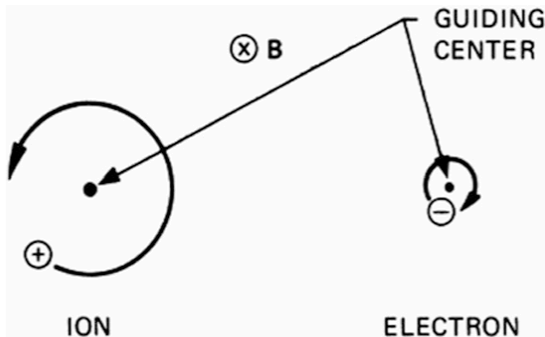


The density and the average energy of the fast alpha particles in the D-He3 reaction are found as  
 Variables:  $n_f = C D C H e_3 n_2$  i  $v D H e_3 f$

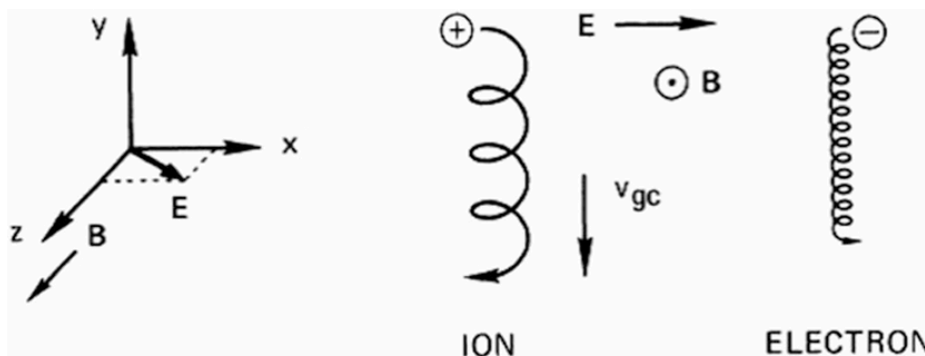


In this case, a charged particle has a simple cyclotron gyration. The equation of motion is  $m \frac{dv}{dt} = q \mathbf{v} \times \mathbf{B}$  and the direction of plasma structures-particles  $\mathbf{B}$  ( $\mathbf{B} \parallel \mathbf{B} \wedge \mathbf{z}$ )

The chemical variable-structures are for example;

$\mathbf{E}$  to lie in the  $x$ - $z$  plane so that  $E_y = 0$ . As before, the  $z$  component of velocity is unrelated to the transverse components and can be treated separately. The equation of motion is now  $m \frac{d\mathbf{v}}{dt} = q \mathbf{E} + \mathbf{v} \times \mathbf{B}$  whose  $z$  component is or  $q \frac{dv_z}{dt} = m E_z$ .

General formula:  $\mathbf{E} \perp \mathbf{v} \times \mathbf{B}$



$$\mathbf{E} \times \mathbf{B} \parallel \mathbf{v} \times \mathbf{B} \Rightarrow \mathbf{v} \perp \mathbf{B} \Rightarrow \mathbf{v} \perp \mathbf{B} \Rightarrow \mathbf{v} \perp \mathbf{B} \Rightarrow \mathbf{v} \perp \mathbf{B}$$

The transverse components of this equation are

$$\mathbf{v} \perp \mathbf{gc} \Rightarrow \mathbf{E} \times \mathbf{B} = B^2 \mathbf{v} \Rightarrow \mathbf{v} \perp \mathbf{B} \Rightarrow \mathbf{v} \perp \mathbf{B} \Rightarrow \mathbf{v} \perp \mathbf{B}$$

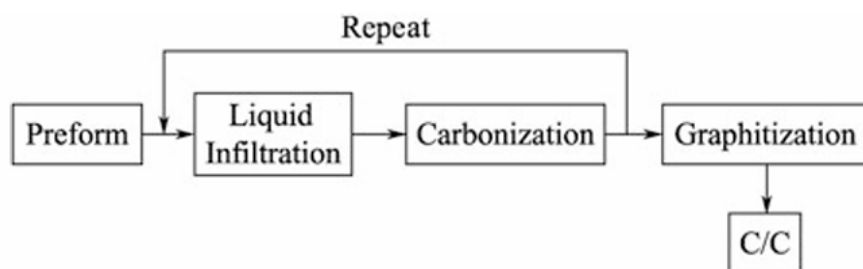
We can define this to be  $\mathbf{v}_E$ , the electric field drift of the guiding center. In magnitude, this drift is  $E/V = m \mathbf{v}_E \times \mathbf{B}$  tesla m sec. A negative electron gyrates in the opposite direction but also gains energy in the opposite direction; it ends up drifting in the same direction as an ion. For particles of the same velocity but different mass, the lighter one will have smaller  $r_L$  and hence drift less per cycle. However, its

gyration frequency is also larger, and the two effects cancel. Two particles of the same mass but different energy would have the same  $\omega c$ . The slower one will have smaller  $r_L$  and hence gain less energy from  $E$  in a half cycle. In the gravitational Field The foregoing result can be applied to other forces by replacing  $qE$  in the equation of motion by a general force  $F$ .

