the form of starburst and craters. This phenomenon may be evidence to the existence of the plasma and discharge.
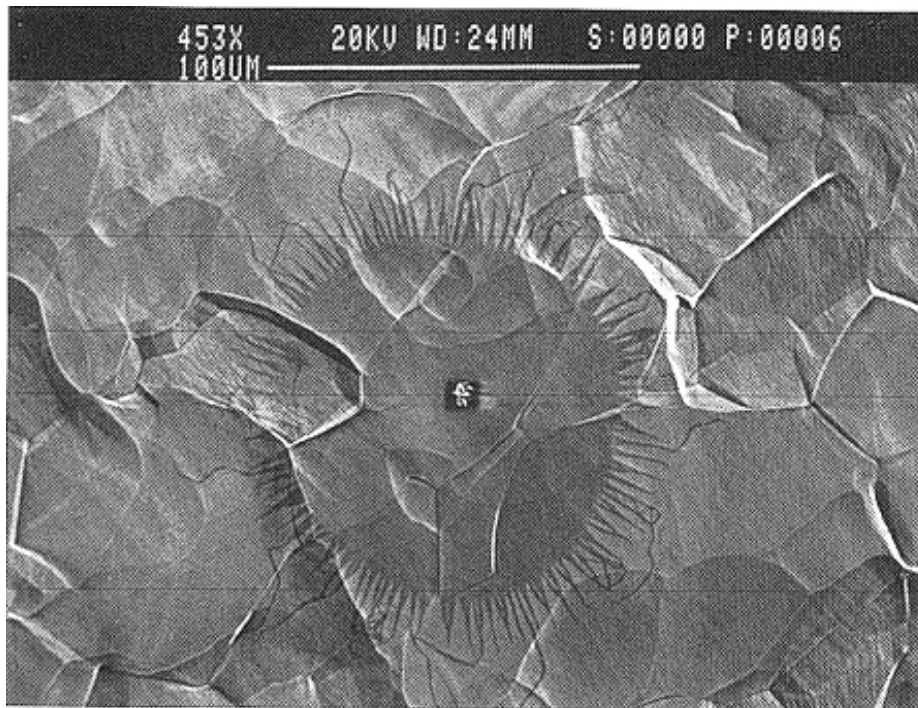
Figure 1 Starburst with crater in the center

The next step in the numerical simulation is to model the electrons as they ionize in a gas. This will hopefully give concrete evidence to the role plasmas

play in the formation of the craters and starbursts due to the dissipated power at the emission sites.

II Simulation

The numerical simulation used for this experiment was Oopic (object-oriented-particle-in-cell code). Oopic is a 2-D relativistic electromagnetic PIC code that supports x-y and r-z (cylindrical) geometries. Oopic has the capabilities to simulate a wide variety of problems such as plasma display panels, ion implementation, high-power microwave devices and next generation linear accelerator concepts. Some examples of problems solved by Oopic include:

Gas.inp: A beam enters the system and causes ionization. The pressure is 1 millitorr.

Dcdis.inp: DC discharge in argon.

Voltest.inp: Particles at low current are dropped through a voltage. Diagnostics of how much energy they have on arrival at the far end of the wall are kept. In this case particles should arrive with an energy of 100V.

Oopic also has a feature that illustrates the geometrical set up of the problem, this is known as the device geometry window.
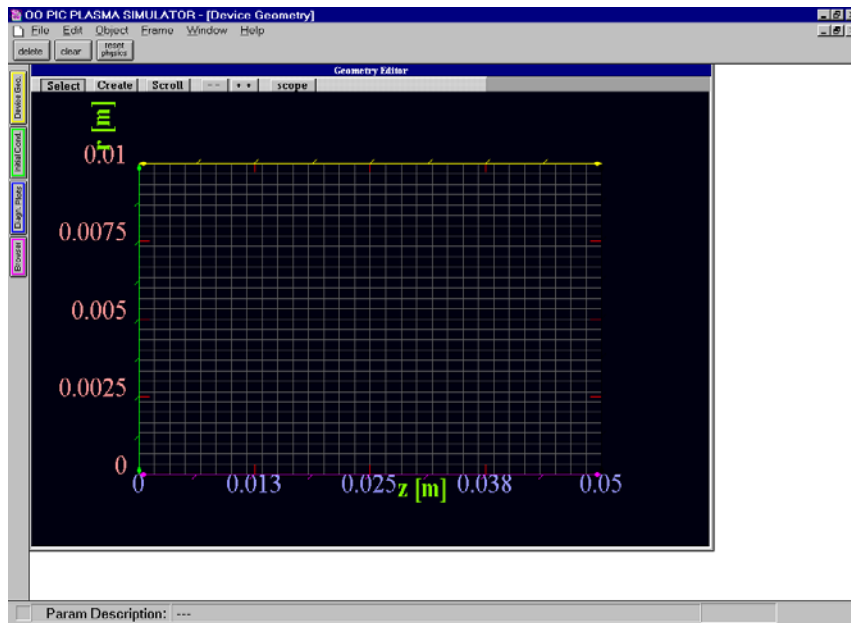
The device geometry window labels the axis, equipotential, conductors, dielectric, and other variables that define the components of the problem. Oopic also has a wide variety of input parameters making it more accessible to solving a wider variety of problems. Some of the parameters include electric field, magnetic field, conductors, current, gas, pressure, and size of the problem, collision model, species, and grid. The input file is broken up into the following parameter groups: [3]

Grid: describes the dimensions of the Region and mesh parameters

Control: simulation parameters, which include time step, static E and B field components

Species: specific particle and characteristics used in simulation, each particle has own Species block

MCC: Monte Carlo collision parameters

Load: parameters that specify initial position of particles; there is a separate block for each particle with an initial spatial distribution

VarWeightLoad: same as Load but used with cylindrical geometry

Boundary Conditions:

Dielectric:

Conductor: has same parameters as dielectric and behaves as conductor

Equipotential: works as a potential but I grounded to some potential

Polarizer: allows a fraction of particles to pass through

Foil: releases secondary electrons when impacted by a particle (non-functional)

Secondary: specifies how secondary particles are to be produced at boundary

DielectricRegion: same parameters as Dielectric, but coordinates define a rectangular region

CylindricalAxis: boundary condition necessary in r-z space if r = 0 included

ExitPort: boundary where waves and particles are treated as if they are leaving the simulation

Emitters:

BeamEmitter: produces beam of particle species

FieldEmitter:

The following is an example input file:

```
voltest
```
Comment block, this does not effect program operation
```
{

  Particles at low current are dropped through a voltage.
  Diagnostics of how much energy they have on arrive at the
  far wall are kept.

  In this case, the particles should arrive with an energy
  of 100v.
}
```

```
Region
```
Region block. All parameter groups must be within Region block.
```
{
Grid
```
Grid block, specifies Region size and mesh parameters.
```
{
      // number of grids in x
      J = 20
      x1s = 0.0
      x1f = 1.0
      n1 = 1.0
      // number of grids in y
      K =20
      x2s = 0.0
      x2f = 1.0
      n2 = 1.0
      Geometry = 1
}
Species
```
Species block
```
{
      name = electrons
```
Name of Species
```
      m = 9.11E-31
```
Mass of individual Species
```
      q = -1.6e-19
```
Charge of individual Species
```
      collisionModel=1
```
Model used for collisions of this species; none(0), electron(1), ion(2),test(3),or boltzmann
```
}
Species
```
second Species block. There MUST be one Species block for each type of particle
```
{
        name = argon
        m = 6.67e-26
        q = 1.6E-19
        subcycle = 10
        collisionModel=2
}
Control
```
Control block
```
{
//the time step
      dt = 1e-9
```
Time step parameter
```
ElectrostaticFlag = 1
```
flag denoting whether initial field solver is electrostatic or electromagnetic
```
}
MCC
{
      gas = Ar
```
Type of Gas

```
        pressure =0.05          Pressure in Torr
        temperature =0.5        Temperature in Kelvin
        eSpecies = electrons    Electron Specie
        iSpecies = argon        Ion Specie
}
Dielectric                      Dielectric block
{
        j1 = 0
        j2 = 0
        k1 = 0
        k2 = 20
}


EmitPort                        Boundary of particles leaving simulation
{
        j1 = 10
        j2 = 11
        k1 = 20
        k2 = 20
        speciesName = electrons
        normal = -1             Denotes direction of EmitPort
        // number of particles
        np2c = 4e3              Number of particles per simulated particle
        // current
        I = 0.000005            Current
        v2drift = 0.01          Speed of particles along second 2nd dimension
}
Dielectric                      Dielectric block
{
        QuseFlag = 0            Determines whether to use accumulated surface
                                charge if the field solve; 0 indicates charge drains
                                off
        j1 = 20
        j2 = 20
        k1 = 0
        k2 = 20
        normal = -1
}
Conductor
{
        name = collector        This block specifies a boundary with conducting
characteristics
        IdiagFlag = 1           Toggles particle current accumulation
        nxbins = 10             Number of spatial bins along boundary segment
                                for distribution accumulation
        j1 = 0
        j2 = 20
        k1 = 0
        k2 = 0
        // resolution of the energy diagnostic
        nenergybins = 400       Number of energy bins for distribution
                                accumulation
```

```
      energy_min = 95
      energy_max = 105
}
Equipotential
{
      j1 = 0
      j2 = 20
      k1 = 20
      k2 = 20
      normal = -1
      // the voltage
      C = -150          DC value for time-dependent function

}
}
```

The simulation uses a mathematical spatial grid to keep track of the behavior of the particles. The leapfrog method is used to navigate the particles for accuracy. This method uses two first-order differential equations to obtain the force and velocity.

$$m \frac{d\mathbf{v}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

$$\frac{d\mathbf{x}}{dt} = \mathbf{v}$$

The equations are then substituted with finite difference equations.

$$\frac{\mathbf{v}_{t+\Delta t/2} - \mathbf{v}_{t-\Delta t/2}}{\Delta t} = q/m \left[\mathbf{E} + \frac{\mathbf{v}_{t+\Delta t/2} + \mathbf{v}_{t-\Delta t/2}}{2} \times \mathbf{B} \right]$$

$$\mathbf{v}'_{old} = \mathbf{v}_{t-\Delta t/2} - \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

$$\mathbf{v}'_{new} = \mathbf{v}_{t+\Delta t/2} - \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

$$\frac{\mathbf{v}'_{new} - \mathbf{v}'_{old}}{\Delta t} = q/m \left[\mathbf{E}_{||} + \frac{\mathbf{v}'_{new} + \mathbf{v}'_{old}}{2} \times \mathbf{B} \right]$$

The electric and magnetic fields are solved for at the particle. Using the spatial grid means that the electric and magnetic fields must be interpolated from the grid to the particle. This is done using the charge density at the grid points from the particle position. The field solver is a Poisson solver. There are two differential equations that combine to form Poisson's equation.

$$\mathbf{E} = -\frac{\partial \Phi}{\partial x}$$

$$\frac{\partial E_x}{\partial x} = \frac{\rho}{\varepsilon_0}$$

$$\frac{\partial^2 \Phi}{\partial x^2} = -\frac{\rho}{\varepsilon_0}$$

This differential equation can be solved using finite difference equations.

$$\frac{\Phi_{i-1}-2\Phi_i+\Phi_{i+1}}{(\Delta x)^2} = \frac{-\rho_i}{\varepsilon_0}$$

The grid has high resolution to observe a small scale. Essentially the spatial grid is composed of "plasma" in which there can be infinite particles in one cell and an area of surrounding cells is called a macro particle. This will be of greater importance when the input parameters are discussed. Oopic is a two and half dimensional simulation, which means there is an x-y position and velocities in v_x, v_y, and vz. The spatial grid is also set in the plasma region to measure the charge and current densities from which the electric and magnetic fields can be calculated. A charged particle at some position will be counted in terms of the density of the nearest four corners of the grid. The force on the charged particle will also be found from the same nearby points.

In running the simulation the most important parameters to keep track of are the voltage applied across the gap, gap size, current, pressure, size of the problem, time step, and np2c, which is the ratio of the number of physical particles to the number of computer particles. For the purposes of this study the size of the problem needs to have an electric field of about 1 MV/m. The time step should be adjusted so that the electrons neither fly by nor take more than a nanosecond to leave the emitter.

III Outline of Experiments

The experiments conducted were organized in the following categories:

I Beam Emitter Studies

    A Ionization

        a) Single Ion

        b) Many Particle Ionization

        c) Macro Particle Ionization

    B Investigation of Dark Space

    C High Pressure

    D High Voltage

    E Gap Studies

    F DC Magnetron Sputtering

II Field Emitter Studies

    A DC/RF Comparison

    B DC/RF Comparison with Gaussian

    C Explosion

IV Experiments and Results

We know that the gas needed to create the plasma can form from the regions of emitter that start to melt due to the ohmic heating or from degassing of the surface near the heated metal. Once a gas is available the field emission current will ionize the gas. The presence of the gas and ionization triggers the explosion process.   The experiments conducted in this project use a numerical simulation to show the chain of events that occur from the early stages of field emission up to the flash.

The experiments conducted can be separated into two main categories, beam emitter experiments and field emitter experiments.   The main point of using the plasma simulation is to calculate the Townsend discharge. The original input file voltest.inp was modified to meet the needs of the experiments. The setup allows a voltage to be dropped across two parallel plates separated by a distance d and solves the simplest Townsend discharge experiments. The volume between the two plates is filled with gas on the order of 1 torr. An electron current I is injected into the gas; the charges are then accelerated by the electric field and ionize the background gas.

The first objective of using Oopic was to track one electron and make sure the simulation set-up was ionizing the gas. The first example we did was composed of a single electron that ionized in the Argon gas. We wanted to track the electron, produce one ion, and keep track of the next two electrons created.

Example 1
Pressure = 0.01 Torr
C = 500 V
I = 5x 10^{-11} A
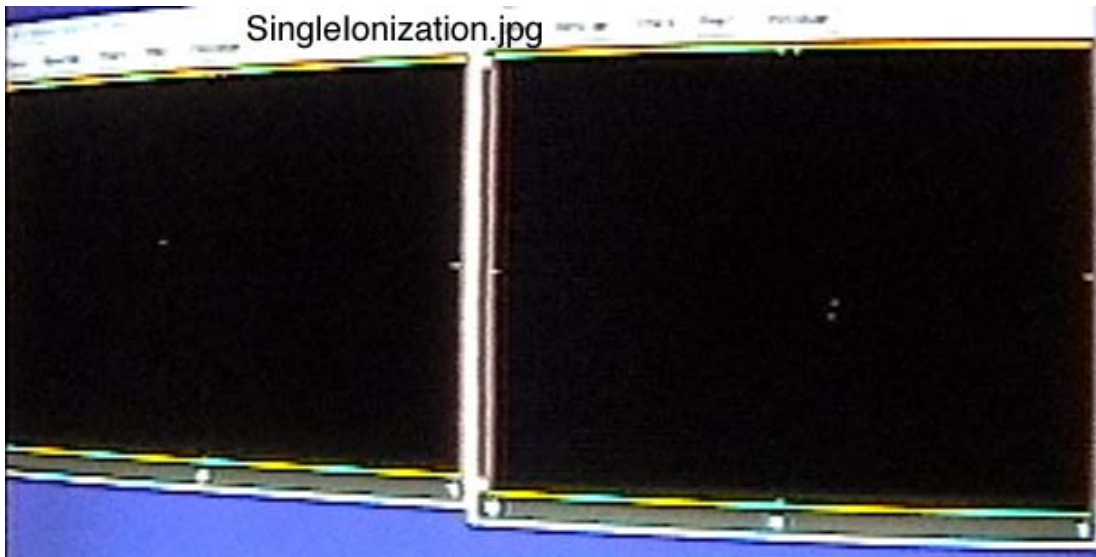
Figure 1 Single Ionization (Electrons on right and Ions on left.)

Systematic studies were conducted throughout all of the experiments in order to see the effects of varied current, pressure, and voltage.

Next, the pressure was raised in order to make more ions. To produce even more ionization the current was increased and the conditions were checked to get a glow discharge.

	Example 2	Example 3	Example4	Example5
Pressure (Torr)	0.05	0.05	0.05	0.05
DC Voltage (V)	-500	-500	-300	-300
Current (A)	$5x\ 10^{-11}$	$5x\ 10^{-9}$	$5x\ 10^{-11}$	$5x\ 10^{-9}$

Figure 2 Glow Discharge

The ratio of physical particles to computer particles is a very important ratio. As more particles are added to each macro particle the simulation becomes more accurate.   To prove that there was actually a discharge each electron in simulation was really 4,000 electrons.

The next run simulated the dark space, or mean-free path. The importance of this run will aid in showing that most of the ionization occurs the distance of a mean-free path away from the emitter. One question we hope to answer is if the field enhancement will affect the mean free path and bring the ionization closer to the RF surface as the field enhancement increases.

	Example 5	Example 6	Example 7
Pressure (Torr)	0.05	0.05	0.05
DC Voltage (V)	-300	-150	-150
Current (A)	5×10^{-8}	5×10^{-7}	5×10^{-6}
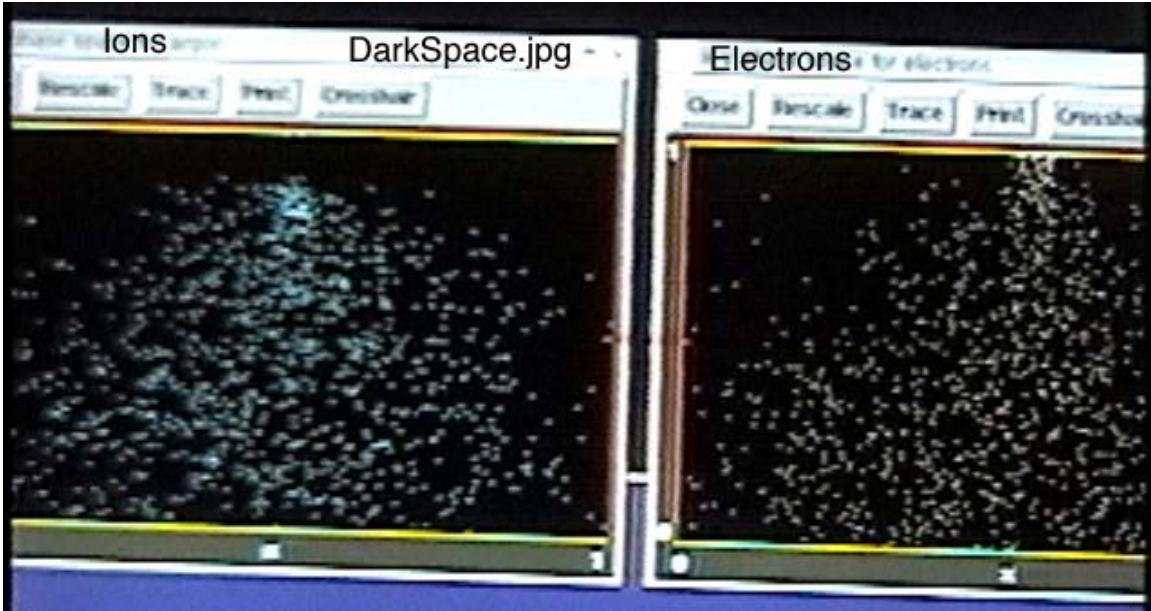
Figure 3 Dark Space

* See input file of Example 5 for further parameters.

```
voltest
{ voltest5 (dark space studies)
  Particles at low current are dropped through a voltage.
  Diagnostics of how much energy they have on arrive at the
  far wall are kept.

  In this case, the particles should arrive with an energy
  of 100v.
}
Region
{
Grid
{
      // number of grids in x
      J = 20
      x1s = 0.0
      x1f = 1.0
      n1 = 1.0
      // number of grids in y
      K = 20
      x2s = 0.0
      x2f = 1.0
      n2 = 1.0
      Geometry = 1
}
Species
{
      name = electrons
      m = 9.11E-31
      q = -1.6e-19
      collisionModel=1
}
Species
{
      name = argon
      m = 6.67e-26
      q = 1.6E-19
      subcycle = 10
      collisionModel=2
}
Control
{
//  the time step
      dt = 1e-9
      ElectrostaticFlag = 1
}
MCC
{
      gas = Ar
      pressure = 0.05
   //temperature = 1.0
      eSpecies = electrons
      iSpecies = argon
}
Dielectric
{
      j1 = 0
      j2 = 0
```

```
        k1 = 0
        k2 = 20
}
EmitPort
{
        j1 = 10
        j2 = 11
        k1 = 20
        k2 = 20
        speciesName = electrons
        normal = -1
        // number of particles
        np2c = 4e3
        // current
        I = 0.00000005
        v2drift = 0.01
}
Dielectric
{
        QuseFlag = 0
        j1 = 20
        j2 = 20
        k1 = 0
        k2 = 20
        normal = -1
}
Conductor
{
        name = collector
        IdiagFlag = 1
        nxbins = 10
        j1 = 0
        j2 = 20
        k1 = 0
        k2 = 0
        // resolution of the energy diagnostic
        nenergybins = 400
        energy_min = 95
        energy_max = 105
}
Equipotential
{
        j1 = 0
        j2 = 20
        k1 = 20
        k2 = 20
        normal = -1
        // the voltage
        C = -300
}
}
```

Previous DC emission studies have observed craters and molten areas due to vacuum breakdown experiencing arching from high DC voltage [2]. It is thought that the emitter processing also occurs as a result of the vacuum breakdown and is accompanied by an arc or spark produced by the RF electric field. This is called microdischarge because of the localized location right above the emitter. The DC emission studies also show that the spark forms in the interval of 10ns-10μs. The time interval from previous studies was used to model experiments in Oopic in which the time steps ranged from 10^{-13}-10^{-9}. To ensure that no events were missed, the simulation ran for at least at nanosecond depending on the scenario. The next set of runs form columns of ions and spreads of ions.

