I. What is plasma?

Plasma is a quasineutral gas of charged and neutral particles, which exhibits collective behavior.

Demos	Questions	Hints
Charged and Neutral particles	**How can the presence of charged and neutral particles be demonstrated?** **Background:** **No electromagnetic force on a neutral atom or molecule**	**Plasma is produced by applying electric fields** **Plasma is affected by magnetic field** **Charged particle motion in Electric / Magnetic Field**
Quasineutral	**What does this mean?**	**Approximately equal numbers of electrons and ions**
Collective behavior **Plasma**	**Suggest examples of collective behavior** **What is the necessary condition for a collective behavior?** **Background:** **In a neutral gas molecules (atoms) interact by collisions only.** **Is what you see in this demonstration, Plasma?**	**A group of friends deciding to attend a concert.** **A "wave" acted out by spectators at a ball game.** **Members of the group must be informed of other's action and/or intentions – physically this means they must interact.** **Long-range Coulomb interaction between charged particles – here depends on there.**
Plasma temperature	**Are plasmas hot?** **Is the chamber hot to touch?** **Where does the plasma energy go?** **Do the ions and electrons have equal temperatures?** **Background:** **Temperature = kinetic energy**	

Plasma Science and Technology

Various types of plasma:

Plasma	Electron temperature, K	Electron density, $(cm)^{-3}$
Sun: center surface corona	$2x10^7$ $5x10^3$ 10^6	10^{26} 10^6 10^5
Fusion experiments (tokamak)	$1x10^8$	10^{14}
Solar wind	$1x10^5$	5
Lightning bolt	$3x10^4$	10^{18}
Glow discharge	$2x10^4$	10^9
Ionosphere	$\sim 2x10^3$	10^5
Ordinary flame	$2x10^4$	10^3

II. How do we make plasma?

Plasma is usually produced by applying electromagnetic field to a gas at moderately low pressure.

Demos	Questions	Hints
The chamber is being pumped down	Why do we bring the pressure down?	Hold on to this question! Keep asking this one!
The voltage is being slowly increased Here dc voltage is used	What is the purpose of applying voltage? Why is the voltage increased slowly? What are we waiting for? Why do we need to increase the energy of the electrons? Why don't all of the electrons just rush to the anode and plasma get extinguished?	To ionize the gas, energetic particles are needed. But if there are no ions or free electrons in the first place, then you can't make more! Luckily there are some electrons in ordinary gas. They accelerate, collide and produce more electrons. There must be enough created continuously so that the operating voltage can sustain the plasma current.
Breakdown voltage is reached and plasma is lit	How do we know that there is plasma? Is watching for plasma the best way of determining the breakdown voltage? Suggest other ways. (How do the resistances of plasma and gas compare?) Now that the plasma is lit can we turn off the voltage?	We see the glow. You can check by measuring the plasma current and then comparing the values for breakdown voltage when observing visually. Plasma is a conductor, so measuring current is a good way.
Glow discharge has structure (diagram) ionization vs. excitation	What can possibly be the difference between the glowing and the dark parts? Or a kinder question: What makes some regions emit light? What is too much and what is not enough? Are all dark spots created equal?	Electrons are accelerated away from the cathode. The fastest will just reach the anode. Other ones collide with the neutral atoms and depending on their energies, either ionize or excite the neutrals. Electrons loose their energy through collisions, and soon are

Magnetic field is applied to plasma	What do you observe? (try later with the fluorescent light) Suggest explanations.	not fast enough for either. They feel the potential of the anode and slowly accelerate. Once they have enough energy, excitation and ionization continue.
Changing gas pressure Start again, or How is the breakdown voltage affected by the change in pressure?	Which area(s) are unaffected? Why? Predict the effect and suggest an explanation.	Increase in the gas pressure increases collision rate. Decreasing pressure decreases the collision rate and plasma becomes unsustainable. Increasing pressure decreases collision rate and the electrons don't gain enough energy between collisions.
Changing the distance between the electrodes. How is the breakdown voltage affected?	Why should the distance matter at all? Predict the effect and discuss the actual result. What is going to happen if the pressure is changed now at the new distance value? Is the higher the vacuum the better?	Decreasing the distance between the electrodes decreases the electric field strength, so longer distances between collisions are needed. Remember the question of why do we pump down in the first place.