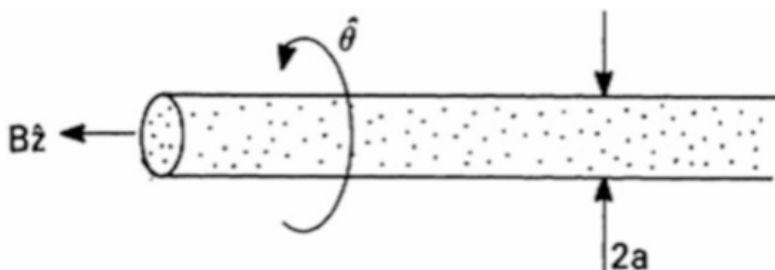
The guiding center drift caused by  $F$  is then  $v_f = \frac{1}{4} \frac{q F B}{B^2}$  In particular, if  $F$  is the force of gravity  $mg$ , there is a drift  $v_g = \frac{1}{4} \frac{m g B}{B^2}$

This is similar to the drift  $v_E$  in that it is perpendicular to both the force and  $B$ , but it differs in one important respect.

Materials: Liquid Infiltration Carbonization Liquid infiltration carbonization is the traditional method used to prepare graphite materials and has become an important technique to prepare C/C composites. A flowchart of this process is shown in Fig. 5.1. Through repeated infiltration:



Unneutralized electron beam has density  $n_e = 10^{14} \text{ m}^{-3}$  and radius  $a = 1 \text{ cm}$  and flows along a 2-T magnetic field. If  $B$  is in the  $+z$  direction and  $E$  is the electrostatic field due to the beam's charge, calculate the magnitude and direction of the  $E \times B$  drift at  $r = a$  :



Structural plasma: The gradient in  $jB_j$  causes the Larmor radius to be larger at the bottom of the orbit than at the top, and this should lead to a drift, in opposite directions for ions and electrons, perpendicular to both  $B$  and  $\nabla B$ . The drift velocity should obviously be proportional to  $r_L/L$  and to  $v_{\perp}$ . Consider the Lorentz force  $F = qv \times B$ , averaged over a gyration. Clearly,  $F_x = 0$ ; since the particle spends as much time moving up as down. We wish to calculate  $F_y$ ; in an approximate fashion, by using the undisturbed orbit of the particle to find the average.