	Example 8	Example 9	Example 10	Example 11
Pressure (Torr)	0.05	0.05	0.05	5
DC Voltage (V)	150	800	1000	100,000
Current (A)	5×10^{-6}	5×10^{-6}		5×10^{-6}
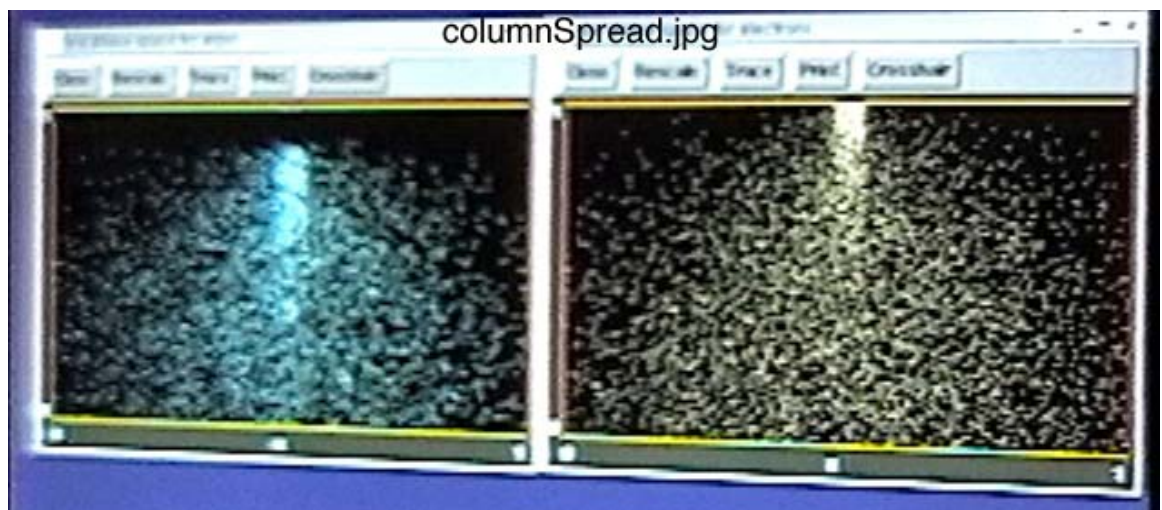
Figure 4 Column of Ions

Notice the density of the ion column and the way the ions spread out around the column. We wanted to have a column of ions to see if we had a plasma cloud. Note that the heavy ions do not move far and tend to accumulate near the emitter. This could be a scenario in which a crater is formed on the emitter surface where the ion column is centered and the wide spread of ions could be explained as the starburst's fingers or streamers. Next, the gas pressure is increased and the column is lost, but there is cloud. There are many of points of interest in this picture.
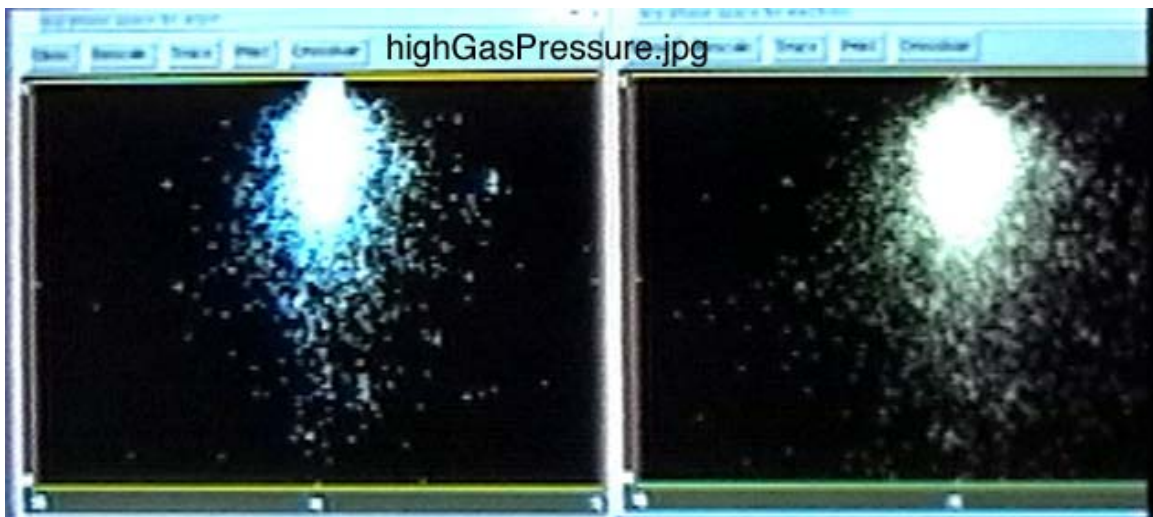
Figure 5 High gas pressure

The particles on the right in both figures have broken away from the "parent" cloud. The production of ions is also concentrated near the emitter where there is positive surface charge. The electric field produced by the ion cloud prevents the emission beam from expanding radially as it passes through the cloud. The new ions produced are concentrated in the volume nearest to the emitter. If sufficient build up of positive charge occurs an ion cloud will be formed and the electrons will be captured, forming quasi-neutral plasma. This plasma is capable of field enhancement. Once the field emission current ionizes the gas the ions

return to bombard the surface, which can eventually melt a particle.   The

parameters in the previous runs have yielded no change in the electric field,

possibly because there is not enough current present. These runs allowed the

exploration of parameters with which a column of electrons could get excited and

move through the gas.

The next study done was based on the field enhancement due to high

current and pressure and the correlation between the size of the gap. The first

test was done at high current and high pressure. When the current was

drastically raised and the np2c was increased, a change was finally witnessed in

the potential and electric field; there is field enhancement here.

	Example 12	Example 13
Pressure (Torr)	50	50
DC Voltage (V)	300	300
Current (A)	0.5	5
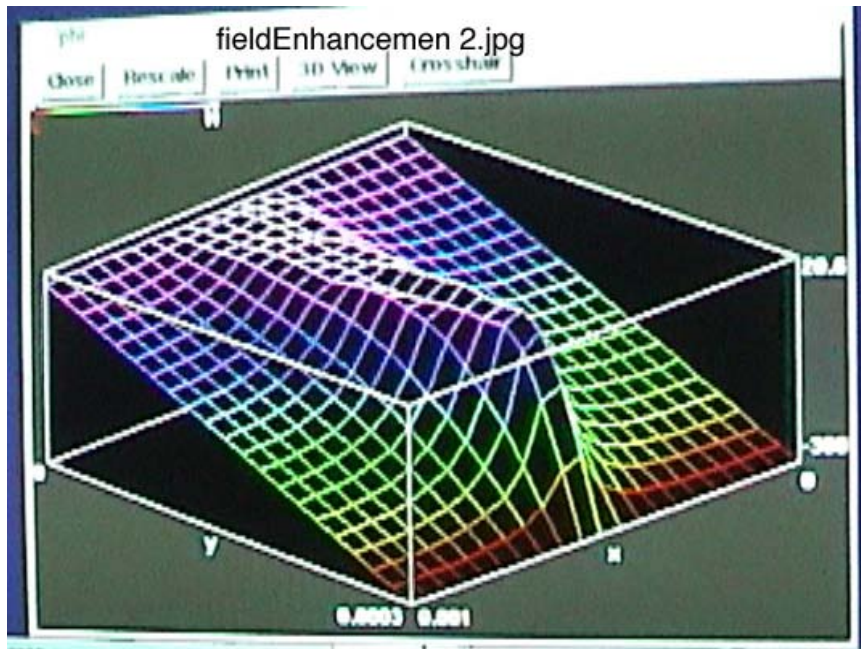
Figure 6 Field enhancement
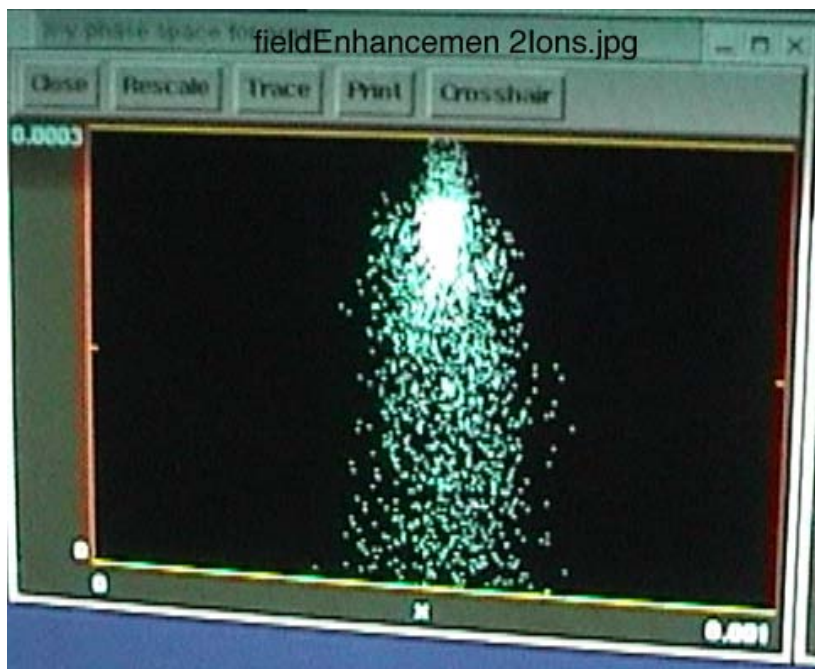
Figure 7 Ions during field enhancement
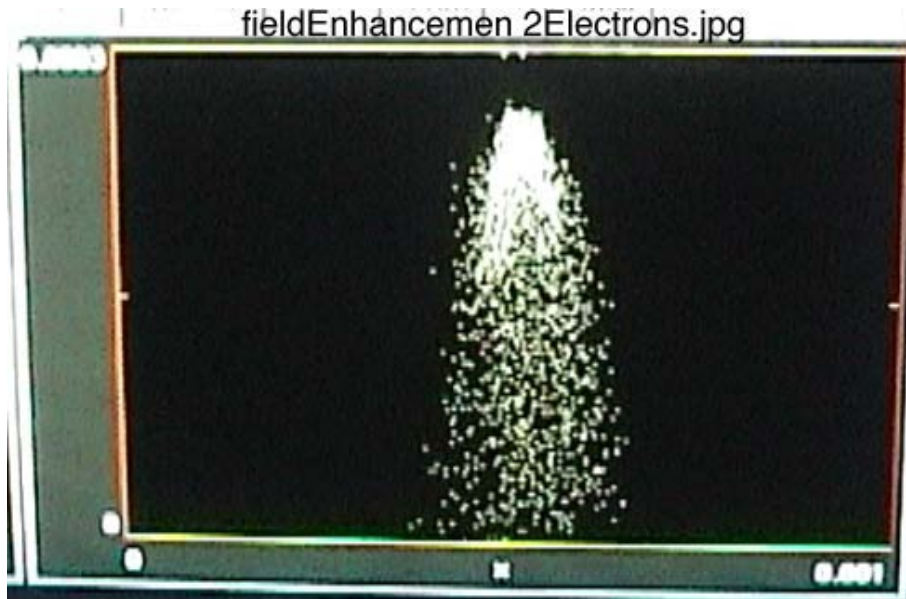
Figure 8 Electrons during field enhancement

In order to get even stronger field enhancement the current was raised.

We want to see if we can keep the field constant and change the effect by changing the gap size. The small gap has less field enhancement and the large gap has more field enhancement. The plasma enhances the electric field near the RF surface (see **Figure 10**). From these results we are starting to see the possibilities of streamers.

	Example 14	Example 15	Example 16
Pressure (Torr)	50	50	50
DC Voltage (V)	50	100	300
Current (A)	5	5	5
Gap Size (mm)	0.05	0.1	0.3

*First set of gap tests
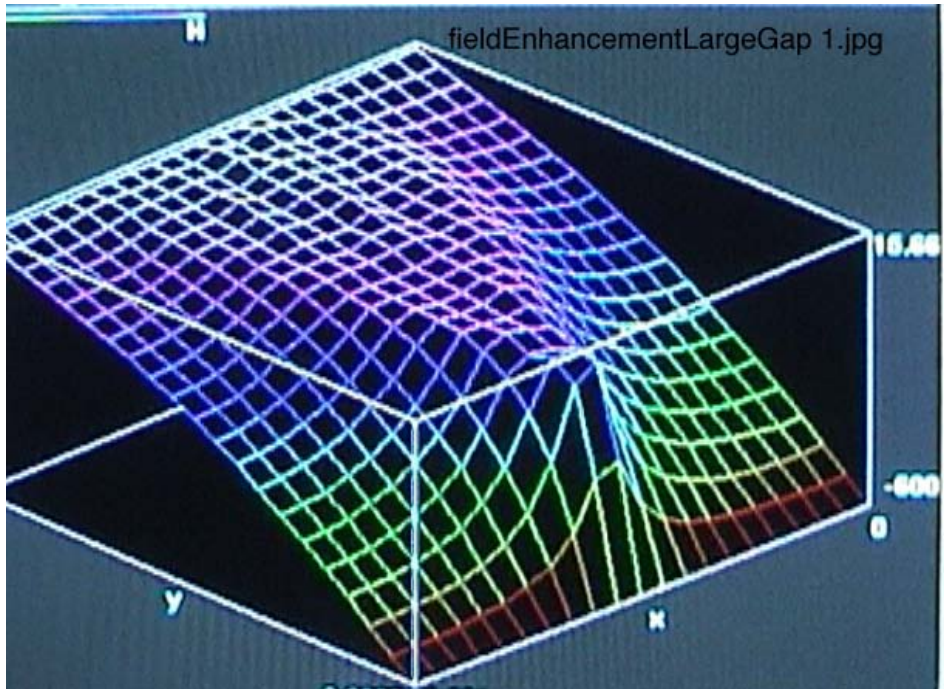
Figure 9 Field Enhancement due to large gap
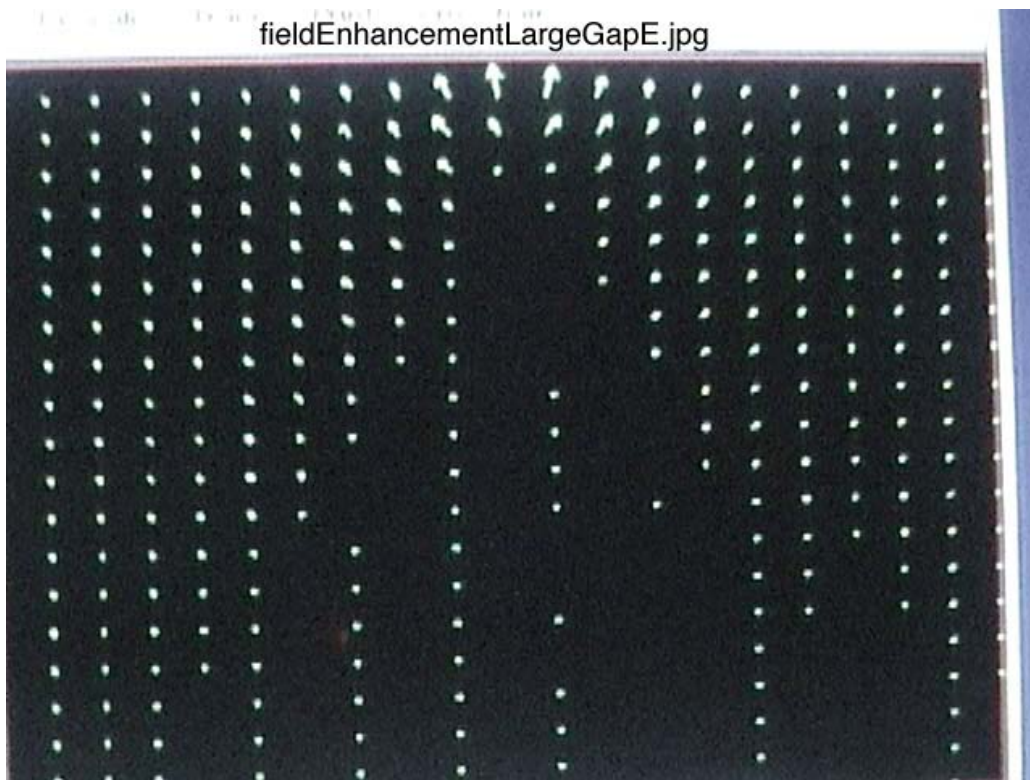
Figure 10
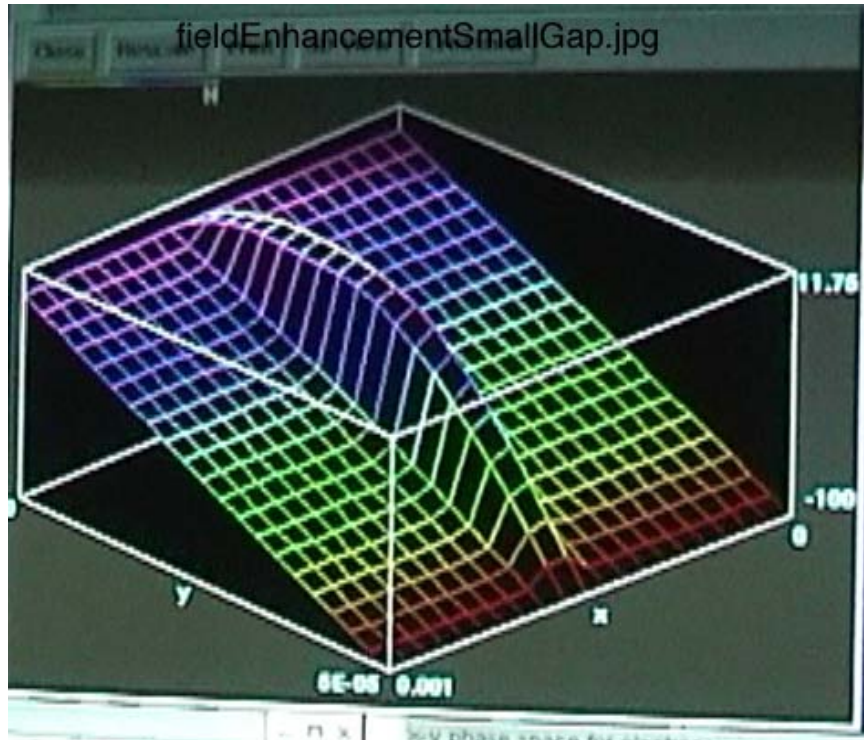
Figure 11 Field Enhancement due to small gap

	Example 17	Example 18	Example 19
Pressure (Torr)	50	50	50
DC Voltage (V)	50	100	600
Current (A)	5	5	5
Gap Size (μm)	50	50	600

*Second set of gap tests

Figure 12 Possibilities of Streamers

We are still looking for streamers in the next result.
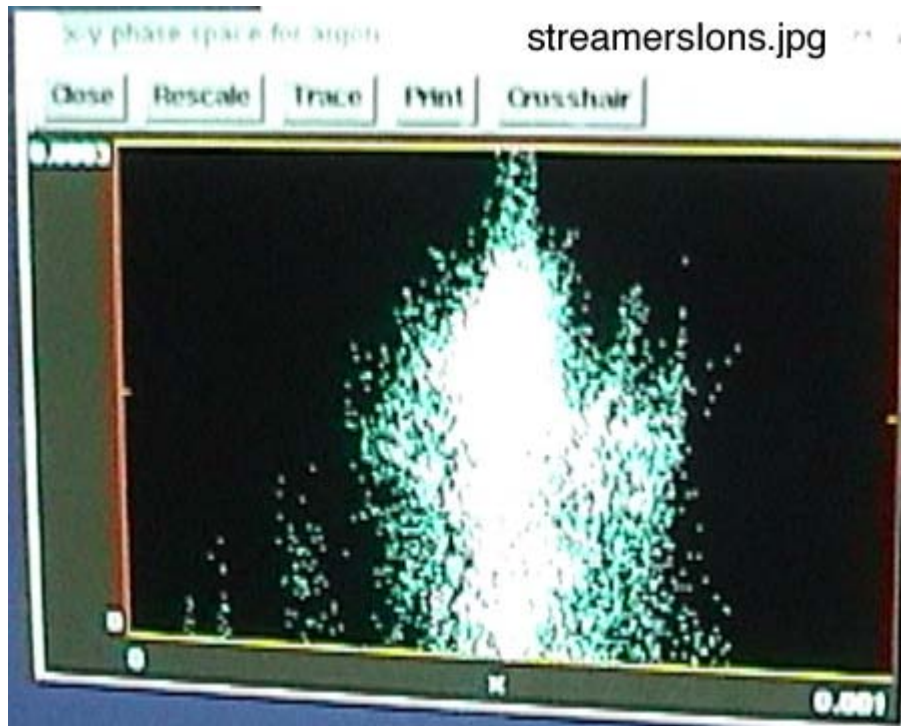
Figure 13

Due to the location of the ion cloud to the RF surface electric fields, drastic field enhancement can occur.

*The following input file was modified for the gap tests and remainder of the studies.

```
voltest
{ voltest24 (gap studies)
  Particles at low current are dropped through a voltage.
  Diagnostics of how much energy they have on arrive at the
  far wall are kept.

  In this case, the particles should arrive with an energy
  of 100v.
}
Region
{
Grid
{
      // number of grids in x
      J = 20
      x1s = 0.0
      x1f = 0.001
      n1 = 1.0
      // number of grids in y
      K = 20
      x2s = 0.0
      x2f = 0.0003
      n2 = 1.0
      Geometry = 1
}
Species
{
      name = electrons
      m = 9.11E-31
      q = -1.6e-19
      collisionModel=1
}
Species
{
        name = argon
        m = 6.67e-26
        q = 1.6E-19
//    subcycle = 100
      collisionModel=2
}
Control
{
//  the time step
      dt = 1e-12
      ElectrostaticFlag = 1
}
MCC
{
      gas = Ar
      pressure = 50.0
//      temperature = 0.1
      eSpecies = electrons
      iSpecies = argon
}
Dielectric
{
      j1 = 0
      j2 = 0
```

```
        k1 = 0
        k2 = 20
}

EmitPort
{
        j1 = 10
        j2 = 11
        k1 = 20
        k2 = 20
        speciesName = electrons
        normal = -1
        // number of particles
        np2c = 4e8
        // current
        I = 5.0
        v2drift = 0.01
}
Dielectric
{
        QuseFlag = 0
        j1 = 20
        j2 = 20
        k1 = 0
        k2 = 20
        normal = -1
}
Conductor
{
        name = collector
        IdiagFlag = 1
        nxbins = 10
        j1 = 0
        j2 = 20
        k1 = 0
        k2 = 0
        // resolution of the energy diagnostic
        nenergybins = 400
        energy_min = 95
        energy_max = 305
}
Equipotential
{
        j1 = 0
        j2 = 20
        k1 = 20
        k2 = 20
        normal = -1
        // the voltage
        C = -300
}
}
```