III. Plasma Diagnostics

Plasma is on – now what?	**What do we want to know?** **Why?** **What do we want to know?**	**Depends on the application** **To use plasma for coating, etching, cleaning, fusion…** **Composition, temperature, confinement, density,…**
Still on…	**Suggest diagnostic techniques**	**Non-invasive:** **Spectroscopy at different wavelengths, pick-up coils, neutrons, etc.** **Invasive:** **Interferometry, scattering, injecting, probes, etc.**
	Classify diagnostic techniques as perturbing ("invasive") and non-perturbing ("noninvasive")	

IV. Some general remarks

The following is a short list of general teaching ideas that can be implemented using plasma related experiments:

Interactive demonstrations using plasma
Teaching scale dependence of science models
Experimental long term projects

A good source on plasma and gas discharge is a book Industrial Plasma Engineering, Volume 1: Principles by J Reece Roth, Institute of Physics Publishing, 1995.

Applications of plasma:
<u>Center for Plasma-Aided Manufacturing University of Wisconsin 1999</u>

<u>Plasma/Fusion Glossary</u>

Definition of Plasma:

A plasma is a quasineutral gas of charged and neutral particles which exhibits collective behavior.

F. F. Chen, Introduction to Plasma Physics and Controlled Fusion, Second Edition, Volume 1, Plenum Press, 1984

Neutral gas – dominated by collisions

Plasma – electromagnetic interactions - long range - collective behavior

EXAMPLES:

Plasma	Electron temperature, K	Electron density, m^{-3}
Sun: center Surface Corona	$2x10^7$ $5x10^3$ 10^6	10^{32} 10^{12} 10^{11}
Fusion experiments	10^9	10^{20}
Lightning bolt	$3x10^4$	10^{18}
Glow discharge	$2x10^4$	10^{15}
Ionosphere	$2x10^3$	10^{11}
Ordinary Flame	$2x10^4$	10^9
Interplanetary space	10^2	10^6
Solar wind	10^5	5

Applications:

Gas Discharges

Lasers
Spark gaps
Welding arcs
Lightning
Fluorescent lights
Flat-screen displays
Etching
Film deposition and cleaning

Controlled Thermonuclear Fusion

Space and Astrophysics

Solid State Plasmas

If you are not using this off a disk here are some of the URL's from above:

http://www.plasmas.org/technology.htm

http://ippex.pppl.gov/ippex/

http://www.plasmas.org/photo.htm
http://www.engr.wisc.edu/centers/ercpam/

<u>Characteristics of Plasma</u>

Bulk Properties

Electrical Resistivity and Conductivity

Conductivity $\sigma = \frac{1}{\rho} = \frac{L}{RA}$

Current density J = env , (A/m^2),
where n - # electrons (ions) per m^3, v – drift velocity, and e- electron charge

$J = \sigma E$

Electron accelerating between collisions: a = eE/m,
where m is the mass of an electron.
Then v = eEt/m , where t – time between collisions, then conductivity

$$\sigma = \frac{e^2 nt}{m}$$

General current density in the presence of magnetic field:

$\mathbf{J} = \sigma[\mathbf{E} + (\mathbf{v} \times \mathbf{B})]$

Bulk Force on Plasma:

$F = J \times B$

$F = \sigma(\mathbf{E} \times \mathbf{B}) - \sigma B^2 \mathbf{v} + \sigma(Bv)\mathbf{B}$

Ohmic Heating of Plasmas

The electrons acquire energy from the electric field and dissipate it in elastic and inelastic collisions.

Power density: $p = \rho J^2 = \sigma E^2$

Plasma Shields Out External Potentials

Characteristic length, Debye length

$$\lambda_d = \left(\frac{kT\varepsilon}{ne^2}\right)^{\frac{1}{2}} \text{ (m)}$$

Plasma Frequency

Using Gauss's Law, the electric field at a distance x from a flat electrode in a plasma

E = enx/ε (V/m)

The equation of motion for an electron in this field is

ma = -eE

$$a = -\left(\frac{ne^2}{m\varepsilon}\right)x$$ which is an equation for simple harmonic motion a = -kx

Plasma frequency $\varpi = \left(\frac{ne^2}{m\varepsilon}\right)^{1/2}$ (rad/s)

$$\nu = 8.980n^{1/2} \text{ (Hz)}$$

Cyclotron Frequency

$$\varpi_c = \frac{eB}{m}$$

Plasma must satisfy the following conditions:

$\lambda_d << L$

$\omega t > 1$