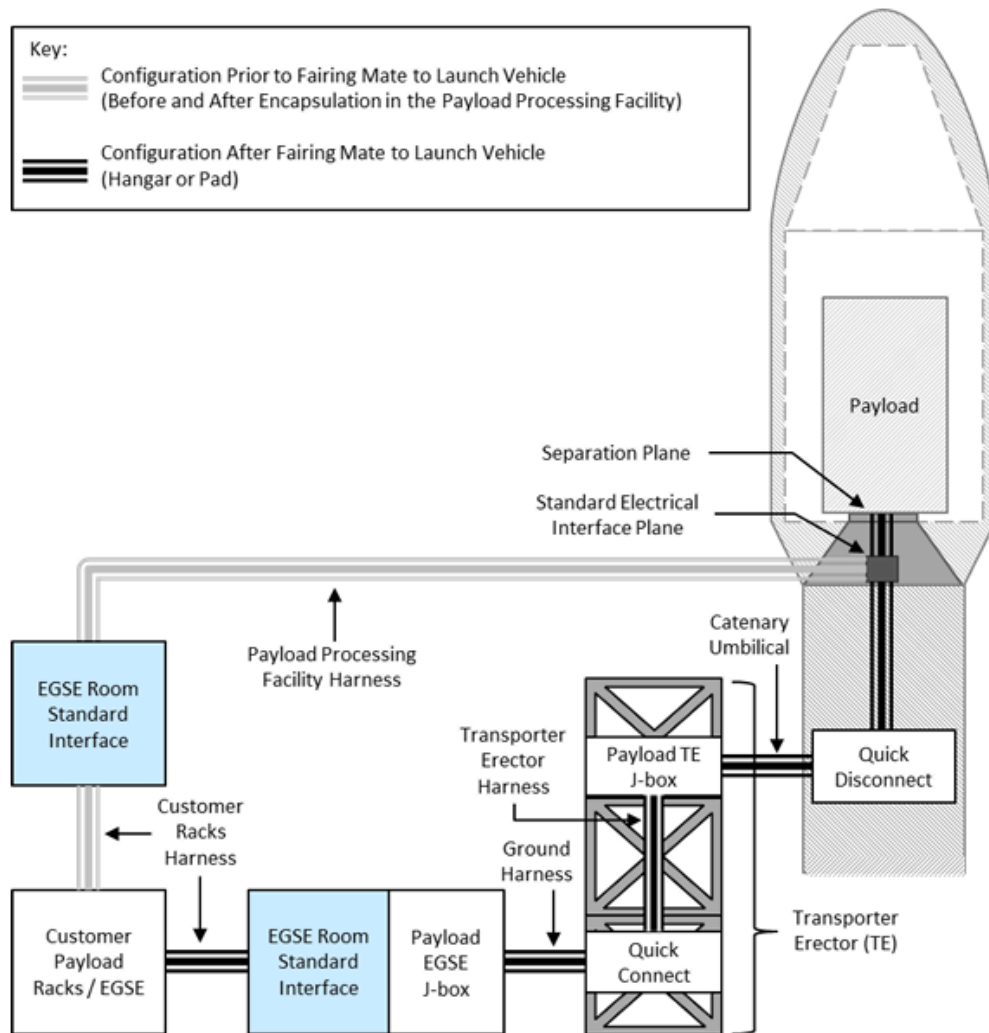


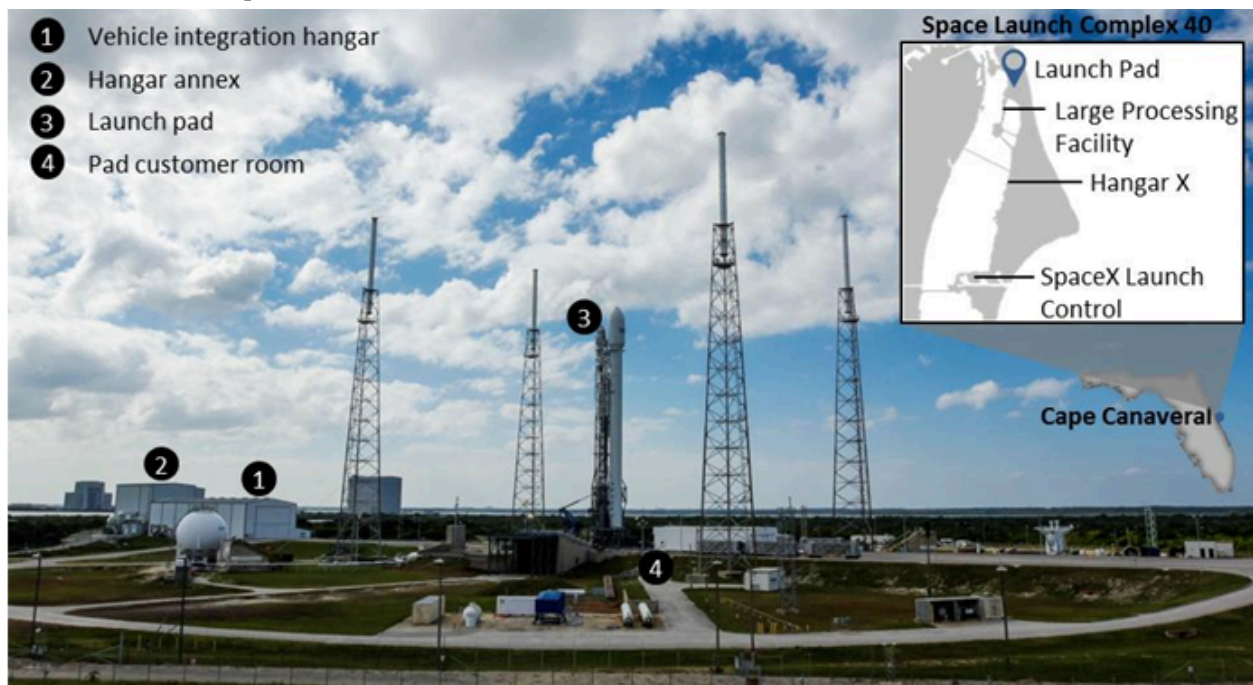
Figure 5-1: On-pad electrical interfaces

Mechanical interface & cooling structural particles in plasma fusion variables:  $B \approx B_0 \left( 1 - \frac{r}{L} \right)$   $\nabla \cdot \mathbf{B} = 0$   $B_z \approx B_0 \left( 1 - \frac{r}{L} \right)$   $\frac{\partial B_z}{\partial y} = \frac{\partial}{\partial y} \left( B_0 \left( 1 - \frac{r}{L} \right) \right)$  This expansion of course requires  $r/L \ll 1$ , where  $L$  is the scale length of  $\frac{\partial B_z}{\partial y}$ .

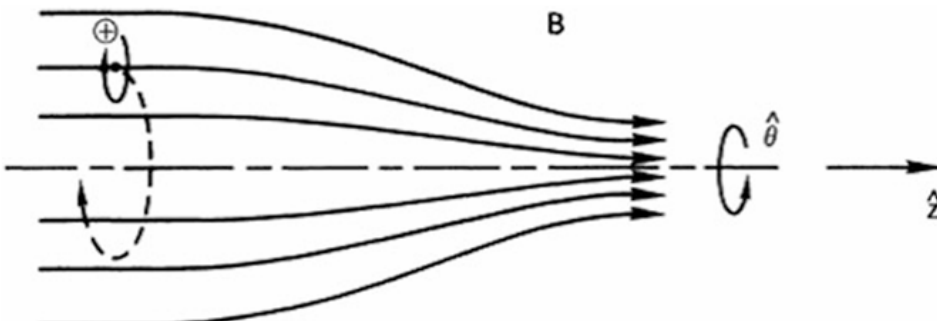
Variables-equation is in this case the center drift velocity is then  $v_{gc} \approx \frac{1}{4} \frac{q}{L} \frac{F}{B} \frac{B^2}{4} \frac{q}{F_y} \frac{B}{j} \hat{x} \approx \frac{1}{4} v \perp \frac{r}{L} \frac{1}{2} \frac{\partial B}{\partial y} \hat{x}$ .

the lines of force to be curved with a constant radius of curvature  $R_c$ , and we take  $jB_j$  to be constant. Such a field does not obey Maxwell's equations in a vacuum, so in practice the grad-B drift will always be added to the effect derived here. A guiding center drift arises from the centrifugal force felt by the particles as they move along the field lines in their thermal motion.