We have a magnetic field in the horizontal direction and an electric field in the perpendicular direction, which allows the electrons to make spirals. This simulates the basic principle of bias magnetron DC sputtering. From the magnetronIons, we are showing a broader sputtering range.
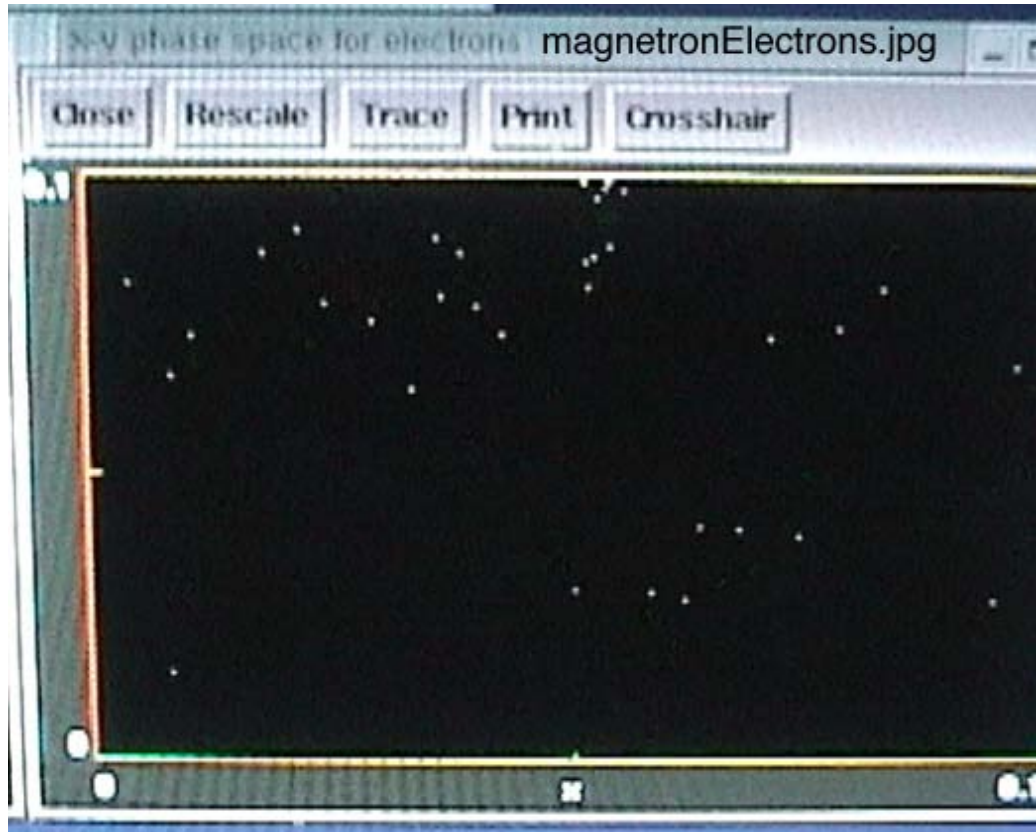
Figure 14
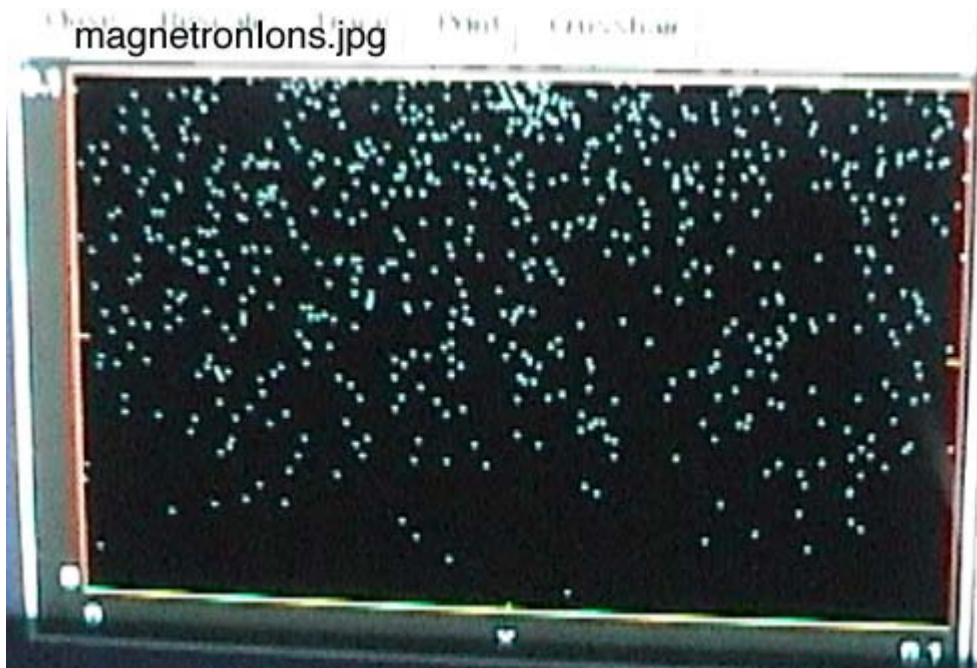
Figure 15

*See the following input file for parameters.

voltest

```
{ Magnetron Sputtering (sputter2mod)
  Particles at low current are dropped through a voltage.
  Diagnostics of how much energy they have on arrive at the
  far wall are kept.

  In this case, the particles should arrive with an energy
  of 100v.
}
Region
{
Grid
{
      // number of grids in x
      J = 20
      x1s = 0.0
      x1f = 1.0
      n1 = 1.0
      // number of grids in y
      K = 20
      x2s = 0.0
      x2f = 1.0
      n2 = 1.0
      Geometry = 1
}
Species
{
      name = electrons
      m = 9.11E-31
      q = -1.6e-19
      collisionModel=1
}
Species
{
        name = argon
        m = 6.67e-26
        q = 1.6E-19
      subcycle = 10
      collisionModel=2
}
Control
{
//  the time step
      dt = 1e-9
      B01 = 0.002
      ElectrostaticFlag = 1
}
MCC
{
      gas = Ar
      pressure = 0.01
      eSpecies = electrons
      iSpecies = argon
}
Dielectric
{
      j1 = 0
```

```
        j2 = 0
        k1 = 0
        k2 = 20
}
EmitPort
{
        j1 = 10
        j2 = 11
        k1 = 20
        k2 = 20
        speciesName = electrons
        normal = -1
        // number of particles
        np2c = 4e3
        // current
        I = 0.00000000005
        v2drift = 0.01
}
Dielectric
{
        QuseFlag = 0
        j1 = 20
        j2 = 20
        k1 = 0
        k2 = 20
        normal = -1
}
Conductor
{
        name = collector
        IdiagFlag = 1
        nxbins = 10
        j1 = 0
        j2 = 20
        k1 = 0
        k2 = 0
        // resolution of the energy diagnostic
        nenergybins = 400
        energy_min = 95
        energy_max = 505
}
Equipotential
{
        j1 = 0
        j2 = 20
        k1 = 20
        k2 = 20
        normal = -1
        // the voltage
        C = -500
        transparency = 50
}
//      Polarizer
//{
//      j1 = 0
//      j2 = 10
//      k1 = 20
//      k2 = 20
```

```
//      normal = -1
//      transmissivity = 50
//}
}
```

The next series of results were run with a field emitter instead of a beam emitter. From the previous results we can begin to see patterns in the behavior of the ions and electrons and the resulting plasma. The next step we took was to add RF studies using a time varying field, which is what exists inside the cavity. Taking the results from the previous simulation runs we can see how accurate the DC experiments are in relation to the RF experiments. We have also added a gaussian distribution to the gas density, however, the first set of results do not use the gaussian. Following each set of pictures is the appropriate input file.

Parameters
Pressure = 50 Torr
DC Voltage = -2000 V
AC Voltage = 2000 V
Current = 5 A

RF vs. DC - DC Results:
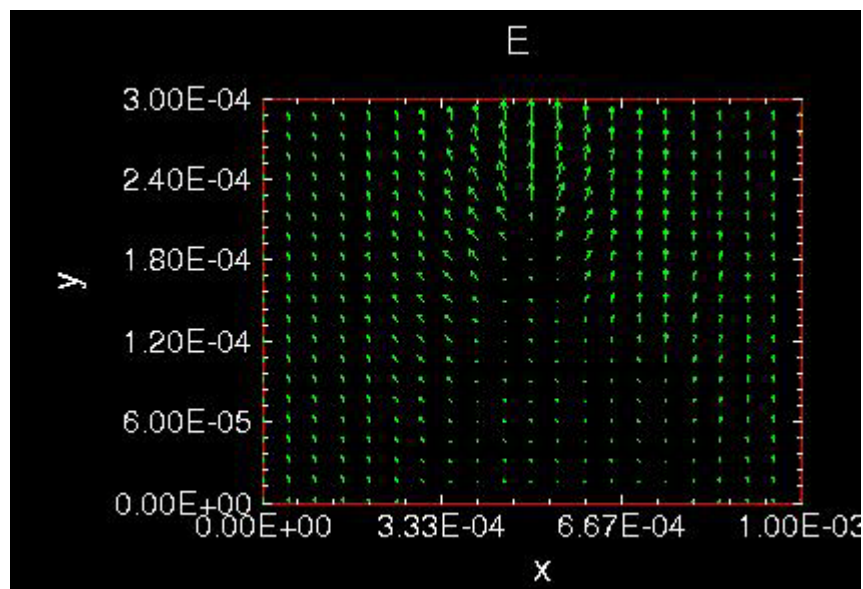
Figure 16 Electric field
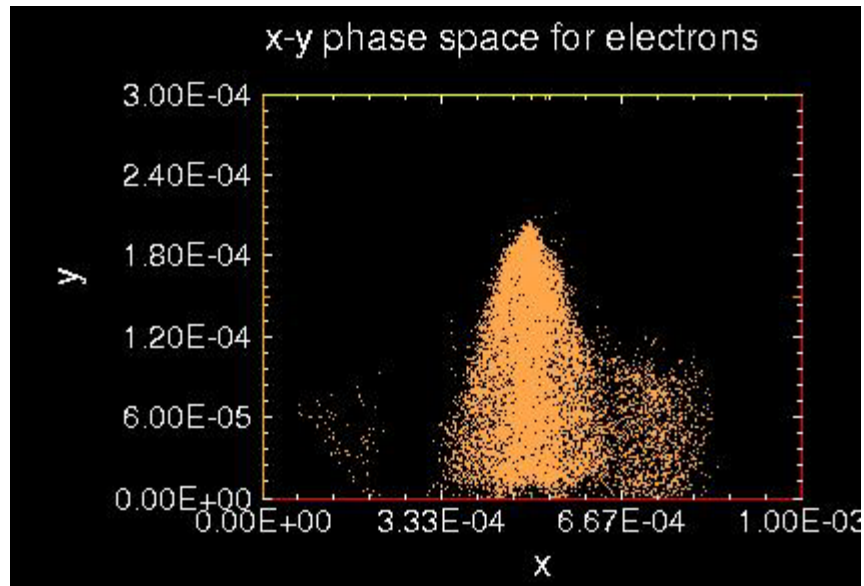
Figure 17
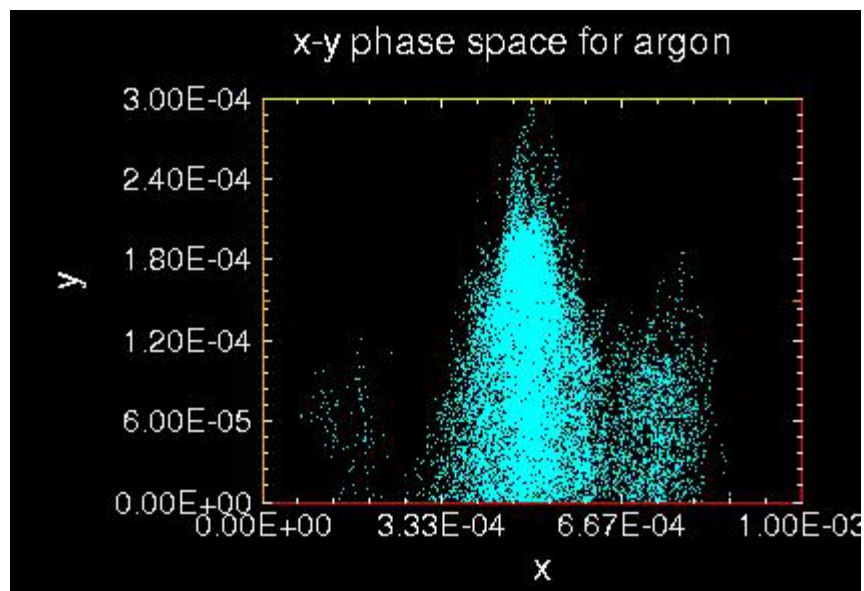
Figure 18
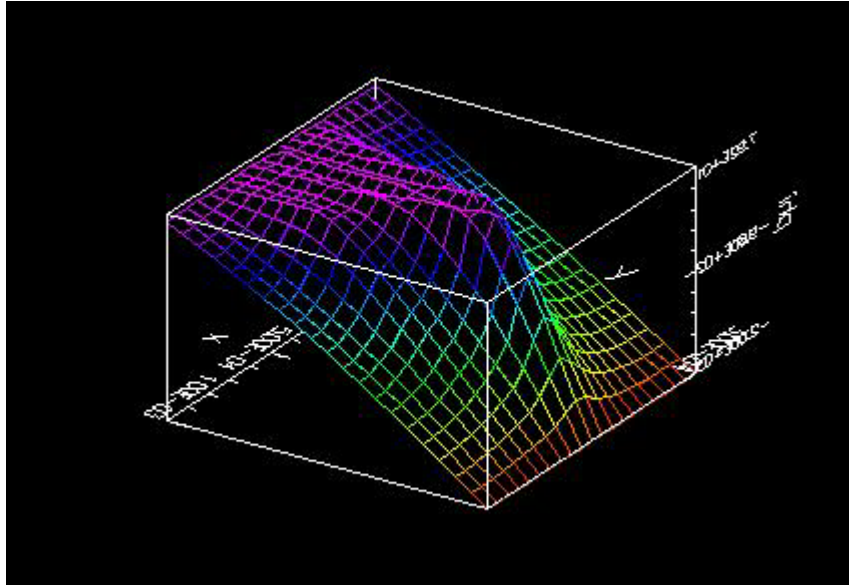
Figure 19 Potential

We can observe the same behavior patterns as before. In Figure 17 we can observe the dark space. There are also possibilities of streamers from the regions of electrons and ions branching away from the "parent" cloud.

```
voltestRF
{ voltestRFtestmoddc
   Particles at low current are dropped through a voltage.
   The voltage varies sinusoidally between 0 and 100 volts.

   This file is derived from the simpler voltest.inp file,
   in which the voltage is held constant at 100 V.

   Diagnostics of the electron positions and energies on
   arrival at the far wall are kept and displayed.  In this
   case, the particles should arrive with a distribution of
   energies, clustered roughly about 50 eV.
}

Variables
{
   numCellsX = 20
   numCellsY = 20
   numCellsEmitter = 1

   xMaxMKS = 0.001          // m
   yMaxMKS = 0.0003          // m

   omega = 1.0e+10        // radian/s
   pi    = 3.14159
   phi   = pi/4.            // radian

   constantAmpV   = -2000.  // V
   //sinusoidalAmpV =  2000.  // V

   timeStep = 5.0e-13     // s (make sure frequency*timeStep << 1)
}

Region
{
Grid
{
   // number of grids in x
   J = numCellsX
   x1s = 0.0
   x1f = xMaxMKS
   n1 = 1.0

   // number of grids in y
   K = numCellsY
   x2s = 0.0
   x2f = yMaxMKS
   n2 = 1.0

   Geometry = 1  // specify Cartesian geometry
}
Species
{
   name = electrons
   m = 9.11E-31
   q = -1.6e-19
  collisionModel=1
}
```

```
Species
{
        name = argon
        m = 6.67e-26
        q = 1.6E-19
//      subcycle = 100
        collisionModel=2
}
Control
{
   dt = timeStep
   ElectrostaticFlag = 1  // specify electrostatic field solve --
                          // assumes omega*yMaxMKS << c
}
MCC
{
        gas = Ar
        pressure = 50.0
//        temperature = 0.1
        eSpecies = electrons
        iSpecies = argon
}

// Top boundary is a time-varying equipotential surface.
Equipotential
{
   j1 = 0
   j2 = numCellsX
   k1 = numCellsY
   k2 = numCellsY
   normal = -1

   C = constantAmpV       // constant potential in V
   A = sinusoidalAmpV     // amplitude of sinusoidal variation in V
   frequency = omega      // frequency of the oscillation
   phase = phi
}

// Embedded within the top boundary is a simple beam emitter that
//   emits a small, constant current of electrons
EmitPort
{
   j1 = (numCellsX-numCellsEmitter) / 2
   j2 = (numCellsX+numCellsEmitter) / 2
   k1 = numCellsY
   k2 = numCellsY
   normal = -1

   speciesName = electrons        // name corresponds to species block
above
   np2c = 4.0e+08                 // numerical weight of the macro-
particles
   I = 5.0                  // emitted current in A
   v2drift = 0.01                 // initial particle velocity in m/s
}

// Bottom boundary is a perfect conductor
// Also, particle diagnostics are being collected
```

```
Conductor
{
   name = collector
   j1 = 0
   j2 = numCellsX
   k1 = 0
   k2 = 0

   IdiagFlag = 1       // turn on the diagnostics
   nxbins = 40         // specify spatial resolution
   nenergybins = 105   // specify energy  resolution
   energy_min = 0
   energy_max = 2005
}

// Left boundary is a simple dielectric
Dielectric
{
   j1 = 0
   j2 = 0
   k1 = 0
   k2 = numCellsY
}

// Right boundary is a simple dielectric
Dielectric
{
   j1 = numCellsX
   j2 = numCellsX
   k1 = 0
   k2 = numCellsY
   normal = -1
}
}
```

In the first set of pictures the ions and electrons have cloud formations similar to the DC. As time progresses we can see that there is more ionization occurring; this is because the probability of collision for the electrons increases due to time varying field.

RF vs. DC - RF Results
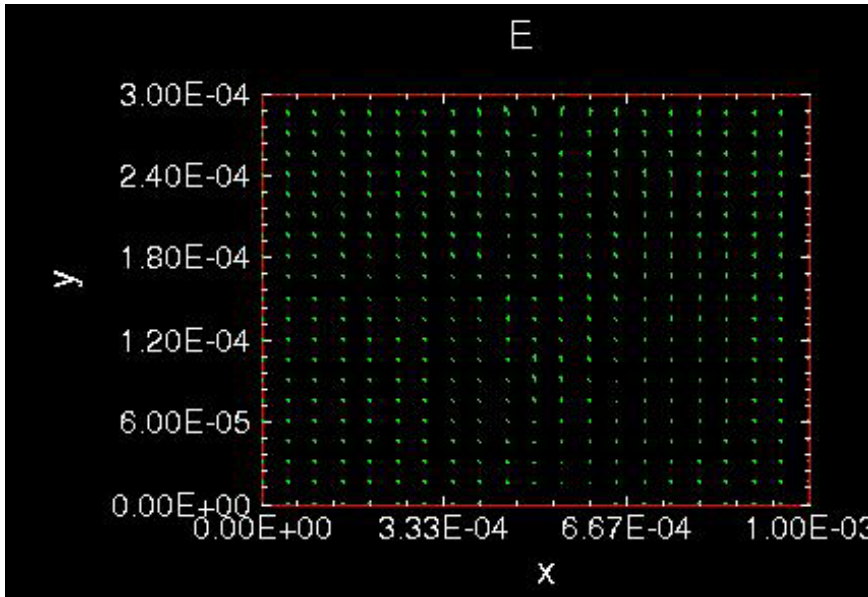
Figure 20 Electric Field
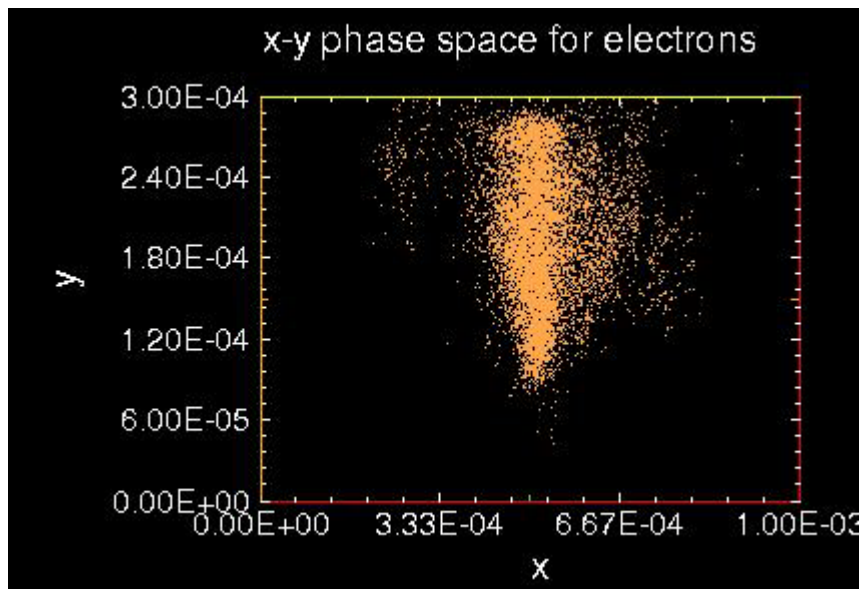
Figure 21
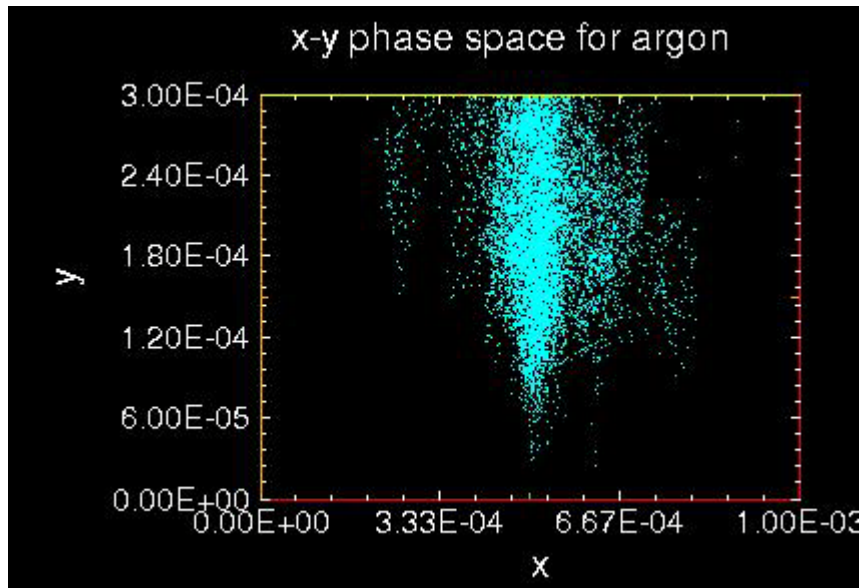
Figure 22
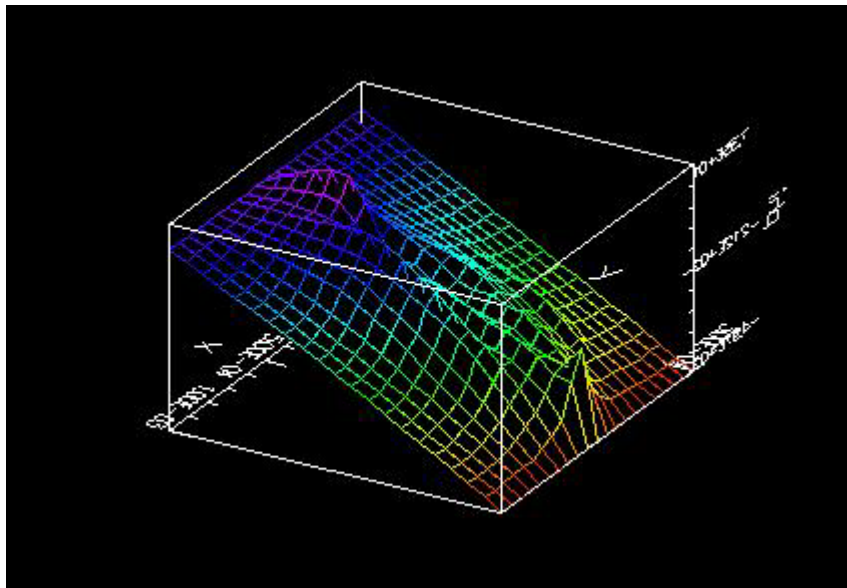
Figure 23 Potential

The following diagrams are of the same run just at a later time to show more ionization.
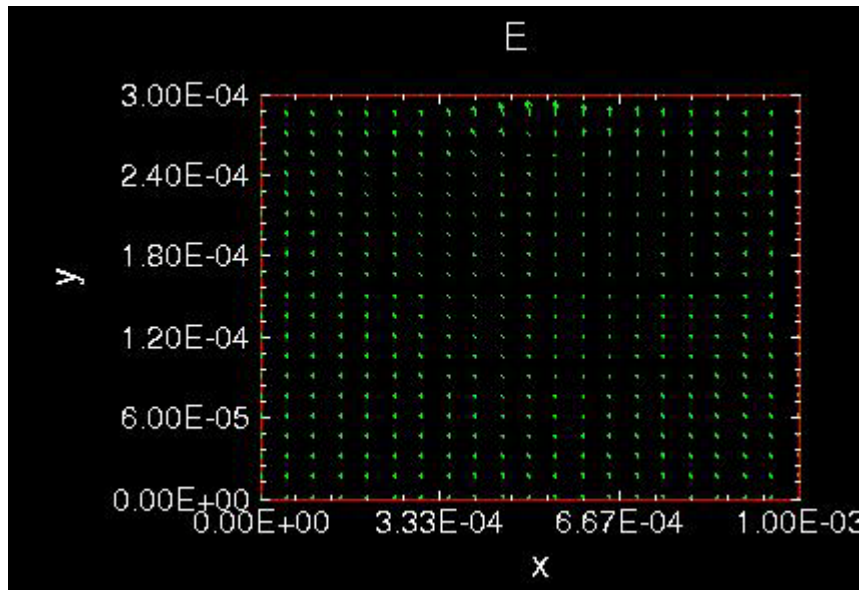
Figure 24 Electric Field
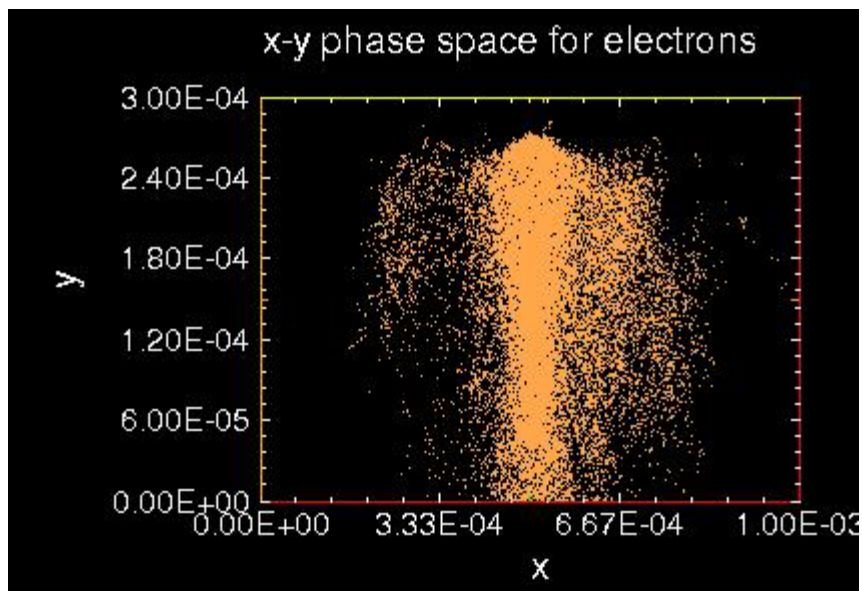
Figure 25
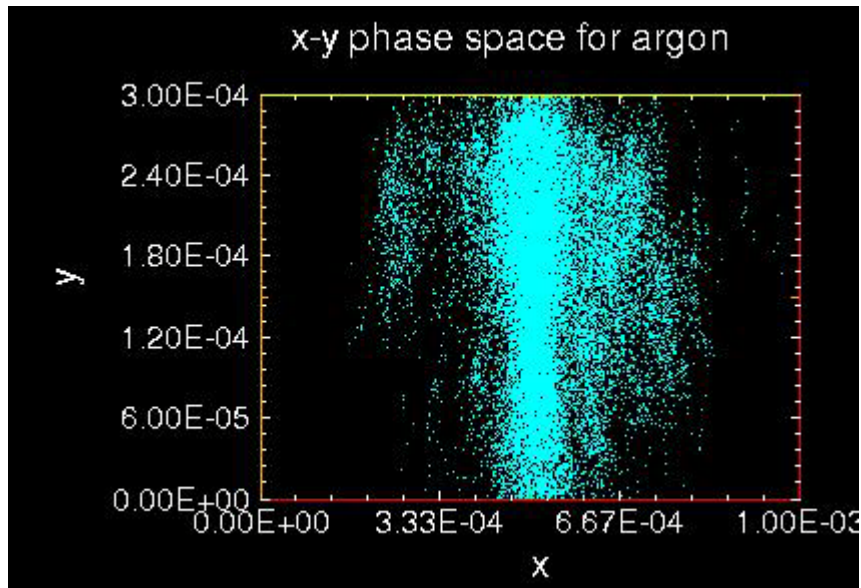
Figure 26
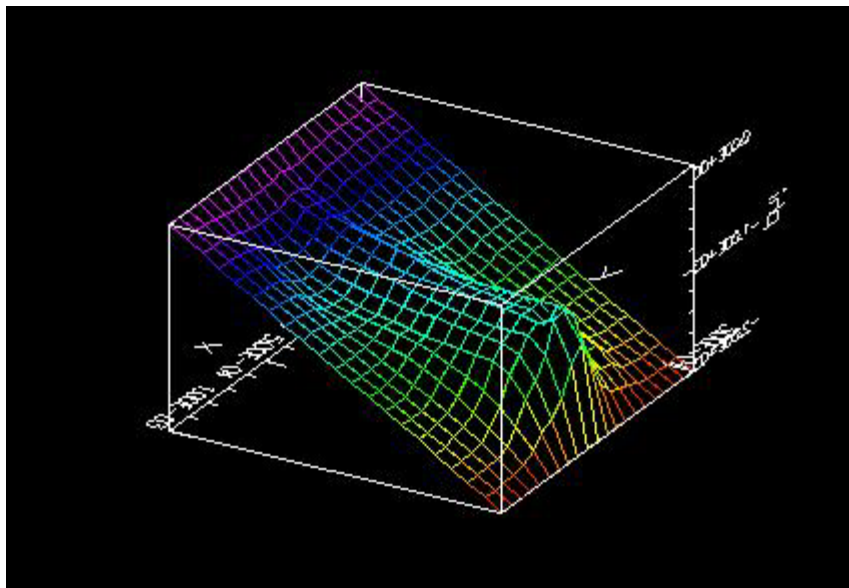
Figure 27

Again, the mean-free path of the electrons is visible. One of the initial

questions we wanted to answer was the effect of field enhancement on the

mean-free path and whether it affected the ions forming closer to the emitter.

The RF results here seem to show that there is a field enhancement of two mesh

elements, which is relatively strong, and ions forming right next to the emitter.

There is also a visible ion column and spreading.

```
voltestRF
{  voltestRFtestmod
   Particles at low current are dropped through a voltage.
   The voltage varies sinusoidally between 0 and 100 volts.

   This file is derived from the simpler voltest.inp file,
   in which the voltage is held constant at 100 V.

   Diagnostics of the electron positions and energies on
   arrival at the far wall are kept and displayed.  In this
   case, the particles should arrive with a distribution of
   energies, clustered roughly about 50 eV.
}

Variables
{
   numCellsX = 20
   numCellsY = 20
   numCellsEmitter = 1

   xMaxMKS = 0.001          // m
   yMaxMKS = 0.0003          // m

   omega = 1.0e+10        // radian/s
   pi    = 3.14159
   phi   = pi/4.            // radian

   //constantAmpV   = -2000.  // V
   sinusoidalAmpV =  2000.  // V

   timeStep = 5.0e-13     // s (make sure frequency*timeStep << 1)
}

Region
{
Grid
{
   // number of grids in x
   J = numCellsX
   x1s = 0.0
   x1f = xMaxMKS
   n1 = 1.0

   // number of grids in y
   K = numCellsY
   x2s = 0.0
   x2f = yMaxMKS
   n2 = 1.0

   Geometry = 1  // specify Cartesian geometry
}
Species
{
   name = electrons
   m = 9.11E-31
   q = -1.6e-19
  collisionModel=1
}
```

```
      Species
      {
              name = argon
              m = 6.67e-26
              q = 1.6E-19
//      subcycle = 100
           collisionModel=2
      }
      Control
      {
         dt = timeStep
         ElectrostaticFlag = 1  // specify electrostatic field solve --
                                // assumes omega*yMaxMKS << c
      }
      MCC
      {
           gas = Ar
           pressure = 50.0
//         temperature = 0.1
           eSpecies = electrons
           iSpecies = argon
      }

      // Top boundary is a time-varying equipotential surface.
      Equipotential
      {
         j1 = 0
         j2 = numCellsX
         k1 = numCellsY
         k2 = numCellsY
         normal = -1

         C = constantAmpV        // constant potential in V
         A = sinusoidalAmpV      // amplitude of sinusoidal variation in V
         frequency = omega       // frequency of the oscillation
         phase = phi
      }

      // Embedded within the top boundary is a simple beam emitter that
      //   emits a small, constant current of electrons
      EmitPort
      {
         j1 = (numCellsX-numCellsEmitter) / 2
         j2 = (numCellsX+numCellsEmitter) / 2
         k1 = numCellsY
         k2 = numCellsY
         normal = -1

         speciesName = electrons        // name corresponds to species block
      above
         np2c = 4.0e+08                 // numerical weight of the macro-
      particles
         I = 5.0                  // emitted current in A
         v2drift = 0.01                 // initial particle velocity in m/s
      }

      // Bottom boundary is a perfect conductor
      // Also, particle diagnostics are being collected
```

```
Conductor
{
   name = collector
   j1 = 0
   j2 = numCellsX
   k1 = 0
   k2 = 0

   IdiagFlag = 1        // turn on the diagnostics
   nxbins = 40          // specify spatial resolution
   nenergybins = 105  // specify energy  resolution
   energy_min = 0
   energy_max = 2005
}

// Left boundary is a simple dielectric
Dielectric
{
   j1 = 0
   j2 = 0
   k1 = 0
   k2 = numCellsY
}

// Right boundary is a simple dielectric
Dielectric
{
   j1 = numCellsX
   j2 = numCellsX
   k1 = 0
   k2 = numCellsY
   normal = -1
}
}
```

The same DC RF comparison was made except now the electrons are confined to the area designated by the gaussian function for the gas density.

Parameters
Pressure = 50 Torr
DC Voltage = -2000 V
AC Voltage = 2000 V
Current = 5 A

RF vs. DC - RF Results
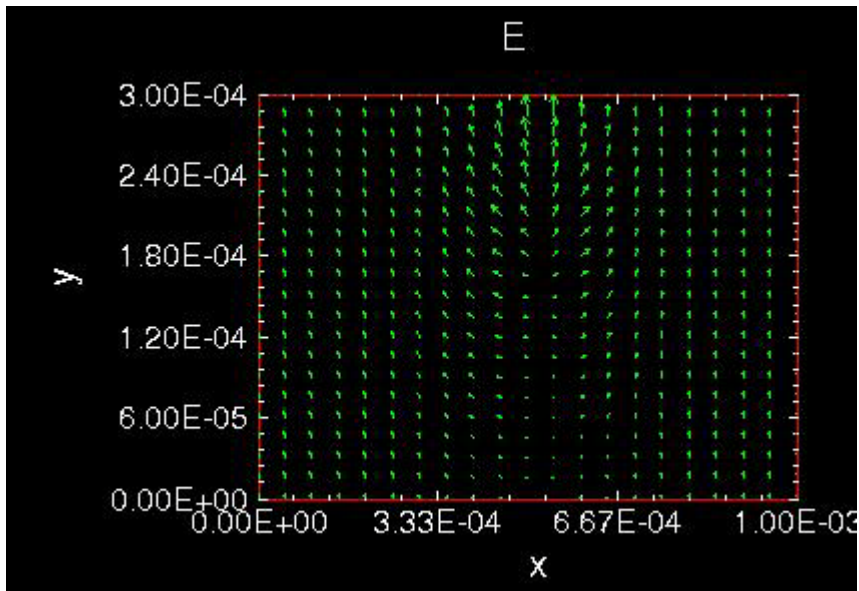
Figure 28 Electric Field
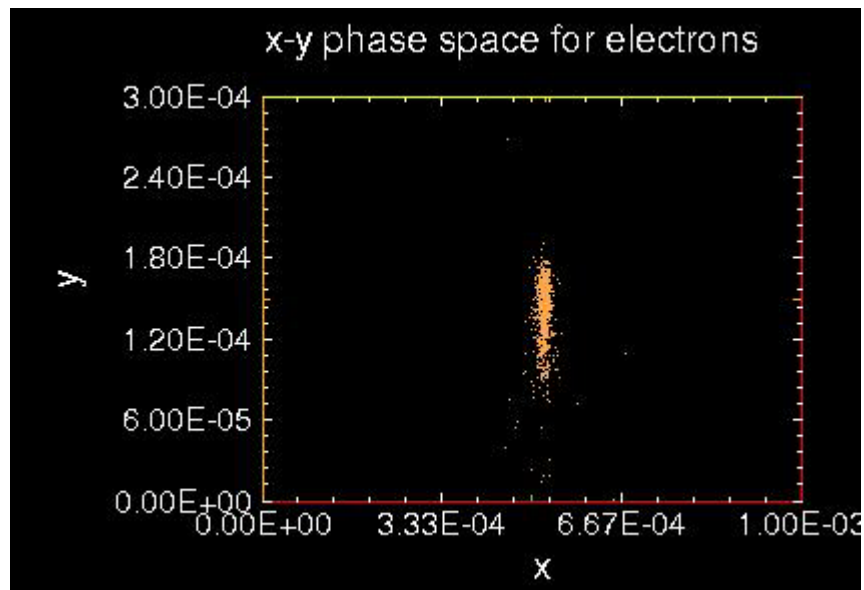
Figure 29
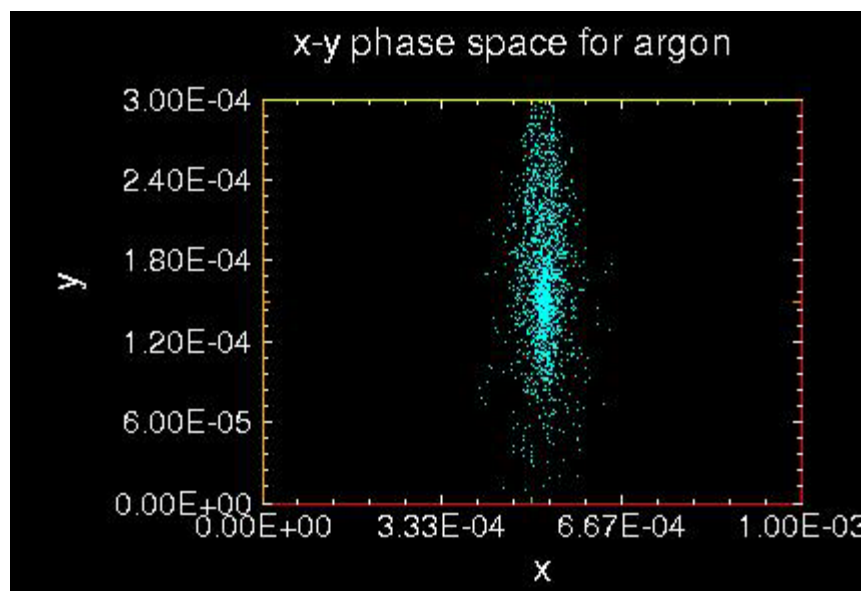
Figure 30
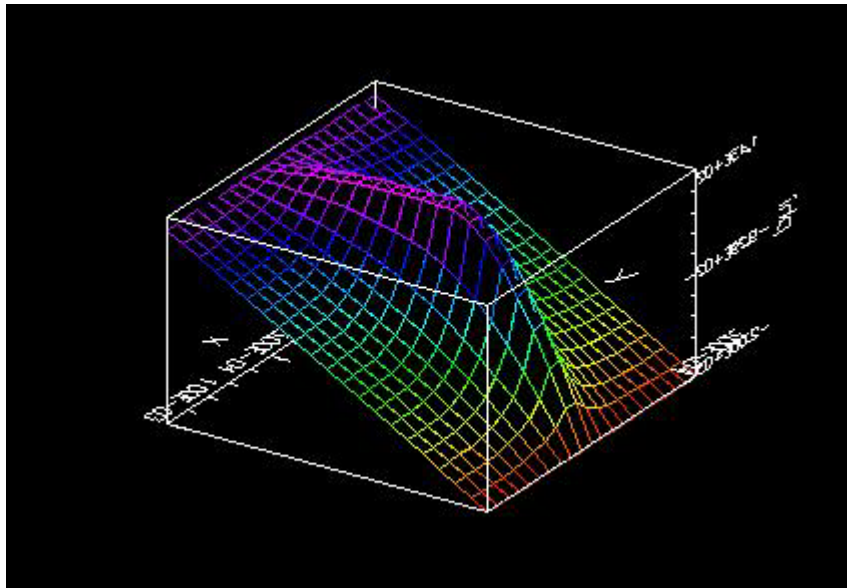
Figure 31 Potential

The following pictures are the same run at a later time.
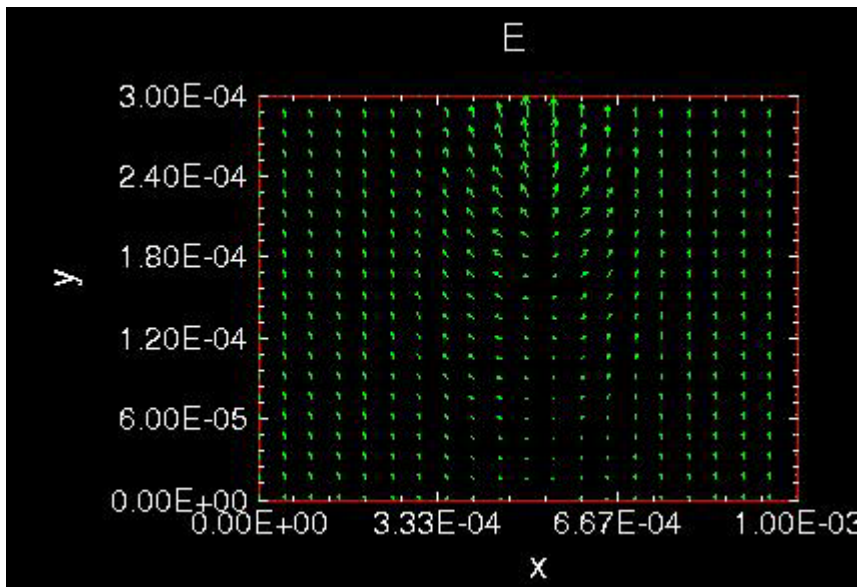
Figure 32 Electric Field
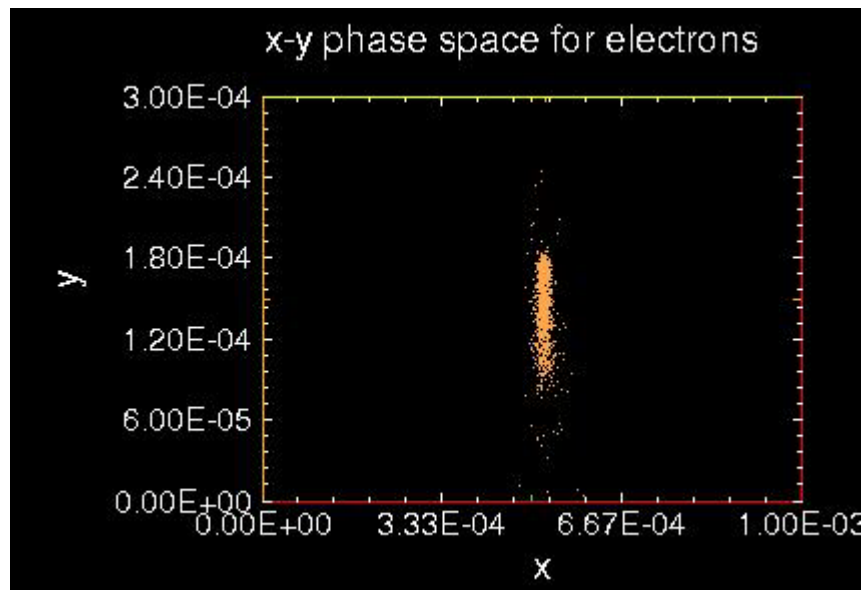
Figure 33
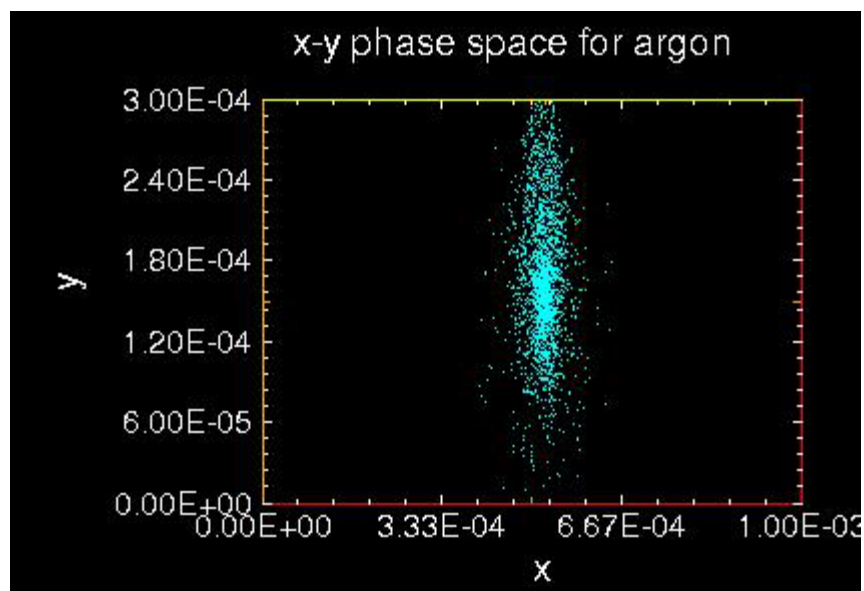
Figure 34
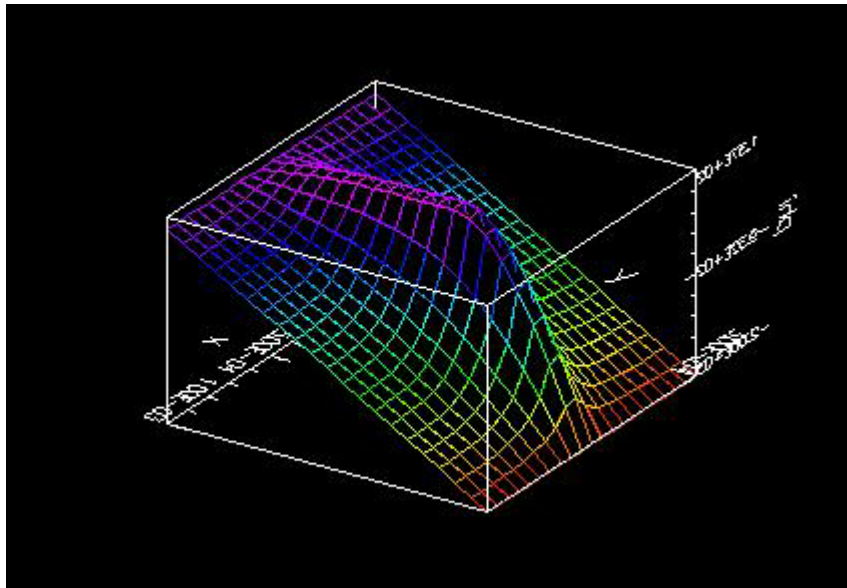
Figure 35 Potential

```
voltestRF
{  voltestRFgaussian
   Particles at low current are dropped through a voltage.
   The voltage varies sinusoidally between 0 and 100 volts.

   This file is derived from the simpler voltest.inp file,
   in which the voltage is held constant at 100 V.

   Diagnostics of the electron positions and energies on
   arrival at the far wall are kept and displayed.  In this
   case, the particles should arrive with a distribution of
   energies, clustered roughly about 50 eV.
}

Variables
{
   numCellsX = 20
   numCellsY = 20
   numCellsEmitter = 1

   xMaxMKS = 0.001          // m
   yMaxMKS = 0.0003          // m
   x1_mid = xMaxMKS / 2.

   gasTempEV       = 0.1  // make gas cold (cannot set temperature to
zero)
   gasPressureTorr = 50.0

   omega = 1.0e+10        // radian/s
   pi    = 3.14159
   phi   = pi/4.            // radian

   constantAmpV   = -2000.  // V
   //sinusoidalAmpV =  2000.  // V

   timeStep = 5.0e-13     // s (make sure frequency*timeStep << 1)
}

Region
{
Grid
{
   // number of grids in x
   J = numCellsX
   x1s = 0.0
   x1f = xMaxMKS
   n1 = 1.0

   // number of grids in y
   K = numCellsY
   x2s = 0.0
   x2f = yMaxMKS
   n2 = 1.0

   Geometry = 1  // specify Cartesian geometry
}
Species
```

```
{
   name = electrons
   m = 9.11E-31
   q = -1.6e-19
  collisionModel=1
}
Species
{
        name = argon
        m = 6.67e-26
        q = 1.6E-19
//     subcycle = 100
       collisionModel=2
}
Control
{
   dt = timeStep
   ElectrostaticFlag = 1  // specify electrostatic field solve --
                          // assumes omega*yMaxMKS << c
}
MCC
{
     gas = Ar
//    pressure = 5.0
        temperature = 0.1
      analyticF = gasPressureTorr * 0.30e+23 * exp(-0.5 * ((x1-
x1_mid)*(x1-x1_mid)+(x2-yMaxMKS)*(x2-yMaxMKS)) /
((xMaxMKS/10.)*(xMaxMKS/10.)) )

        eSpecies = electrons
      iSpecies = argon
}

// Top boundary is a time-varying equipotential surface.
Equipotential
{
   j1 = 0
   j2 = numCellsX
   k1 = numCellsY
   k2 = numCellsY
   normal = -1

   C = constantAmpV      // constant potential in V
   A = sinusoidalAmpV    // amplitude of sinusoidal variation in V
   frequency = omega     // frequency of the oscillation
   phase = phi
}

// Embedded within the top boundary is a simple beam emitter that
//   emits a small, constant current of electrons
EmitPort
{
   j1 = (numCellsX-numCellsEmitter) / 2
   j2 = (numCellsX+numCellsEmitter) / 2
   k1 = numCellsY
   k2 = numCellsY
   normal = -1
```

```
    speciesName = electrons           // name corresponds to species block
above
    np2c = 4.0e+08                    // numerical weight of the macro-
particles
    I = 5.0                       // emitted current in A
    v2drift = 0.01                    // initial particle velocity in m/s
}

// Bottom boundary is a perfect conductor
// Also, particle diagnostics are being collected
Conductor
{
    name = collector
    j1 = 0
    j2 = numCellsX
    k1 = 0
    k2 = 0

    IdiagFlag = 1      // turn on the diagnostics
    nxbins = 40        // specify spatial resolution
    nenergybins = 105  // specify energy  resolution
    energy_min = 0
    energy_max = 2005
}

// Left boundary is a simple dielectric
Dielectric
{
    j1 = 0
    j2 = 0
    k1 = 0
    k2 = numCellsY
}

// Right boundary is a simple dielectric
Dielectric
{
    j1 = numCellsX
    j2 = numCellsX
    k1 = 0
    k2 = numCellsY
    normal = -1
}
}
```