If  $\langle v_{\parallel}^2 \rangle$  denotes the average square of the component of random velocity along  $B$ , the average centrifugal force is  $F_{cf} = \frac{1}{4} m v_{\perp}^2 / R = \frac{1}{4} m v_{\perp}^2 / R$ . According to Eq. (2.17), this gives rise to a drift  $v_R = \frac{1}{4} \frac{q F_{cf} B}{B^2} = \frac{1}{4} \frac{c R}{2} \frac{m v_{\perp}^2}{q B^2 R} = \frac{1}{4} \frac{c}{2} \frac{m v_{\perp}^2}{q B^2 R}$ .



$\nabla B \cdot \mathbf{j}$ : Magnetic Mirrors are a magnetic field which is pointed primarily in the  $z$  direction and whose magnitude varies in the  $z$  direction. Let the field be axisymmetric, with  $B_{\theta} \neq 0$  and  $\partial/\partial\theta = 0$ . Since the lines of force converge and diverge, there is necessarily a component  $B_r$ . A magnetic field trapping particles structural variables or parameters can be in a technical draw:

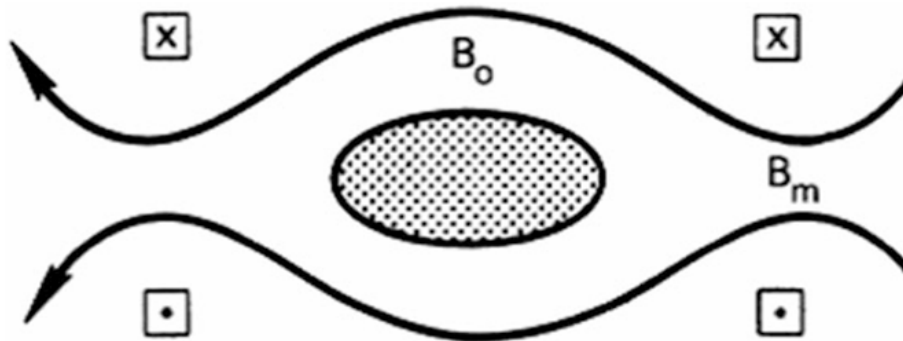


The invariance of  $\mu$  is the basis for one of the primary schemes for plasma confinement: the magnetic mirror. As a particle moves from a weak-field region to a strong-field region in the course of its thermal motion, it sees an increasing  $B$ , and therefore its  $v_{\perp}$  must increase in order to keep  $\mu$  constant. Since its total energy must remain constant,  $v_{\parallel}$  must necessarily decrease. If  $B$  is high enough in the "throat" of the mirror,  $v_{\parallel}$  eventually becomes zero; and the particle is "reflected" back to the weak-field region. It is, of course, the force  $F_{\parallel}$  which causes the reflection. The nonuniform field of a simple pair of coils forms two magnetic mirrors between which a plasma can be trapped. This effect works on both ions and electrons.

The trapping is not perfect, however. For instance, a particle with  $v_{\perp} \neq 0$  will have no magnetic moment and will not feel any force along  $B$ .

A particle with small  $v_{\perp} = v_k$  at the midplane ( $B = B_0$ ) will also escape if the maximum field  $B_m$  is not large enough. For given  $B_0$  and  $B_m$ , which particles will escape? A particle with  $v_{\perp} = v_0$  and  $v_k = 0$  at the midplane will have  $v_{\perp} = v_0$  and  $v_k = 0$  at its turning point. Let the field be  $B_0$  there. Then the invariance of  $\mu$  yields  $\frac{1}{2} m v_0^2 = B_0 \frac{1}{2}$

Conservation of energy requires  $\frac{1}{2} m v_0^2 = B_0 \frac{1}{2}$



The Structure and Propulsion The first-stage propellant tank walls of the Falcon vehicles are made from an aluminum lithium alloy. Tanks are manufactured using friction stir welding—the highest strength and most reliable welding technique available. Figure 2-1 Falcon 9 Overview On the first stage of the Falcon 9, an insulated common dome separates the LOX and RP-1 tanks, and an insulated transfer tube carries LOX through the center of the RP-1 tank to the engine section. Four grid fins near the top of the first stage along with four deployable legs are nominally flown at the base of the first stage to support recovery operations. The second-stage tank for Falcon vehicles is a shorter version of the first-stage tank and uses most of the same materials, construction, tooling and manufacturing techniques as the first-stage tank. A single Merlin Vacuum (MVac) engine powers the second stage, using a fixed 165:1 expansion nozzle. For added reliability of restart, the engine contains dual redundant triethylaluminum-triethylborane (TEA-TEB) pyrophoric igniters. In addition, the second stage contains a cold nitrogen gas (GN<sub>2</sub>) attitude control system (ACS) for pointing and roll control. The GN<sub>2</sub> ACS is more reliable and produces less contamination than a propellant-based reaction control system.