The key to understanding the nature of starbursts is to reveal the physics behind the emitter explosion and the microdischarge. We have already looked at the discharge; the final study simulates an explosion under both DC and RF conditions.   Previous studies have already shown that in the presence of gas and its ionization an explosion process occurs. [2] We also know that a dense cloud increases the power dissipation in the field emitter by the ion bombardment. When the dissipated power drastically increases, it too triggers an explosion.

	Example 20	Example 21
Pressure (Torr)	100	500
DC Voltage (V)	-2000	-2000
AC Voltage (V)	2000	2000
Current (A)	50	50

RF vs. DC Explosion 100T- DC Results
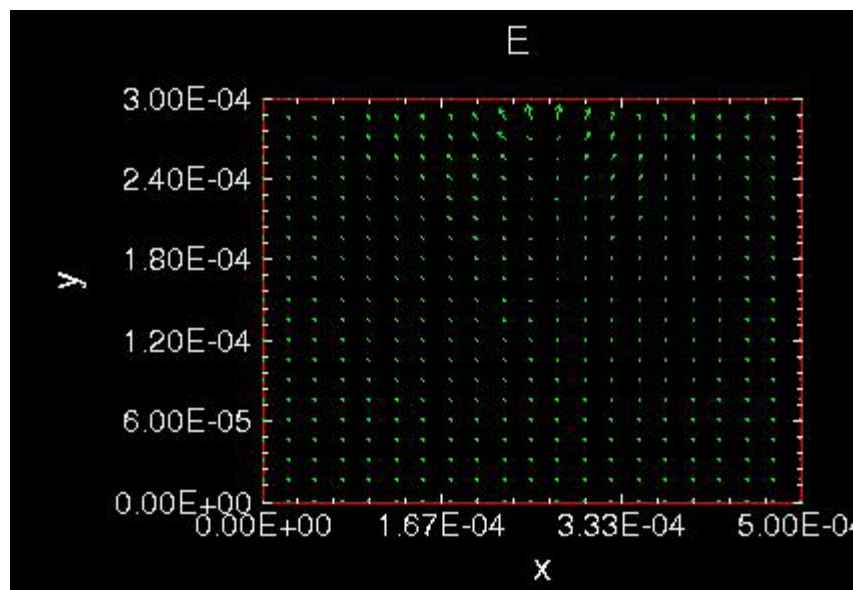
Figure 36 Electric Field
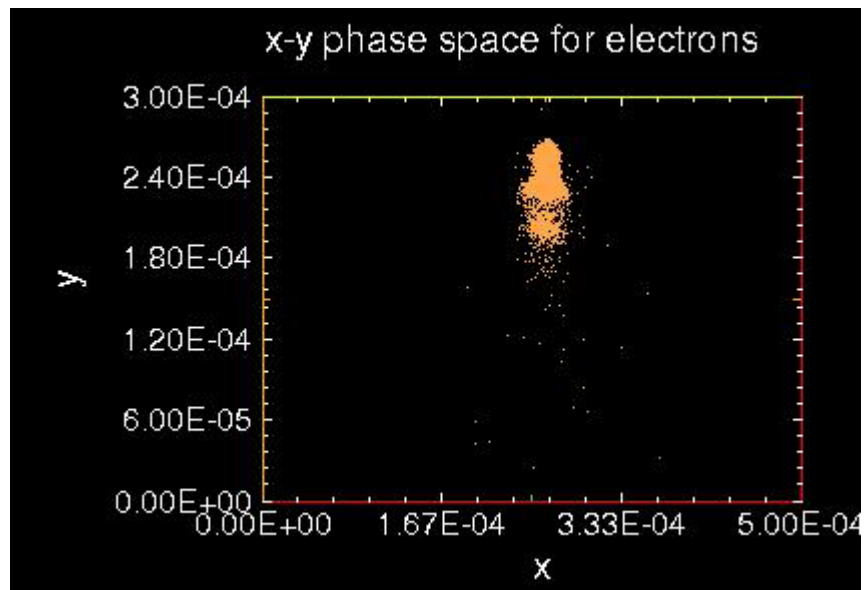
Figure 37
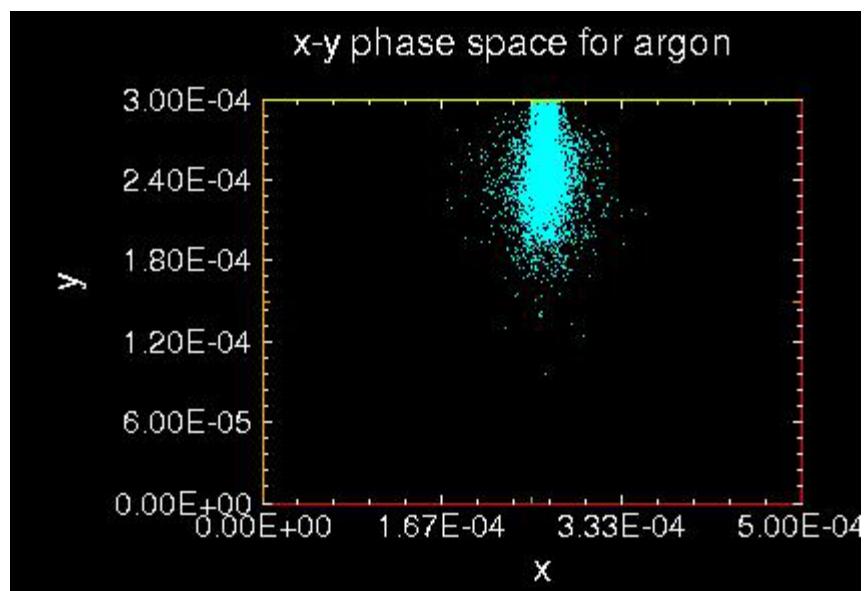
Figure 38
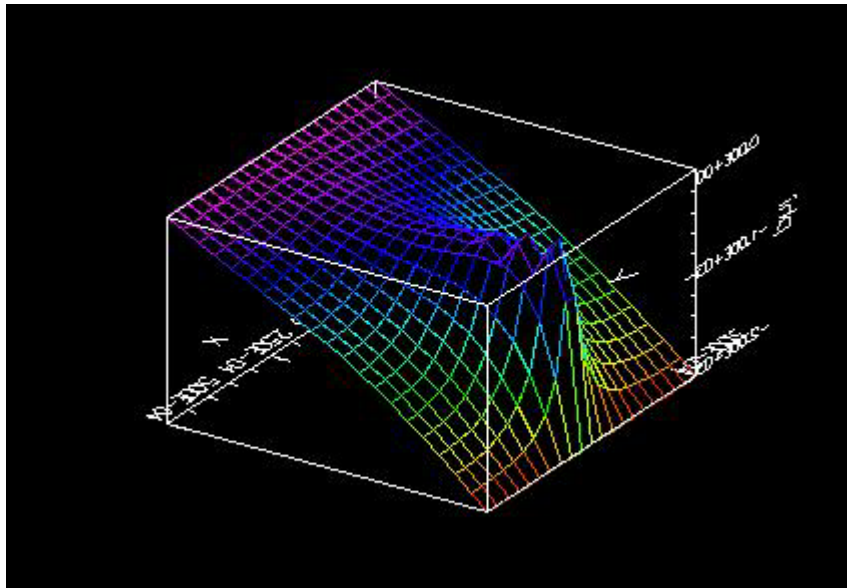
Figure 39 Potential

Same simulation at time of explosion.
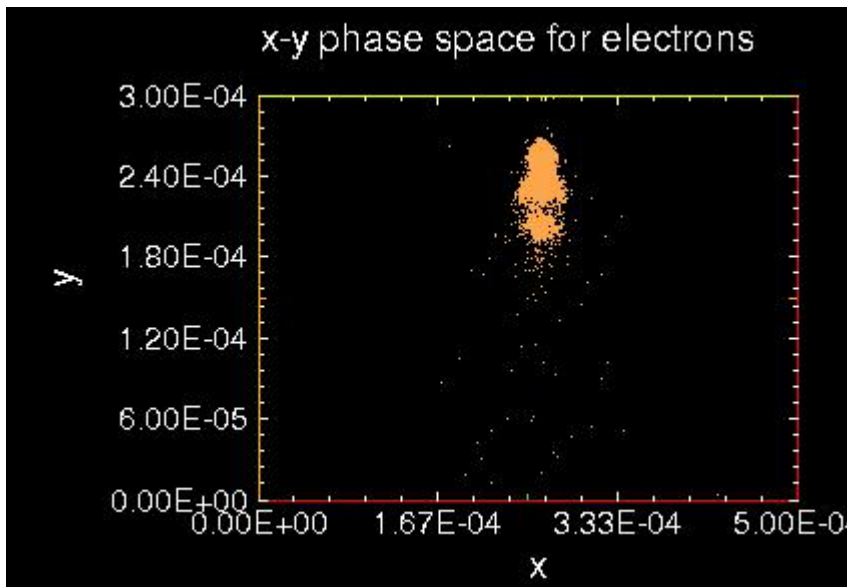
Figure 40
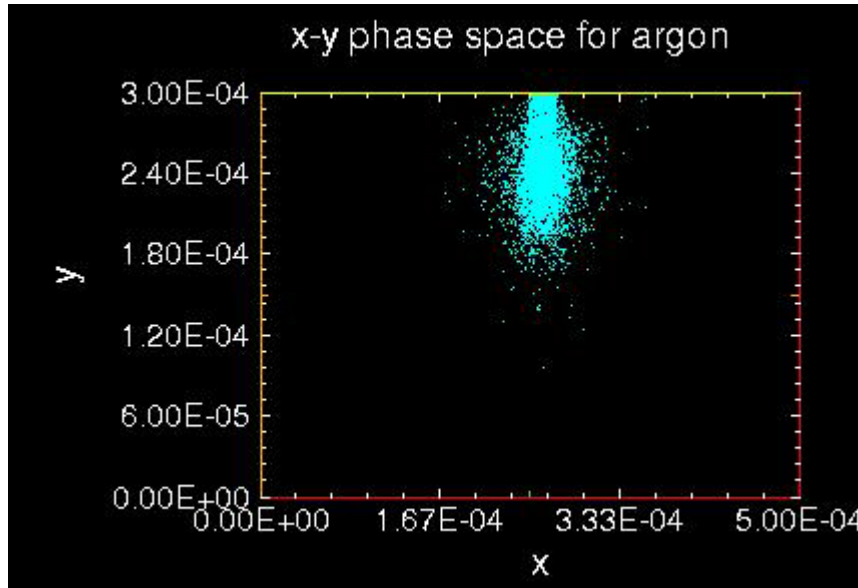
Figure 41
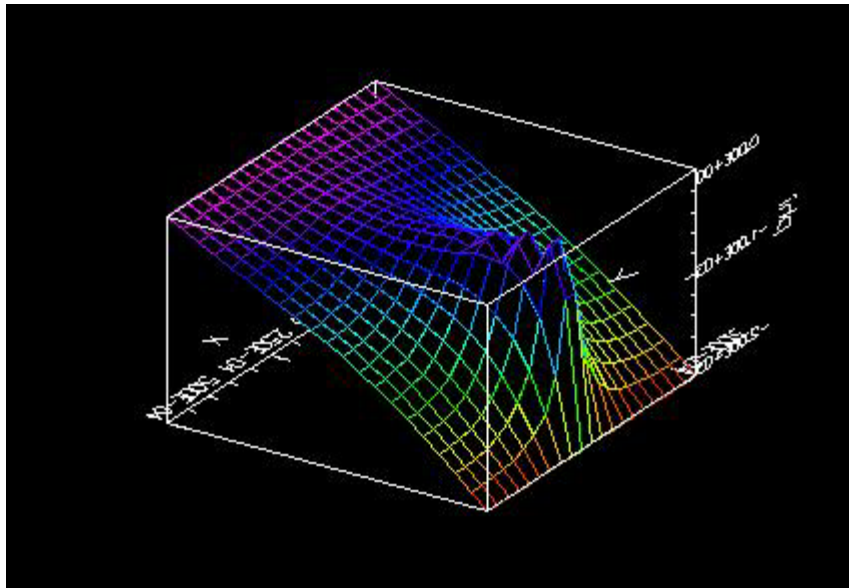
Figure 41 Potential

As the electrons accumulate they build up into three distinct regions.   The area becomes denser and the holes between the regions begin to fill in with electrons. Notice that the field enhancement is very high. Eventually the potential begins to jump and the electron cloud explodes. Although we know some of the factors that trigger the explosion, the explosion in Oopic is only accurate up to the initial explosion. Our np2c is now 4×10^8. As more and more particles are created the Poisson solver has a hard time keeping track of all the particles, which could lead to some inaccuracies after the explosion.

```
      voltestRF
{ explosionDC100Tgaussian
   Particles at low current are dropped through a voltage.
   The voltage varies sinusoidally between 0 and 100 volts.

   This file is derived from the simpler voltest.inp file,
   in which the voltage is held constant at 100 V.

   Diagnostics of the electron positions and energies on
   arrival at the far wall are kept and displayed.  In this
   case, the particles should arrive with a distribution of
   energies, clustered roughly about 50 eV.
}

Variables
{
   numCellsX = 20
   numCellsY = 20
   numCellsEmitter = 1

   xMaxMKS = 0.0005          // m
   yMaxMKS = 0.0003          // m
   x1_mid = xMaxMKS / 2.

   gasTempEV        = 0.1  // make gas cold (cannot set temperature to
zero)
   gasPressureTorr = 100.0

   omega = 1.0e+10        // radian/s
   pi    = 3.14159
   phi   = pi/4.             // radian

   constantAmpV    = -2000.  // V
   //sinusoidalAmpV =  2000.  // V

   timeStep = 7.0e-13    // s (make sure frequency*timeStep << 1)
}

Region
{
Grid
{
   // number of grids in x
   J = numCellsX
   x1s = 0.0
   x1f = xMaxMKS
   n1 = 1.0

   // number of grids in y
   K = numCellsY
   x2s = 0.0
   x2f = yMaxMKS
   n2 = 1.0

   Geometry = 1  // specify Cartesian geometry
}
Species
{
```

```
   name = electrons
   m = 9.11E-31
   q = -1.6e-19
  collisionModel=1
}
Species
{
        name = argon
        m = 6.67e-26
        q = 1.6E-19
//     subcycle = 100
      collisionModel=2
}
Control
{
   dt = timeStep
   ElectrostaticFlag = 1  // specify electrostatic field solve --
                          // assumes omega*yMaxMKS << c
}
MCC
{
      gas = Ar
//     pressure = 5.0
        temperature = 0.1
      analyticF = gasPressureTorr * 0.30e+23 * exp(-0.5 * ((x1-
x1_mid)*(x1-x1_mid)+(x2-yMaxMKS)*(x2-yMaxMKS)) /
((xMaxMKS/10.)*(xMaxMKS/10.)) )

        eSpecies = electrons
      iSpecies = argon
}

// Top boundary is a time-varying equipotential surface.
Equipotential
{
   j1 = 0
   j2 = numCellsX
   k1 = numCellsY
   k2 = numCellsY
   normal = -1

   C = constantAmpV        // constant potential in V
   A = sinusoidalAmpV      // amplitude of sinusoidal variation in V
   frequency = omega       // frequency of the oscillation
   phase = phi
}

// Embedded within the top boundary is a simple beam emitter that
//   emits a small, constant current of electrons
EmitPort
{
   j1 = (numCellsX-numCellsEmitter) / 2
   j2 = (numCellsX+numCellsEmitter) / 2
   k1 = numCellsY
   k2 = numCellsY
   normal = -1
```

```
    speciesName = electrons          // name corresponds to species block
above
    np2c = 4.0e+08                    // numerical weight of the macro-
particles
    I = 50.0                     // emitted current in A
    v2drift = 0.01                   // initial particle velocity in m/s
}

// Bottom boundary is a perfect conductor
// Also, particle diagnostics are being collected
Conductor
{
    name = collector
    j1 = 0
    j2 = numCellsX
    k1 = 0
    k2 = 0

    IdiagFlag = 1      // turn on the diagnostics
    nxbins = 40        // specify spatial resolution
    nenergybins = 105  // specify energy  resolution
    energy_min = 0
    energy_max = 1005
}

// Left boundary is a simple dielectric
Dielectric
{
    j1 = 0
    j2 = 0
    k1 = 0
    k2 = numCellsY
}

// Right boundary is a simple dielectric
Dielectric
{
    j1 = numCellsX
    j2 = numCellsX
    k1 = 0
    k2 = numCellsY
    normal = -1
}
}
```

RF vs. DC Explosion 100 T-RF Results
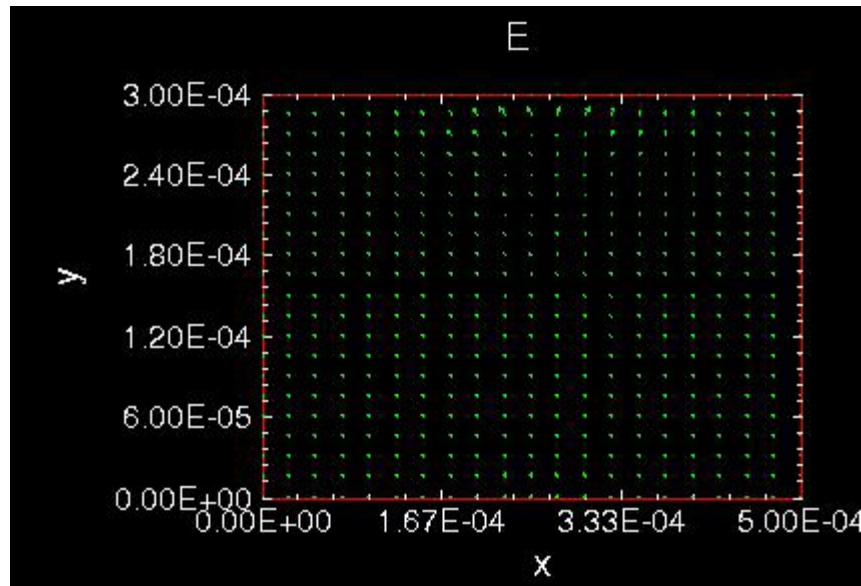
Figure 42 Electric Field