**Table 2-1: Falcon 9 Dimensions and Characteristics**

**Characteristic**

**First Stage**

**Structure**

**Second Stage**

**Height**

70 m (229 ft) (including both stages, interstage, and fairing)

*Diameter*

*3.66 m (12 ft)*

*Type*

*3.66 m (12 ft)*

*LOX tank - monocoque*

*Fuel tank - skin and stringer*

*Material*

*LOX tank - monocoque*

*Fuel tanks - skin and stringer*

*Aluminum lithium skin; aluminum domes*

*Propulsion*

*Engine Type*

*Liquid, gas generator*

*Engine Designation*

*Merlin 1D (M1D)*

*Engine Designer*

*MVac*

*SpaceX*

*Engine Manufacturer*

*SpaceX*

*Number of Engines*

*First Stage: 9*

*Second Stage: 1*

*Propellant*

*Liquid oxygen/kerosene (RP-1)*

*Thrust (Stage Total)*

*Sea Level: 6,804 kN (1,530,000 lbf)*

*Vacuum: 934 kN (210,000 lbf)*

*Propellant Feed System*

*Turbopump*

*Throttle Capability*

*Yes (170,000 lbf to 119,000 lbf sea level)*

*Restart Capability*

*Yes (210,000 lbf to 81,000 lbf)*

*Tank Pressurization*

*Yes*

*Heated helium*

***Ascent Attitude Control***  
***Pitch, Yaw: Gimbaled engines***

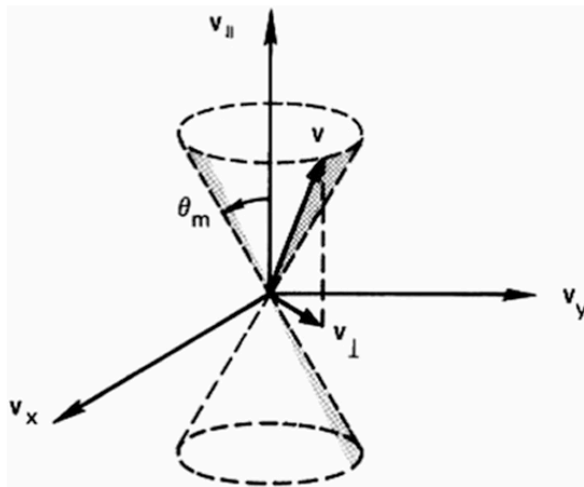
***Coast Attitude Control***  
***Gimbaled engine/nitrogen gas thrusters***

The first and second stages are mated by mechanical latches at three points between the top of the interstage and the base of the second-stage fuel tank. After the first-stage engine shut down, a high pressure helium circuit is used to release the latches via redundant actuators. The helium system also preloads three pneumatic pushers, which provide positive-force stage separation after latch release. For added reliability, a redundant center pusher attached to the first stage is designed to dramatically decrease the probability of re-contact between the stages following separation. The two halves of the fairing are fastened by mechanical latches along the fairing vertical seam. To deploy the fairing, a high-pressure helium circuit releases the latches, and four pneumatic pushers facilitate positive-force deployment of the two halves. The use of all-pneumatic separation systems provides a benign shock environment, allows acceptance and preflight testing of the actual separation system hardware, and minimizes debris created during the separation event.

Avionics, and Guidance, Navigation and Control Falcon avionics feature a three-string, fault-tolerant architecture that has been designed to human-rating requirements. Avionics include flight computers, Global Positioning System (GPS) receivers, inertial measurement units, SpaceX-designed and manufactured controllers for vehicle control (propulsion, valve, pressurization, separation and payload interfaces), a network backbone, S-band transmitters and a C-band transponder for range safety tracking. The S-band transmitters are used to transmit telemetry and video to the ground, from both the first and second stages, even after stage separation. Our launch vehicles are equipped with a flight termination system to limit the potential damage caused by a launch vehicle malfunction. The system terminates the flight of the vehicle either when commanded by the range mission flight control officer or automatically in the case of premature stage separation. 2.5 Coordinate Frame Falcon vehicles use a right-hand X-Y-Z coordinate frame centered 440.69 cm (173.5 in.) aft of the first stage radial engine gimbal, with +X aligned with the vehicle long axis and +Z opposite the transporter erector strongback.

X is the roll axis, Y is the pitch axis, and Z is the yaw axis. Additional coordinate frames may be defined with reference to the payload interface for specific missions. Plasma: The magnetic mirror was first proposed by Enrico Fermi as a mechanism for the acceleration of cosmic rays. Protons bouncing between

magnetic mirrors approaching each other at high velocity could gain energy at each bounce:



Non Uniform E Field Now Let the magnetic field be uniform and the electric field be non uniform. For simplicity, we assume E to be in the x direction and to vary sinusoidally in the x direction (Fig. 2.11):  $E = E_0 \cos kx$   $\vec{p} \cdot \vec{x}$   $\delta$  2:47P

This magnetic mirror field distribution has a wavelength  $\lambda/42\pi/k$  and is the result of a sinusoidal distribution of charges, which we need not specify. In practice, such a charge distribution can arise in a plasma during a wave motion. The equation of motion is  $m dv = dt \delta \vec{p} \cdot \vec{q} E_x \delta \vec{p} \cdot \vec{v} B$ .