Figure 43

x-y phase space for argon
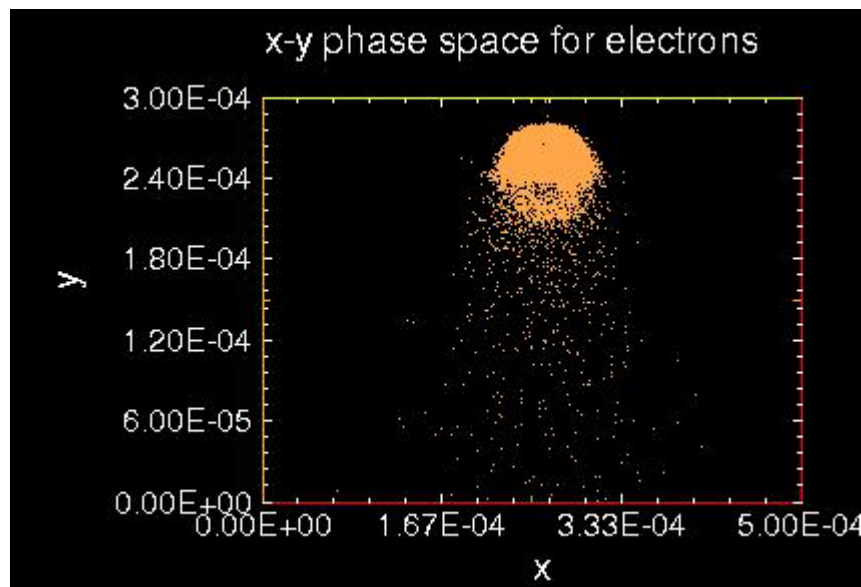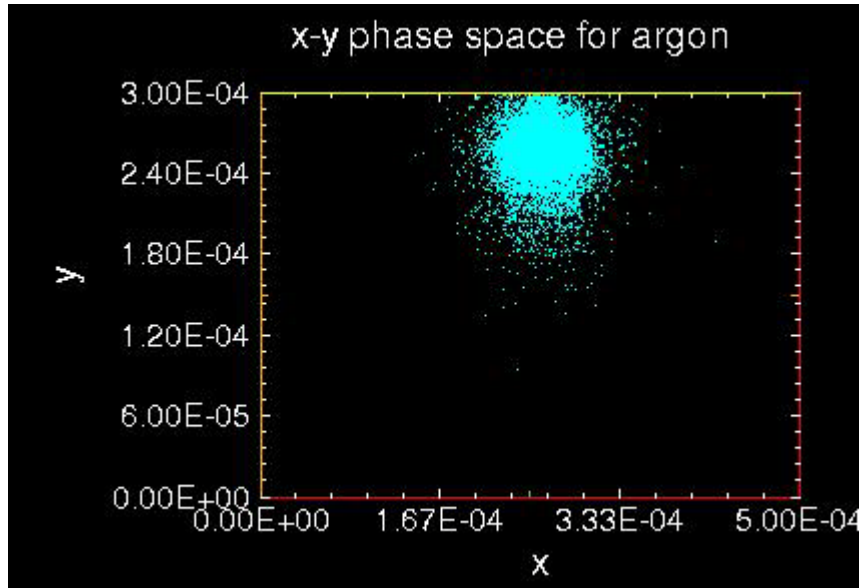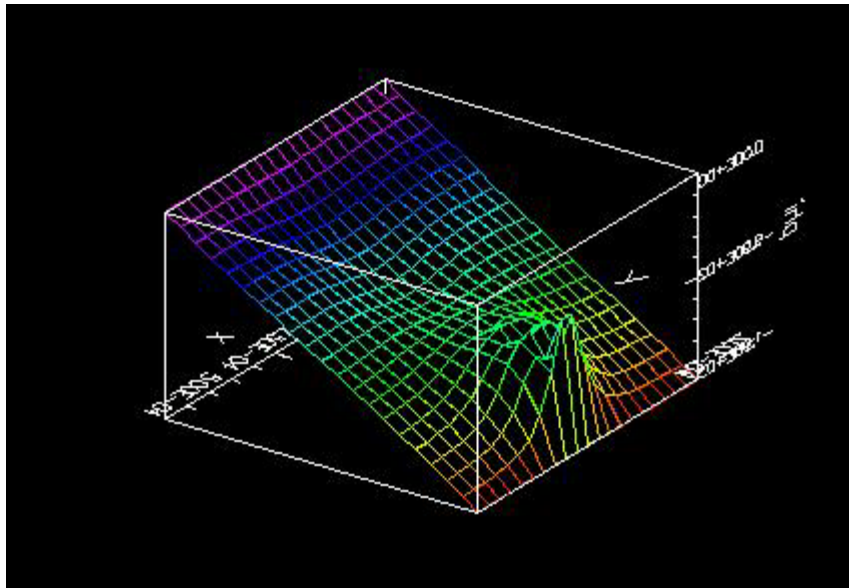
Figure 44

Figure 45 Potential

The electron cloud has two distinct regions. In the next series of figures

the electron cloud begins to look like one cloud right before the explosion.
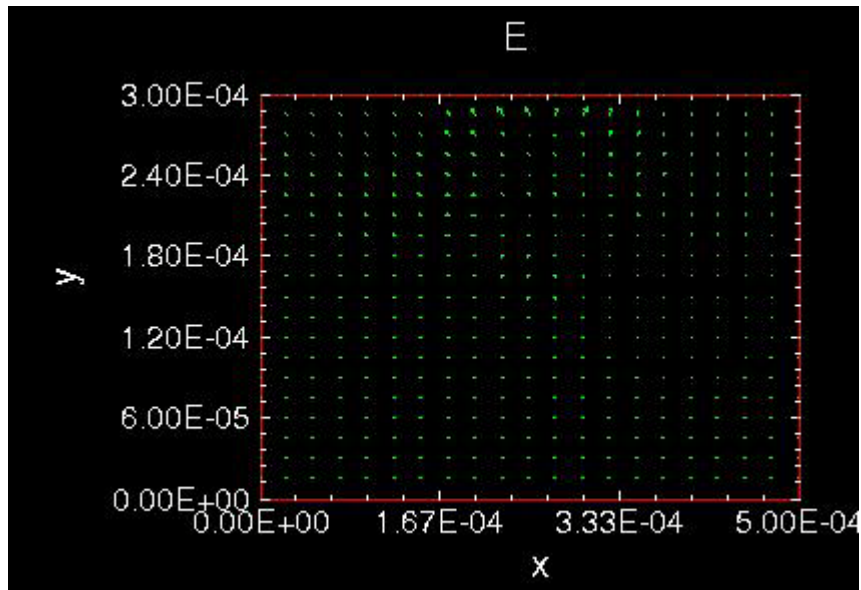
Figure 46 Electric Field

Figure 47

x-y phase space for argon
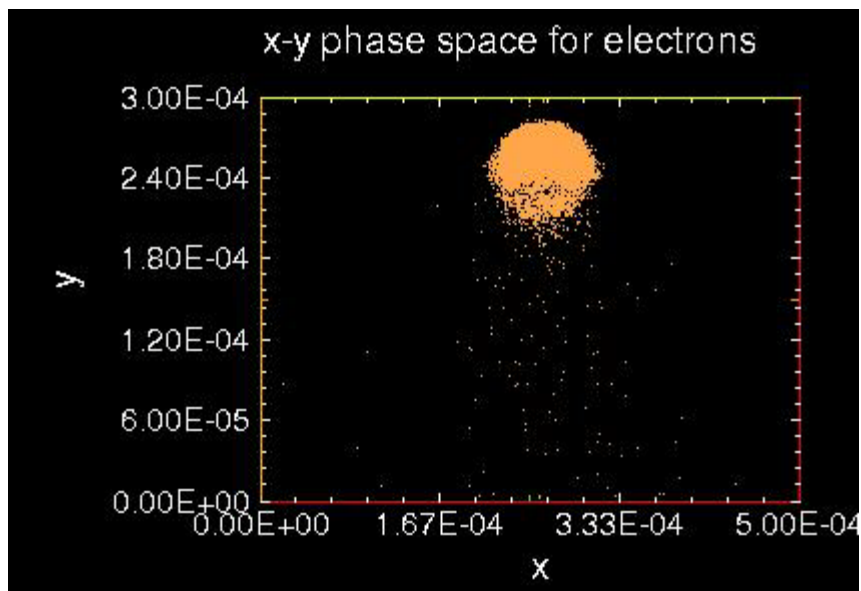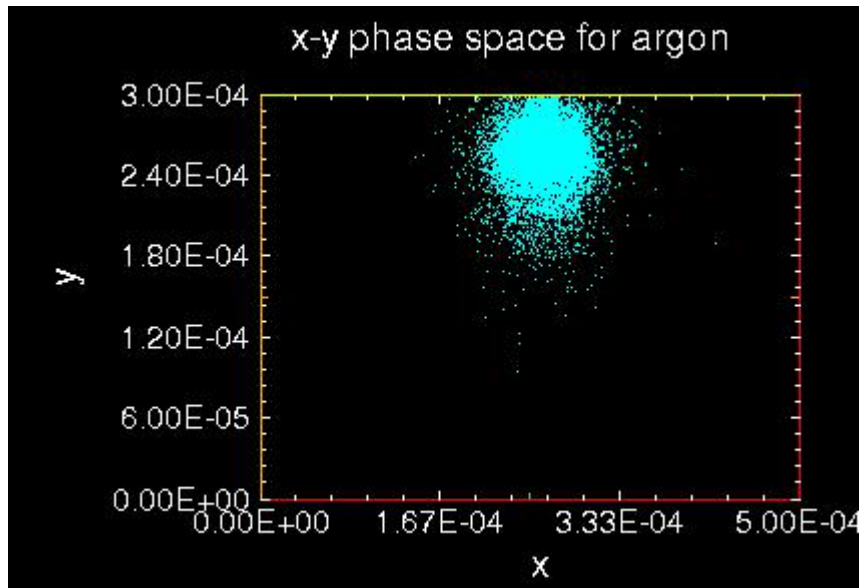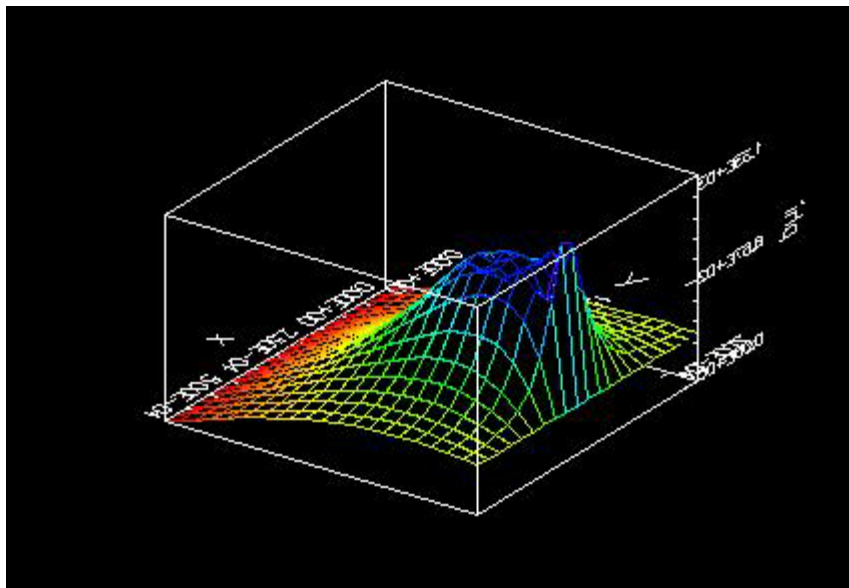
Figure 48

Figure 49 Potential

The next series shows the explosion of the electron cloud.
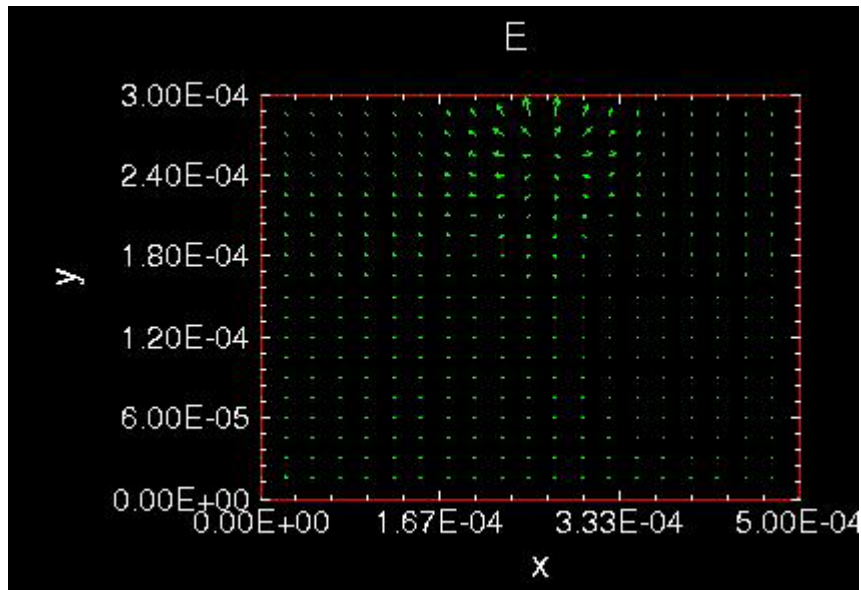
Figure 50 Electric Field
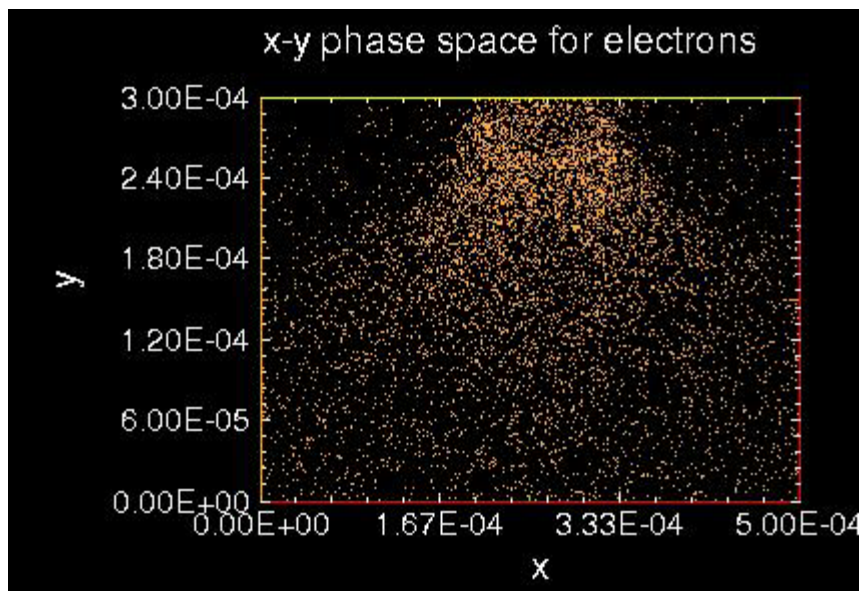
Figure 51 Explosion
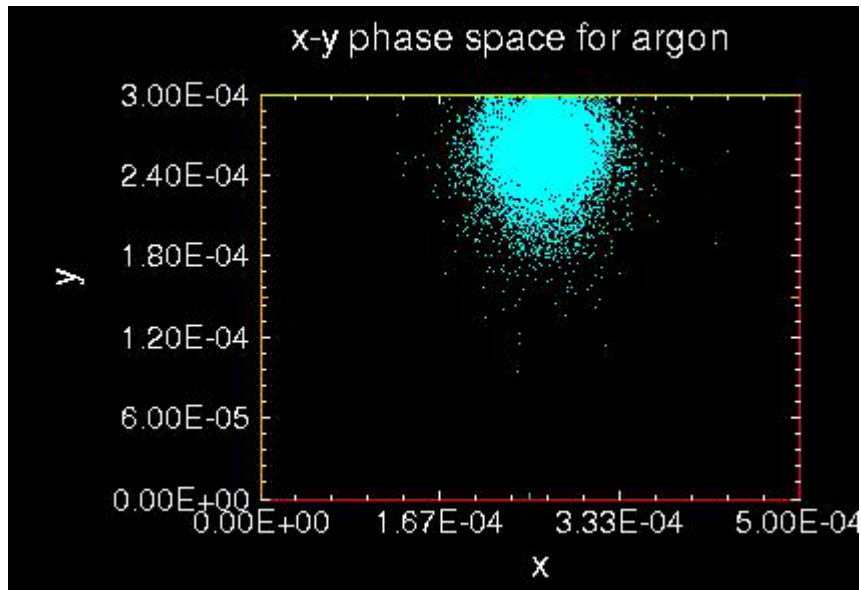
Figure 52
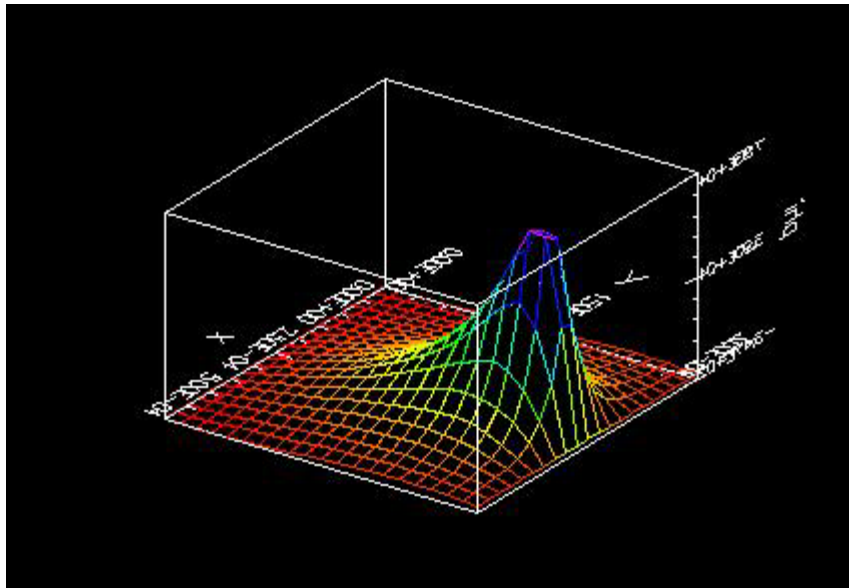
Figure 53 Potential

```
voltestRF
{  explosionRF100Tw10^10gaussian
   Particles at low current are dropped through a voltage.
   The voltage varies sinusoidally between 0 and 100 volts.

   This file is derived from the simpler voltest.inp file,
   in which the voltage is held constant at 100 V.

   Diagnostics of the electron positions and energies on
   arrival at the far wall are kept and displayed.  In this
   case, the particles should arrive with a distribution of
   energies, clustered roughly about 50 eV.
}

Variables
{
   numCellsX = 20
   numCellsY = 20
   numCellsEmitter = 1

   xMaxMKS = 0.0005          // m
   yMaxMKS = 0.0003          // m
   x1_mid = xMaxMKS / 2.

   gasTempEV       = 0.1  // make gas cold (cannot set temperature to
zero)
   gasPressureTorr = 100.0

   omega = 1.0e+10        // radian/s
   pi    = 3.14159
   phi   = pi/4.            // radian

   //constantAmpV   = -2000.  // V
   sinusoidalAmpV =  2000.  // V

   timeStep = 7.0e-13    // s (make sure frequency*timeStep << 1)
}

Region
{
Grid
{
   // number of grids in x
   J = numCellsX
   x1s = 0.0
   x1f = xMaxMKS
   n1 = 1.0

   // number of grids in y
   K = numCellsY
   x2s = 0.0
   x2f = yMaxMKS
   n2 = 1.0

   Geometry = 1  // specify Cartesian geometry
}
Species
{
```

```
   name = electrons
   m = 9.11E-31
   q = -1.6e-19
  collisionModel=1
}
Species
{
        name = argon
        m = 6.67e-26
        q = 1.6E-19
//     subcycle = 100
       collisionModel=2
}
Control
{
   dt = timeStep
   ElectrostaticFlag = 1  // specify electrostatic field solve --
                          // assumes omega*yMaxMKS << c
}
MCC
{
      gas = Ar
//     pressure = 5.0
        temperature = 0.1
       analyticF = gasPressureTorr * 0.30e+23 * exp(-0.5 * ((x1-
x1_mid)*(x1-x1_mid)+(x2-yMaxMKS)*(x2-yMaxMKS)) /
((xMaxMKS/10.)*(xMaxMKS/10.)) )

        eSpecies = electrons
       iSpecies = argon
}

// Top boundary is a time-varying equipotential surface.
Equipotential
{
   j1 = 0
   j2 = numCellsX
   k1 = numCellsY
   k2 = numCellsY
   normal = -1

   C = constantAmpV        // constant potential in V
   A = sinusoidalAmpV      // amplitude of sinusoidal variation in V
   frequency = omega       // frequency of the oscillation
   phase = phi
}

// Embedded within the top boundary is a simple beam emitter that
//   emits a small, constant current of electrons
EmitPort
{
   j1 = (numCellsX-numCellsEmitter) / 2
   j2 = (numCellsX+numCellsEmitter) / 2
   k1 = numCellsY
   k2 = numCellsY
   normal = -1
```

```
   speciesName = electrons          // name corresponds to species block
above
   np2c = 4.0e+08                    // numerical weight of the macro-
particles
   I = 50.0                     // emitted current in A
   v2drift = 0.01                    // initial particle velocity in m/s
}

// Bottom boundary is a perfect conductor
// Also, particle diagnostics are being collected
Conductor
{
   name = collector
   j1 = 0
   j2 = numCellsX
   k1 = 0
   k2 = 0

   IdiagFlag = 1       // turn on the diagnostics
   nxbins = 40         // specify spatial resolution
   nenergybins = 105   // specify energy  resolution
   energy_min = 0
   energy_max = 1005
}

// Left boundary is a simple dielectric
Dielectric
{
   j1 = 0
   j2 = 0
   k1 = 0
   k2 = numCellsY
}

// Right boundary is a simple dielectric
Dielectric
{
   j1 = numCellsX
   j2 = numCellsX
   k1 = 0
   k2 = numCellsY
   normal = -1
}
}
```