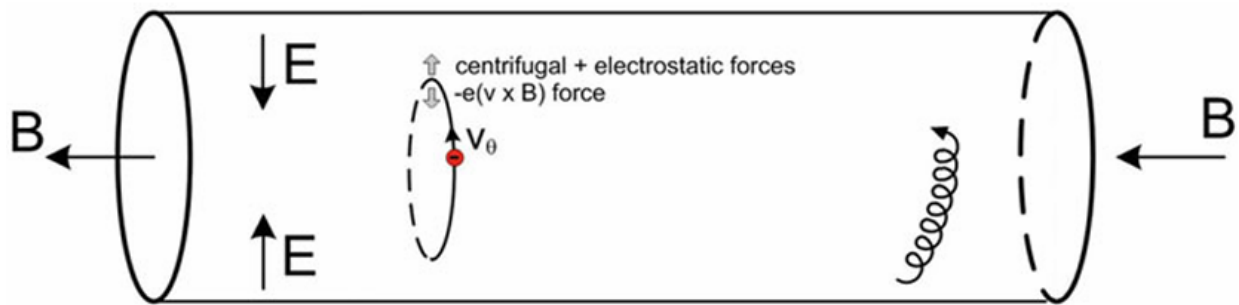
### Composites summary:

Resin Infiltration Carbonization The resin used in liquid infiltration carbonization must be selected carefully. The resin must meet the following conditions [1, 6]:

1. Appropriate viscosity, good flowability, and easily infiltrates into the preform;
2. High carbon yields after carbonization to increase infiltration efficiency and gives high bulk density; 3. Low volume shrinkage during infiltration, solidification, and carbonization processes to decrease damage to fibers.

Staple thermoplastic resins used to prepare C/C composites are polyetheretherketone (PEEK) and polyetherimide (PEI). Although using these resins can efficiently decrease the number of infiltration times, pressure is needed to increase the efficiency during solidification. Most resins used in this industry are thermosetting ones, such as phenolic, ethoxyline, furan, furyl ketone, acetylenic, and polyimide. Most thermosetting resins readily cross-link at relatively low temperature to form thermosetting, infusible, and vitreous solids. The resin carbon after carbonization is difficult to graphitize; however, resin carbon can also be graphitized under stress at high temperature and pressure.



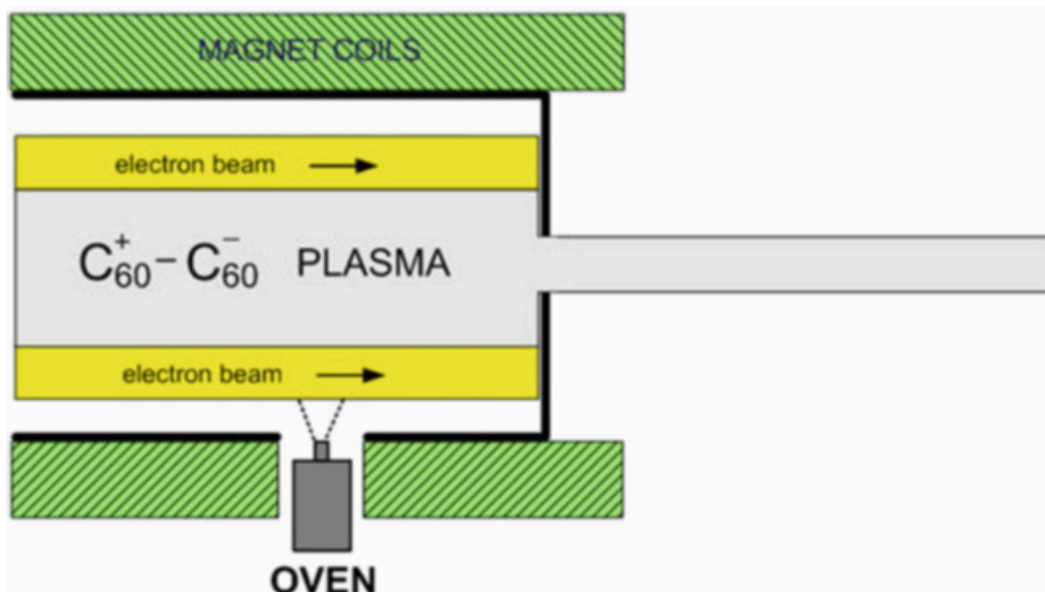


Variables:  $\omega r$  is independent of radius, we see that such a pure electron plasma rotates as a solid body. When  $\omega^2 p = \omega^2 c > 1/2$ , there is no solution; otherwise, there are two solutions. For  $2\omega^2 p = \omega^2 c \ll 1$ , expanding the square root yields the frequencies  $\omega r$  and  $\omega c$ , and the lower frequency  $\omega r = \omega^2 p = 2\omega c$ . Called the diocotron frequency,  $\omega D$  has an orbit like the one at the right in Fig. 9.1. With appropriate modifications, these equations can also describe pure ion plasmas.

**Solid, Ultra-Cold Plasmas** By freezing the plasma in an ion trap to sub-Kelvin temperatures, it is possible to create liquid and solid plasmas. As the thermal motions of the particles decrease, their thermal energies become comparable to the Coulomb energy  $W_c$  between particles. This condition can be quantified by defining a coupling parameter  $\Gamma$ , the ratio between the average  $W_c$  and  $kT$ . Two singly charged particles separated by a distance  $a$  have a Coulomb energy  $e^2/a$ .

Hence  $\Gamma = \frac{1}{4} \frac{e^2}{a kT}$ : The Pair-ion Plasmas parameters that a plasma with equal masses would behave quite differently from a normal plasma with slow ions immersed in a sea of fast electrons. Though it is possible to make a positronium plasma, the recombination rate is so fast that there is no time to do experiments. Fullerenes, stable molecules of 60 carbon atoms arranged in a hollow sphere, move and recombine slowly because of the large mass. It is thus possible to produce a long-lived pair-ion plasma with C60. In Fig. 9.5, neutral C60 is injected from an oven. A ring of fast electrons up to 150 eV driven through the C60 forms  $C_{60}^+$  ions by ionization and  $C_{60}^-$  ions by attachment. A magnetic field confines the electrons but allows the heavy ions to diffuse into the center to form a fullerene pair-ion plasma. The plasma then passes through a hole into a chamber for experimentation. Consider a singly charged pair-ion plasma with a common mass  $M$  and temperature  $kT$ . The equations of motion for the ions of charge  $\pm e$  are  $M n_0 \frac{dv}{dt} = \pm e n_0 E - \nabla p$ :

Dust grains have sizes from tens of nanometers to hundreds of microns. Since electrons impinge on them much more often than ions do, the grains will have a negative surface potential  $V_s$ . Consider a spherical grain of radius  $a$  and charge  $q < 0$ . The capacitance of the sphere (with distant walls) is  $C = 4\pi\epsilon_0 a$ : The surface charge  $q$  is then  $q = CV_s = 4\pi\epsilon_0 a V_s$ . The value of either  $q$  or  $V_s$  depends on the Debye length  $\lambda_D$  in the background plasma. If  $\lambda_D$  is  $\gg a$ , the grain is a small, isolated particle like a spherical Langmuir.



### Variables-structure:

The Dust Acoustic Waves The dust acoustic wave is a very low-frequency, longitudinal compressional wave involving the motions of the dust particles. Because the heavy dust moves more slowly than the ions and electrons, the latter have time to relax into Maxwellian distributions:

1.  $n_e = \frac{1}{4} n_{e0} \exp \left( \frac{e\phi}{K T_e} \right) \quad \frac{\partial P_e}{\partial \phi} = K T_e n_e$
2.  $\frac{\partial P_i}{\partial \phi} = K T_i n_i = \frac{1}{4} n_{i0} \exp \left( \frac{e\phi}{K T_i} \right) \quad \frac{\partial P_i}{\partial \phi} = K T_i n_i$
3.  $\frac{1}{4} n_{e0} \exp \left( \frac{e\phi}{K T_e} \right) = \frac{\partial P_e}{\partial \phi} \quad \frac{1}{4} n_{i0} \exp \left( \frac{e\phi}{K T_i} \right) = \frac{\partial P_i}{\partial \phi}$

Variables-expressions-python:

### Fluid Motion Equation (Including Collisions)

For any species, the equation of motion is:

$$m n \frac{dv}{dt} = m n \left( \frac{\partial v}{\partial t} \right) + v \nabla (v) = e n E - \nabla p - m n \nu v$$

- The term " $e n E$ " represents the force due to an electric field.
- " $\nabla p$ " accounts for pressure gradients within the fluid.
- The averaging process ensures Eq. (5.5) remains valid.
- In a **steady-state plasma**,  $\frac{\partial v}{\partial t} = 0$ , meaning fluid elements do not move into regions with different  $E$  or  $\nabla p$  within a collision time.

Setting  $\frac{dv}{dt} = 0$  leads to:

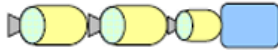

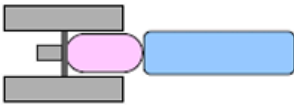
$$v = \left( \frac{1}{m n \nu} \right) * (e n E - K T \nabla n)$$

$$= e / (mvE) - (KT / mv) * \nabla (n/n)$$

**Key Coefficients:**

- **Mobility**:  $\mu = |q| / mv$
- **Diffusion Coefficient**:  $D = KT / mv$

These coefficients determine how charged particles move through the plasma, describing their **response to electric fields** and **thermal diffusion**.