RF vs. DC Explosion 500T- DC Results
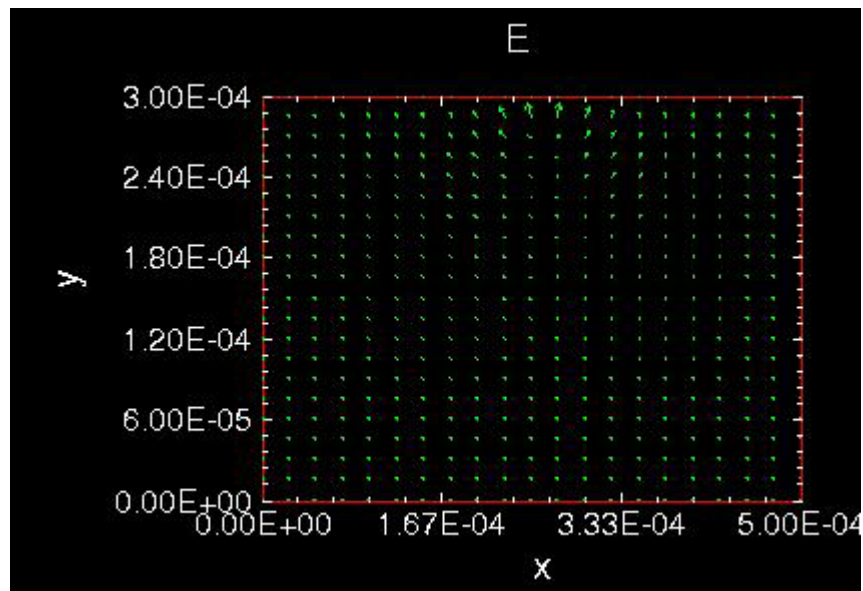
Figure 53 Electric Field
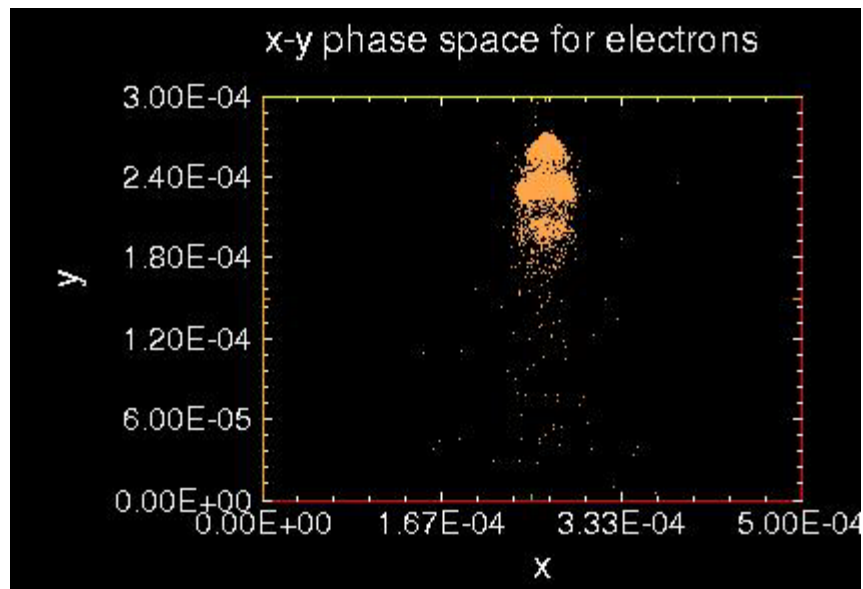
Figure 54
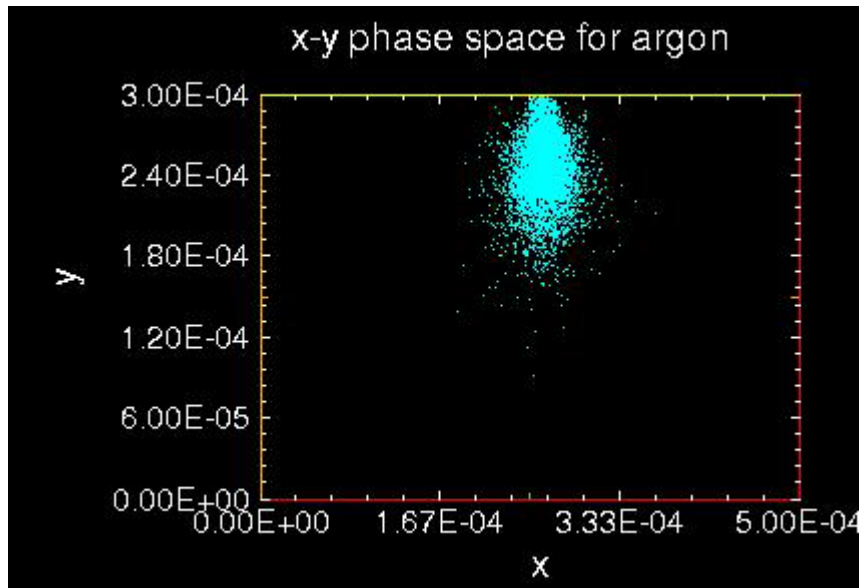
Figure 55
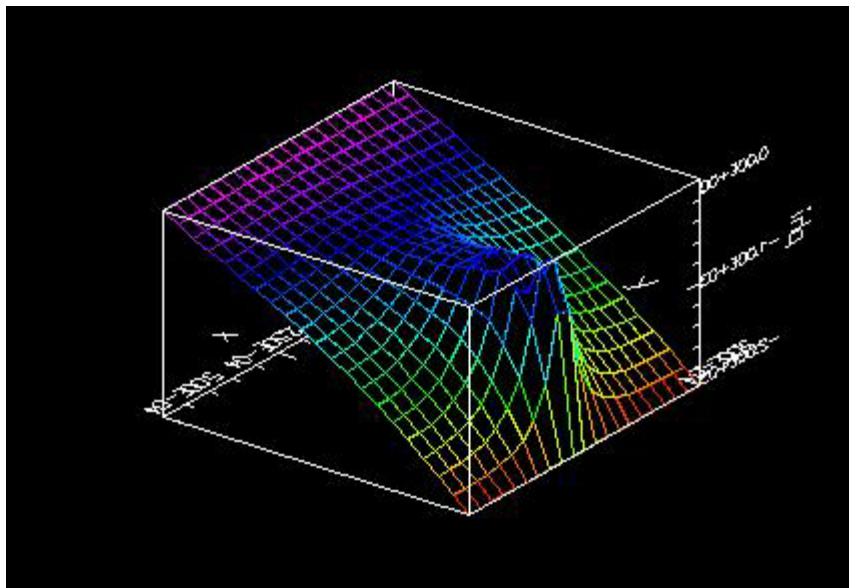
Figure 56 Potential

For the explosion studies we can compare the DC and RF cases for the 100T and 500 T cases. There are three discs of electrons forming in the electron cloud just like in the 100T case. The ions and field enhancement are also similar. The electron and ion clouds are denser because of the 500T pressure.
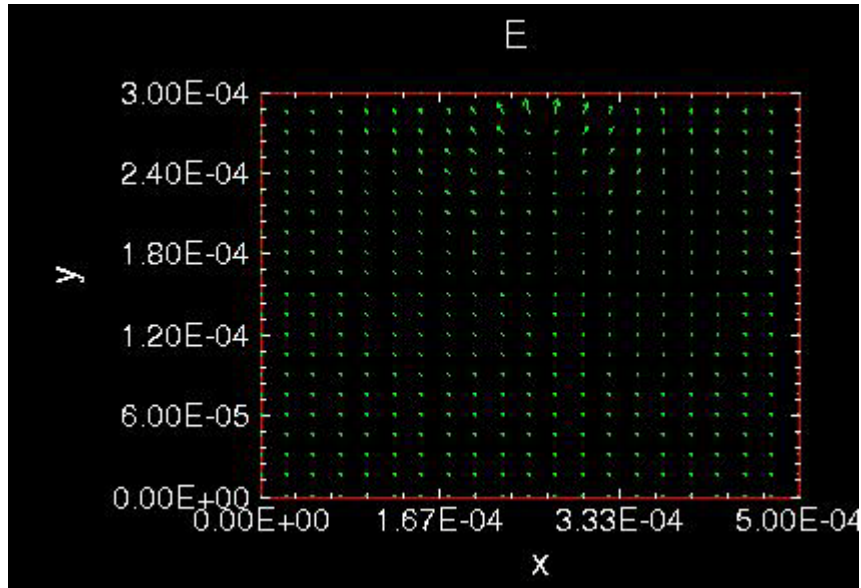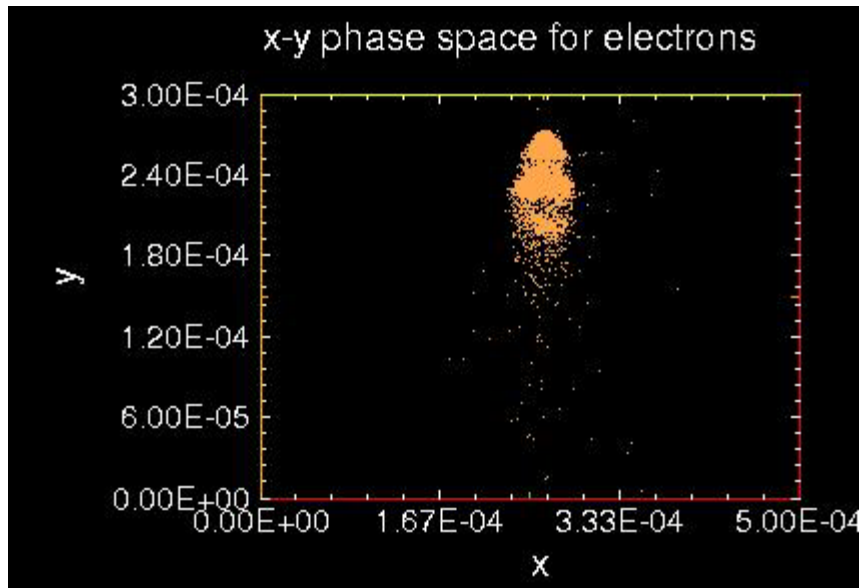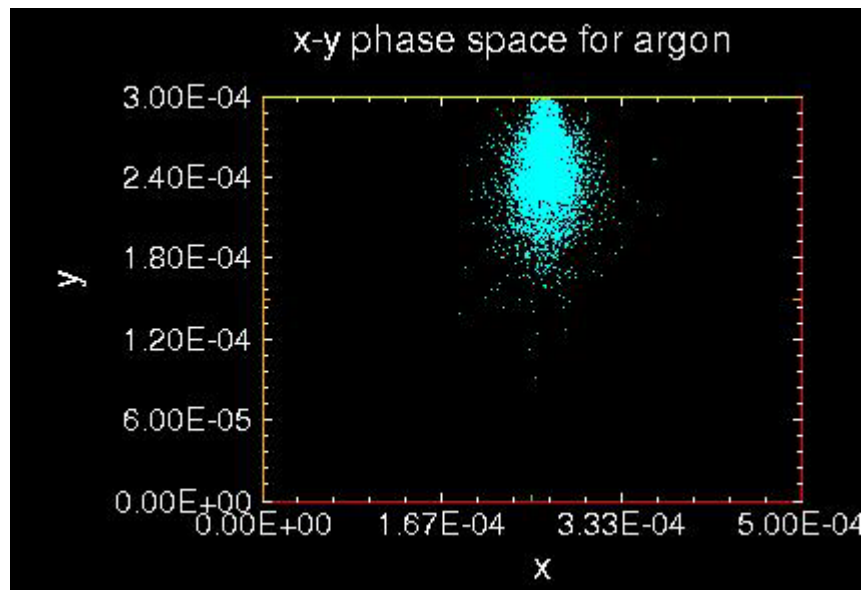
Figure 57 Electric Field

Figure 58 Electrons before explosion

Figure 59
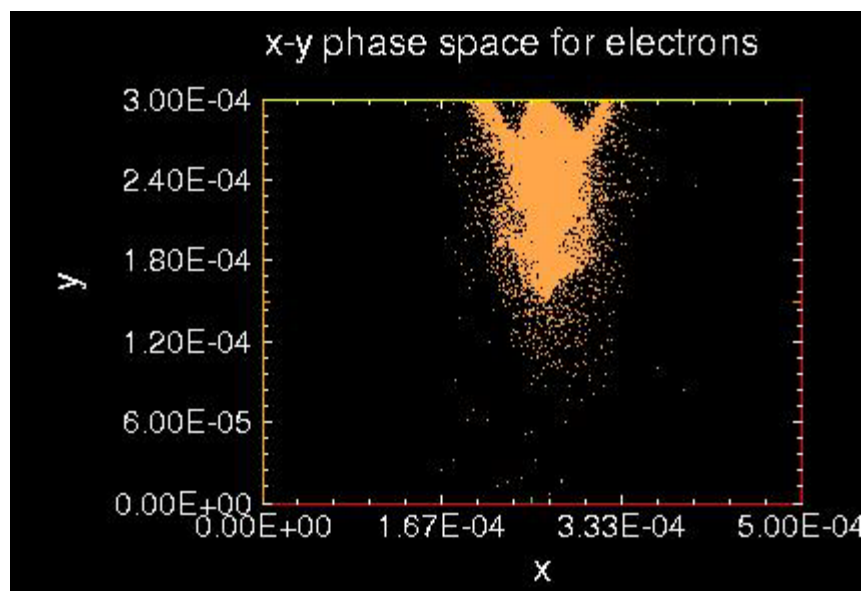
Figure 60 Explosion
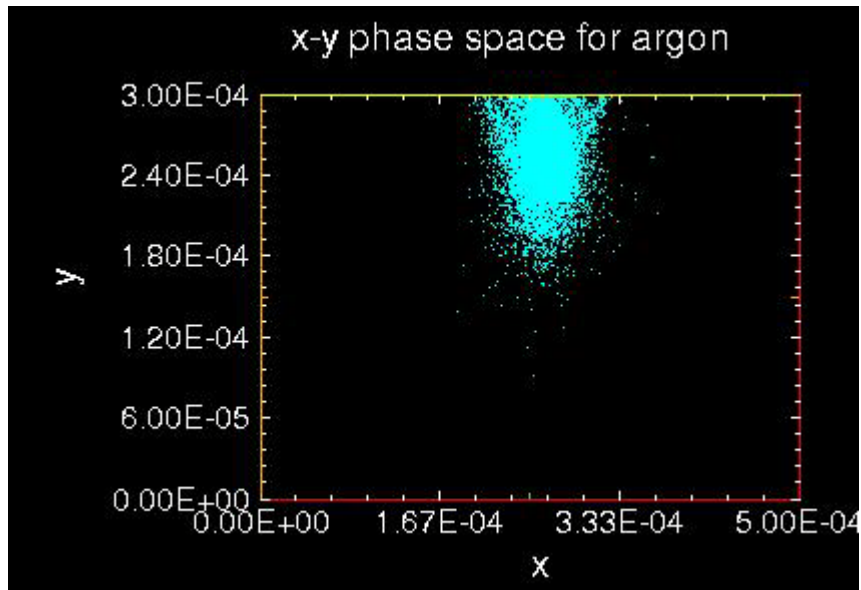
Figure 61
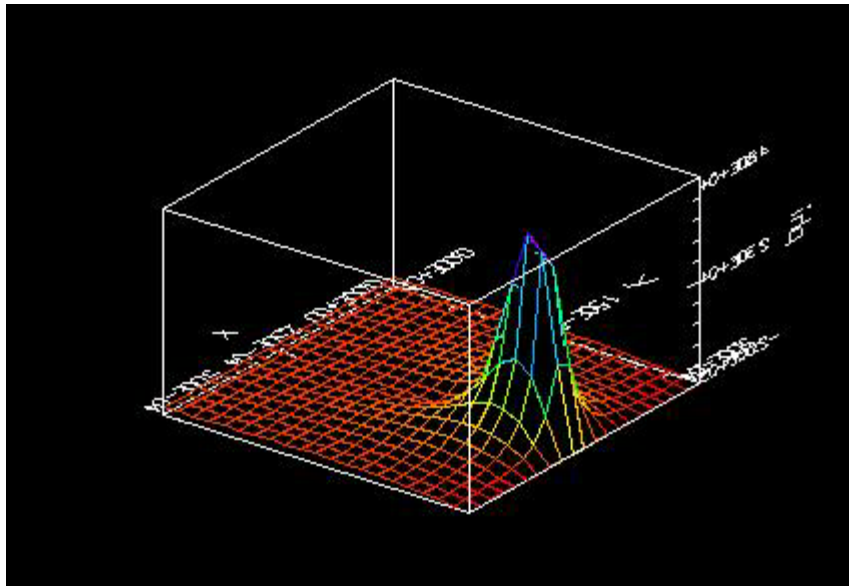
Figure 62 Potential

From the explosions the regions of possible steamers are visible.
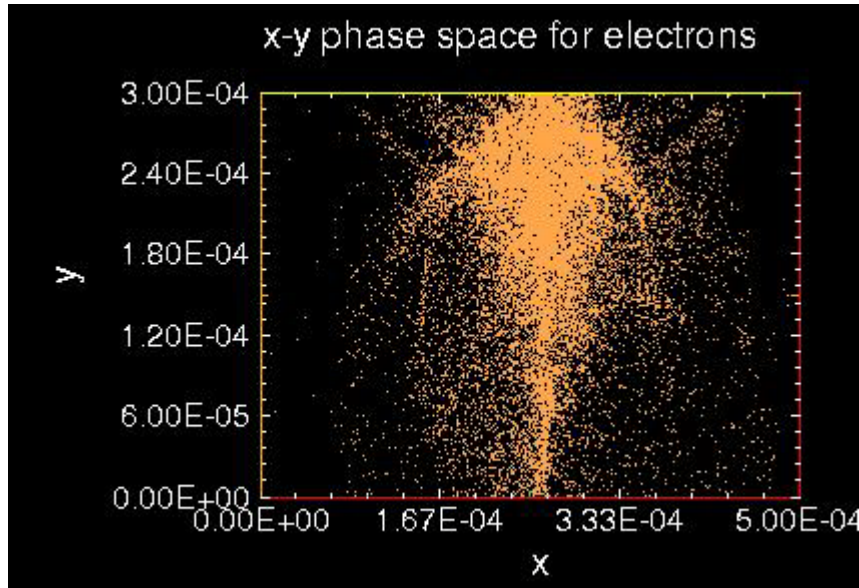
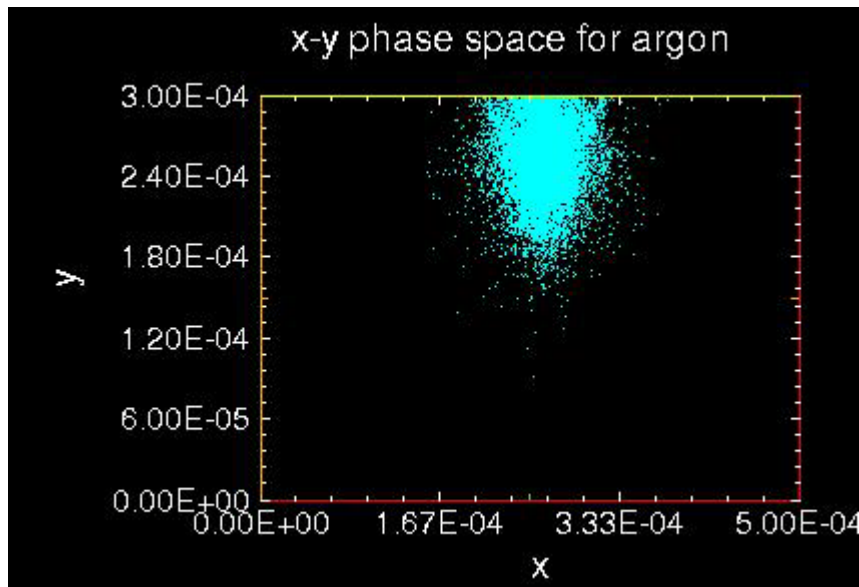**Figure 63** Further picture of explosion (same run)

Figure 64

Notice how the explosion spreads out away from the emitter site, this could be a possible starburst.

```
voltestRF
{  500TexplosionDCgaussian
   Particles at low current are dropped through a voltage.
   The voltage varies sinusoidally between 0 and 100 volts.

   This file is derived from the simpler voltest.inp file,
   in which the voltage is held constant at 100 V.

   Diagnostics of the electron positions and energies on
   arrival at the far wall are kept and displayed.  In this
   case, the particles should arrive with a distribution of
   energies, clustered roughly about 50 eV.
}

Variables
{
   numCellsX = 20
   numCellsY = 20
   numCellsEmitter = 1

   xMaxMKS = 0.0005          // m
   yMaxMKS = 0.0003          // m
   x1_mid = xMaxMKS / 2.

   gasTempEV       = 0.1  // make gas cold (cannot set temperature to
zero)
   gasPressureTorr = 500.0

   omega = 1.0e+10        // radian/s
   pi    = 3.14159
   phi   = pi/4.            // radian

   constantAmpV   = -2000.  // V
   //sinusoidalAmpV =  2000.  // V

   timeStep = 7.0e-13     // s (make sure frequency*timeStep << 1)
}

Region
{
Grid
{
   // number of grids in x
   J = numCellsX
   x1s = 0.0
   x1f = xMaxMKS
   n1 = 1.0

   // number of grids in y
   K = numCellsY
   x2s = 0.0
   x2f = yMaxMKS
   n2 = 1.0

   Geometry = 1  // specify Cartesian geometry
}
Species
{
```

```
   name = electrons
   m = 9.11E-31
   q = -1.6e-19
  collisionModel=1
}
Species
{
        name = argon
        m = 6.67e-26
        q = 1.6E-19
//    subcycle = 100
      collisionModel=2
}
Control
{
   dt = timeStep
   ElectrostaticFlag = 1  // specify electrostatic field solve --
                          // assumes omega*yMaxMKS << c
}
MCC
{
      gas = Ar
//    pressure = 5.0
        temperature = 0.1
      analyticF = gasPressureTorr * 0.30e+23 * exp(-0.5 * ((x1-
x1_mid)*(x1-x1_mid)+(x2-yMaxMKS)*(x2-yMaxMKS)) /
((xMaxMKS/10.)*(xMaxMKS/10.)) )

        eSpecies = electrons
      iSpecies = argon
}

// Top boundary is a time-varying equipotential surface.
Equipotential
{
   j1 = 0
   j2 = numCellsX
   k1 = numCellsY
   k2 = numCellsY
   normal = -1

   C = constantAmpV        // constant potential in V
   A = sinusoidalAmpV      // amplitude of sinusoidal variation in V
   frequency = omega       // frequency of the oscillation
   phase = phi
}

// Embedded within the top boundary is a simple beam emitter that
//   emits a small, constant current of electrons
EmitPort
{
   j1 = (numCellsX-numCellsEmitter) / 2
   j2 = (numCellsX+numCellsEmitter) / 2
   k1 = numCellsY
   k2 = numCellsY
   normal = -1
```

```
   speciesName = electrons           // name corresponds to species block
above
   np2c = 4.0e+08                    // numerical weight of the macro-
particles
   I = 50.0                     // emitted current in A
   v2drift = 0.01                   // initial particle velocity in m/s
}

// Bottom boundary is a perfect conductor
// Also, particle diagnostics are being collected
Conductor
{
   name = collector
   j1 = 0
   j2 = numCellsX
   k1 = 0
   k2 = 0

   IdiagFlag = 1      // turn on the diagnostics
   nxbins = 40        // specify spatial resolution
   nenergybins = 105  // specify energy  resolution
   energy_min = 0
   energy_max = 1005
}

// Left boundary is a simple dielectric
Dielectric
{
   j1 = 0
   j2 = 0
   k1 = 0
   k2 = numCellsY
}

// Right boundary is a simple dielectric
Dielectric
{
   j1 = numCellsX
   j2 = numCellsX
   k1 = 0
   k2 = numCellsY
   normal = -1
}
}
```
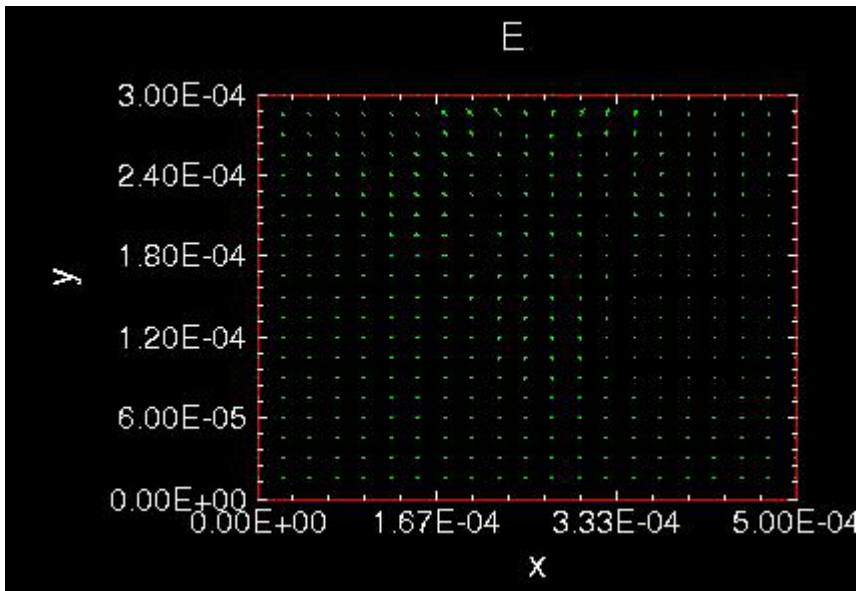
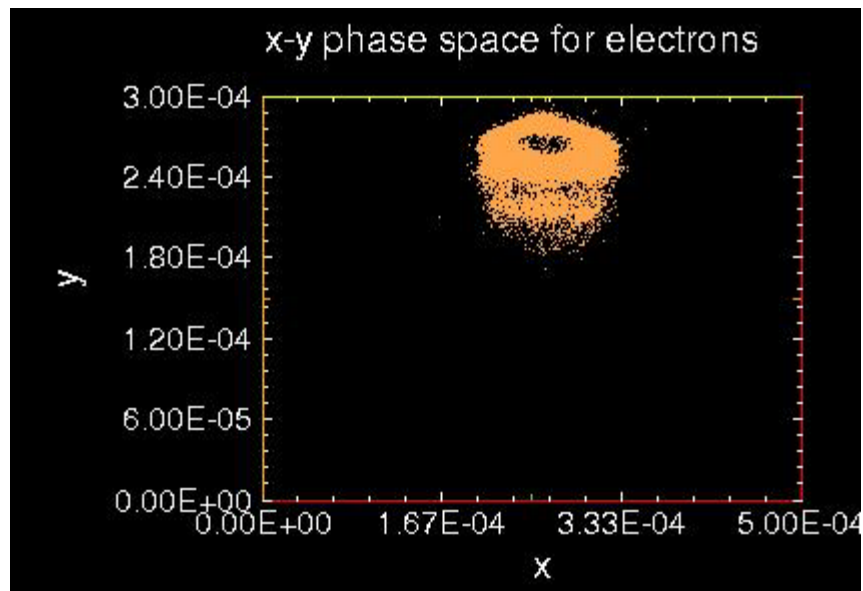**RF vs. DC Explosion 500T - RF Results**
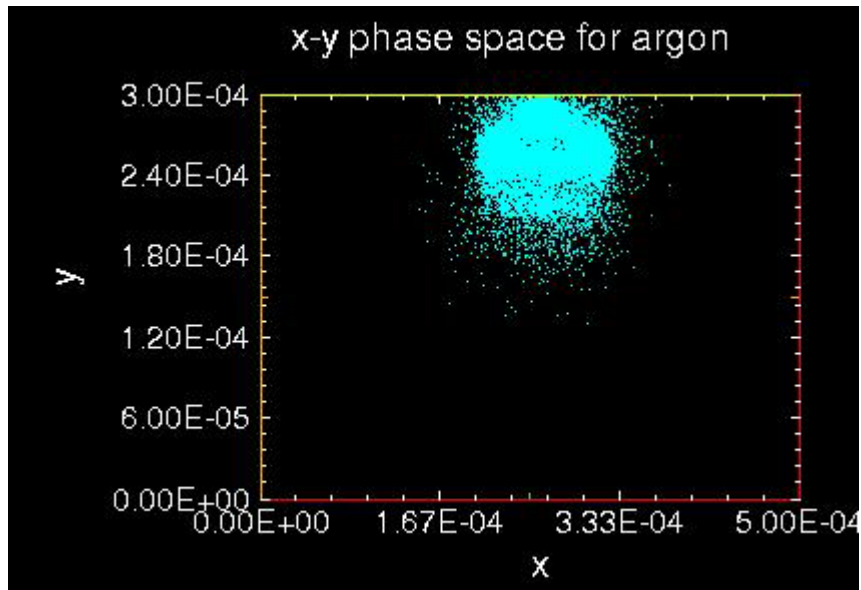

Figure 65 Electric Field
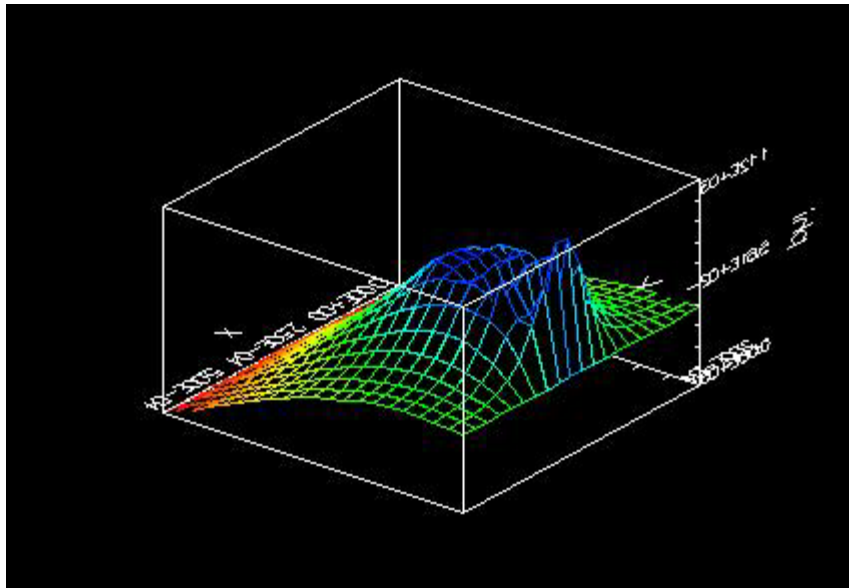

Figure 66

Figure 67

Figure 68

The electron cloud is forming two regions with a hole in the center of the top disc. The circular regions of both the ion and electron clouds are visible in the potential graph. The next figures take place right before the explosion.
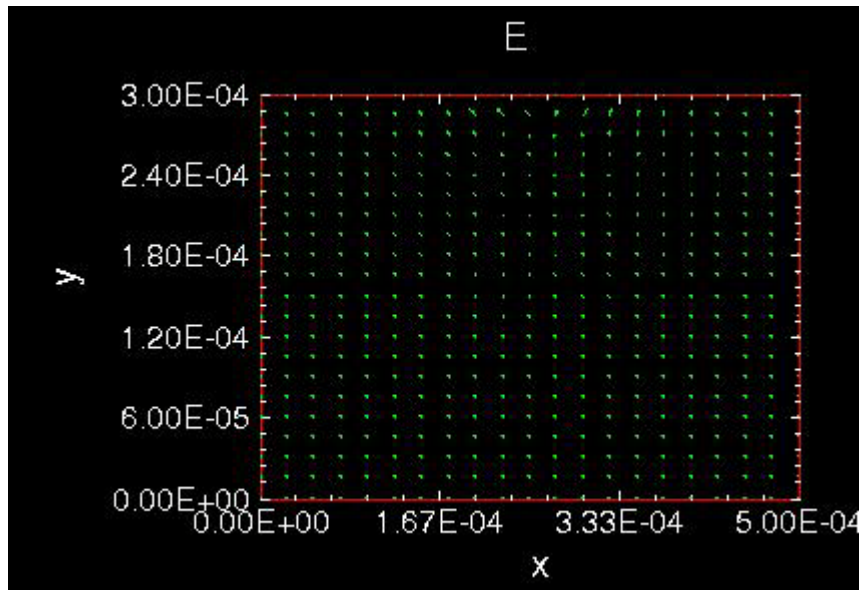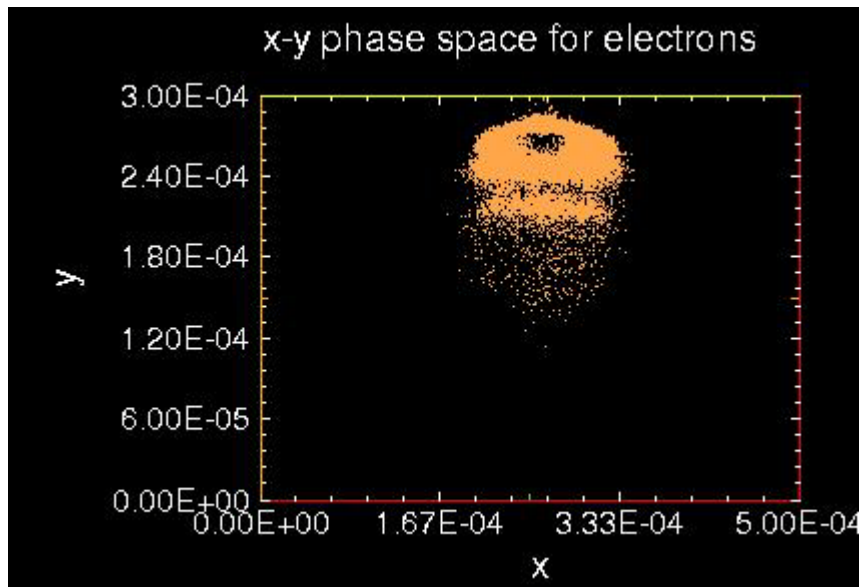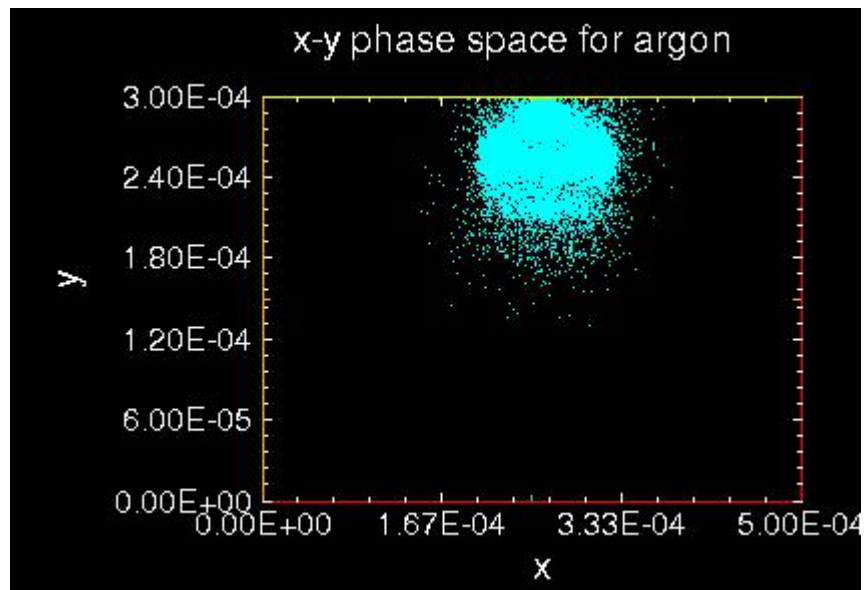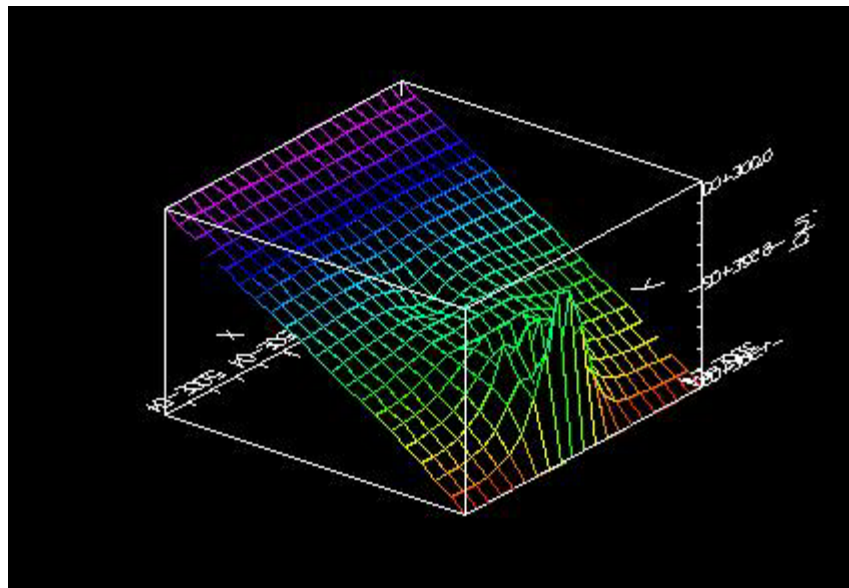
Figure 69 Electric Field

Figure 70

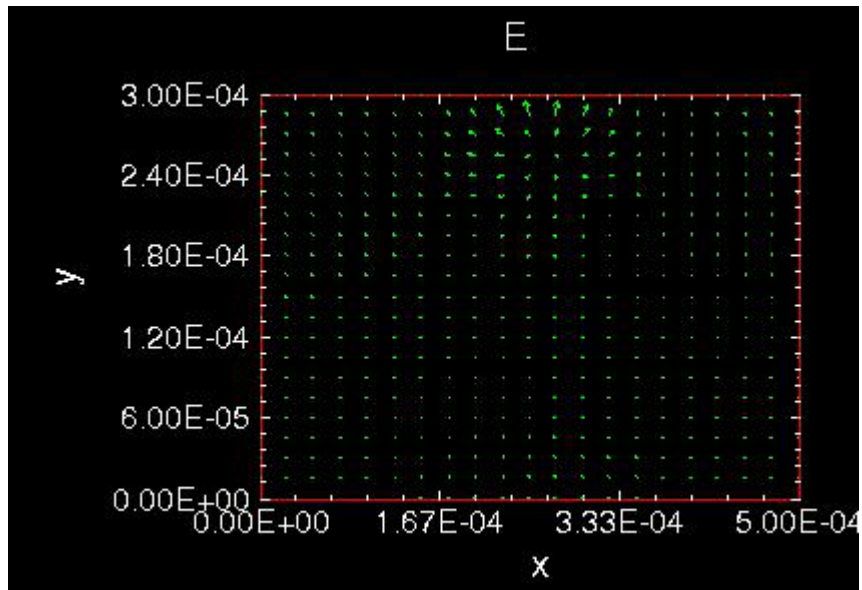**Figure 71**

Figure 72 Potential

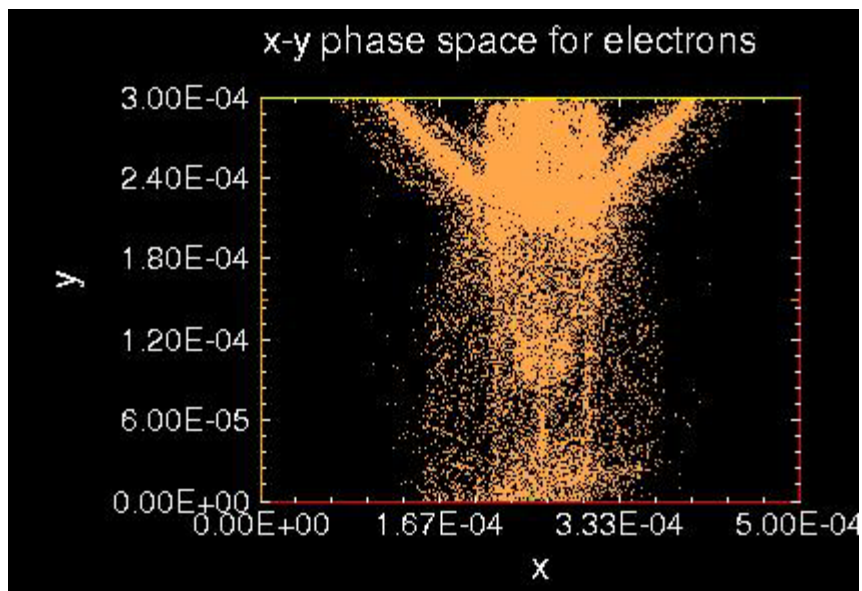**Figure 73** Electric Field

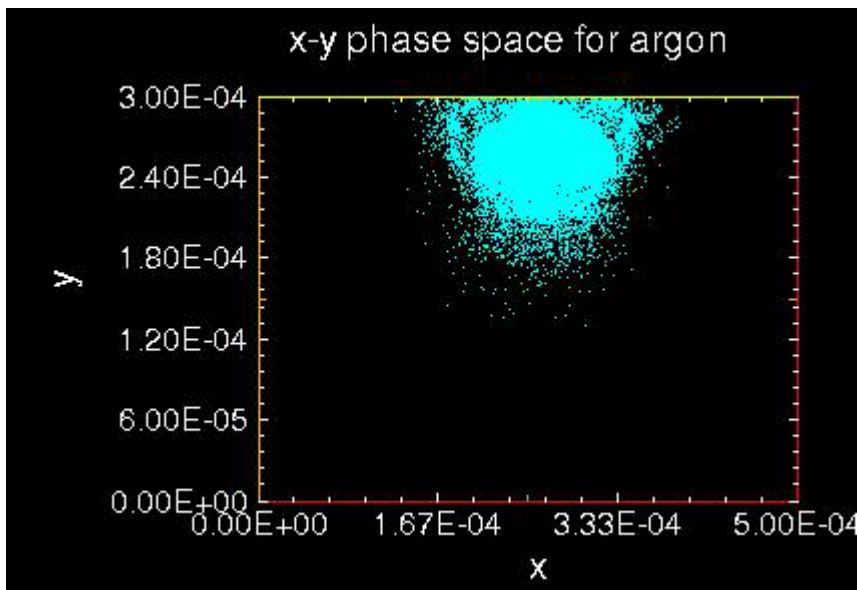**Figure 74** Explosion

Figure 75

```
voltestRF
{  500TexplosionRFw10^10gaussian
   Particles at low current are dropped through a voltage.
   The voltage varies sinusoidally between 0 and 100 volts.

   This file is derived from the simpler voltest.inp file,
   in which the voltage is held constant at 100 V.

   Diagnostics of the electron positions and energies on
   arrival at the far wall are kept and displayed.  In this
   case, the particles should arrive with a distribution of
   energies, clustered roughly about 50 eV.
}

Variables
{
   numCellsX = 20
   numCellsY = 20
   numCellsEmitter = 1

   xMaxMKS = 0.0005          // m
   yMaxMKS = 0.0003          // m
   x1_mid = xMaxMKS / 2.

   gasTempEV       = 0.1  // make gas cold (cannot set temperature to
zero)
   gasPressureTorr = 500.0

   omega = 1.0e+10        // radian/s
   pi    = 3.14159
   phi   = pi/4.             // radian

   //constantAmpV   = -2000.  // V
   sinusoidalAmpV =  2000.  // V

   timeStep = 7.0e-13    // s (make sure frequency*timeStep << 1)
}

Region
{
Grid
{
   // number of grids in x
   J = numCellsX
   x1s = 0.0
   x1f = xMaxMKS
   n1 = 1.0

   // number of grids in y
   K = numCellsY
   x2s = 0.0
   x2f = yMaxMKS
   n2 = 1.0

   Geometry = 1  // specify Cartesian geometry
}
Species
{
```

```
   name = electrons
   m = 9.11E-31
   q = -1.6e-19
  collisionModel=1
}
Species
{
        name = argon
        m = 6.67e-26
        q = 1.6E-19
//      subcycle = 100
        collisionModel=2
}
Control
{
   dt = timeStep
   ElectrostaticFlag = 1  // specify electrostatic field solve --
                          // assumes omega*yMaxMKS << c
}
MCC
{
      gas = Ar
//    pressure = 5.0
        temperature = 0.1
      analyticF = gasPressureTorr * 0.30e+23 * exp(-0.5 * ((x1-
x1_mid)*(x1-x1_mid)+(x2-yMaxMKS)*(x2-yMaxMKS)) /
((xMaxMKS/10.)*(xMaxMKS/10.)) )

        eSpecies = electrons
      iSpecies = argon
}

// Top boundary is a time-varying equipotential surface.
Equipotential
{
   j1 = 0
   j2 = numCellsX
   k1 = numCellsY
   k2 = numCellsY
   normal = -1

   C = constantAmpV       // constant potential in V
   A = sinusoidalAmpV     // amplitude of sinusoidal variation in V
   frequency = omega      // frequency of the oscillation
   phase = phi
}

// Embedded within the top boundary is a simple beam emitter that
//   emits a small, constant current of electrons
EmitPort
{
   j1 = (numCellsX-numCellsEmitter) / 2
   j2 = (numCellsX+numCellsEmitter) / 2
   k1 = numCellsY
   k2 = numCellsY
   normal = -1
```

```
      speciesName = electrons         // name corresponds to species block
above
      np2c = 4.0e+08                   // numerical weight of the macro-
particles
      I = 50.0                     // emitted current in A
      v2drift = 0.01                   // initial particle velocity in m/s
}

// Bottom boundary is a perfect conductor
// Also, particle diagnostics are being collected
Conductor
{
      name = collector
      j1 = 0
      j2 = numCellsX
      k1 = 0
      k2 = 0

      IdiagFlag = 1      // turn on the diagnostics
      nxbins = 40         // specify spatial resolution
      nenergybins = 105  // specify energy  resolution
      energy_min = 0
      energy_max = 1005
}

// Left boundary is a simple dielectric
Dielectric
{
      j1 = 0
      j2 = 0
      k1 = 0
      k2 = numCellsY
}

// Right boundary is a simple dielectric
Dielectric
{
      j1 = numCellsX
      j2 = numCellsX
      k1 = 0
      k2 = numCellsY
      normal = -1
}
}
```

V Conclusions

Although we are still in the beginning stages of using the simulation, we can still form several conclusions.   The first few studies showed that we could successfully ionize a gas. There was no field enhancement when the current was less than 10 amps and the gas pressure was under 1 torr. As the pressure, current, and DC voltage were varied, we could simulate effects such as a glow discharge and the mean-free path of the electron. As we began to increase the gas pressure we saw columns of ions and spreads of ions, which were the first signs of possible craters and starbursts. As the gas pressure was increased even more we began to lose the columns and watch the formation of ion clouds near the emitter that eventually trapped the electrons and neutralized the plasma. We also saw branches of ions and electrons breaking away form the "parent" cloud and forming possible streamers.   Up to this point we saw no change in the electric field. When we drastically increased the current we finally started to see the beginnings of field enhancement. As we reached values greater than 5 amps and a gas pressure of at least 50 torr we began to see field enhancement values of 10 or one mesh element. We were also able to simulate the gap effect and show that the field enhancement was dependent on the gap size. The larger the gap was, the higher the field enhancement. Finally, as we experimented with gas pressures over 50 torr we were able to simulate an explosion of the electron cloud. We were also able to compare DC and RF results with a gaussian distribution that occur under circumstances similar to those inside the cavity. The use of Oopic has allowed us to successfully simulate field enhancement due to plasma and voltage breakdown under both DC and AC conditions.

Acknowledgements

References

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