100 mT IMLEO System	Specific Impulse (seconds)	Payload from 400 km LEO to 1-sol Mars orbit (mT)	Total Flight Time (months)
Chemical 	450	29	9
Nuclear Thermal 	925	44	9
1 MW Solar Electric 	5000	48 – 58 ( $\alpha = 20, \alpha = 10$ )	27

Velocities in plasma are  $\Gamma_i$  and  $\Gamma_e$  were not equal, a serious charge imbalance would soon arise. If the plasma is much larger than a Debye length, it must be quasineutral; and one would expect that the rates of diffusion of ions and electrons would somehow adjust themselves so that the two species leave at the same rate. How this happens is easy to see. The electrons, being lighter, have higher thermal velocities and tend to leave the plasma first. A positive charge is left behind, and an electric field is set up of such a polarity as to retard the loss of electrons and accelerate the loss of ions. The required E field is found by setting  $\Gamma_i = \frac{1}{4}\Gamma_e$ .

## PYTHON

```
### Plasma Fluid Motion & Transport Properties

Plasma is a highly dynamic, electrically charged fluid where
particles interact
through electromagnetic forces and collisions. Understanding **plasma
transport**
involves analyzing how ions and electrons move under different
influences.

#### General Fluid Equation of Motion:


$$mndv/dt = enE - \nabla p - mnvv$$


Where:
- **m** → Mass of the charged species
- **n** → Number density of species
-  $dv/dt$  → Convective derivative (fluid acceleration)
- **E** → Electric field applied to plasma
-  $\nabla p$  → Pressure gradient affecting particle flow
-  $mnvv$  → Collision term representing momentum exchange between
species

Assuming **steady-state conditions** ( $\partial v / \partial t = 0$ ), the equation
simplifies to:


$$v = (1 / mnv) * (enE - KT \nabla n)$$


This relationship highlights two primary factors:
1. **Mobility ( $\mu$ )** → Response of charged particles to an electric
field

$$\mu = |q| / mv$$

2. **Diffusion Coefficient (D)** → Spread of particles due to
temperature gradients

$$D = KT / mv$$


---

### **Mobility and Diffusion in Plasma Transport**

#### **Mobility ( $\mu$ ) - How Particles Respond to Fields**
Mobility **quantifies how quickly charged species move under an
electric field**,
depending on mass, charge, and collision frequency.
- **Low-mass particles (electrons)** → Higher mobility, rapid
response
- **High-mass ions** → Lower mobility, slower reaction
- **High collision rates** → Reduce mobility by disrupting particle
acceleration
```

When mobility is **high**, charged species accelerate efficiently, leading to rapid flow.

In **low-mobility conditions**, external forces struggle to drive plasma movement.

Applications of mobility:

- **Plasma thrusters** → Ion propulsion in spacecraft
- **Fusion reactors** → Maintaining plasma confinement
- **Semiconductor processing** → Controlling ionized particles

---

#### **Diffusion (D) - Random Motion from Thermal Effects**

Diffusion describes how particles spread **due to temperature variations** rather than direct electromagnetic forces.

- **High-temperature plasma** → More rapid diffusion
- **Dense plasma** → Slower diffusion due to frequent collisions

In weakly ionized plasmas, diffusion often **dominates** transport, meaning particles move **without a significant electric field influence**.

Applications of diffusion:

- **Magnetosphere studies** → Understanding charged particle dispersion
- **Controlled fusion** → Managing energy losses
- **Space plasma physics** → Investigating solar wind interactions

---

### **Steady-State Plasma & Collisional Effects**

In many plasma applications, assuming a **steady-state condition** simplifies analysis:

$$\partial v / \partial t = 0$$

- **Low collision plasma** → Transport dominated by electromagnetic forces
- **High collision plasma** → Transport dominated by diffusion & thermal gradients

In cases where **fluid elements cannot move into regions of different  $E$  and  $\nabla p$  within a collision time**, the **convective derivative  $dv/dt$  effectively vanishes**, leading to:

- **Electromagnetic term ( $e\mathbf{n}E$ )** → Governs charged particle movement
- **Thermal term ( $KT\nabla n$ )** → Determines temperature-driven spread
- **Balancing both effects** → Controls overall plasma behavior

---

### **Experimental Techniques to Measure Mobility & Diffusion**

Scientists use various methods to evaluate plasma transport coefficients:

1. **Langmuir Probes** → Measure plasma electron density & temperature
2. **Laser-Induced Fluorescence** → Tracks ion velocity distributions
3. **Electromagnetic Interferometers** → Detect charge density fluctuations
4. **Magnetically Confined Plasma Tests** → Observe charged particle drift

---

### **Real-World Plasma Applications**

- **Spacecraft Propulsion** → Ion thrusters rely on precise mobility control
- **Astrophysical Plasmas** → Understanding interstellar gas behavior
- **Fusion Plasma Confinement** → Magnetic fields regulate charged species diffusion
- **Advanced Materials Processing** → Plasma etching in semiconductor industries

Plasma transport dynamics play a **critical role** in aerospace, astrophysics, and energy research.

By optimizing **mobility and diffusion**, engineers improve plasma confinement, propulsion efficiency, and material interactions.

Would you like further expansions on **specific equations or real-world plasma applications**? 🚀