西安交通大学电子与信息工程学院研究生课程

《等离子体电子学》

第三章 等离子体宏观特性

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等离子体宏观特性

- 准中性

□ 等离子体的准中性

- 在等离子体内部，电子和正离子的密度处处相等
- 鞘层（器壁附近），不相等
- 由于正离子和电子的巨大质量差，相对于接地器壁，等离子体具有正电位（等离子体电位）

$$divE = e\frac{n_p - n_e}{\epsilon_0},$$

主等离子体：E=0

鞘层：|E|>0

$n_p \sim ne$

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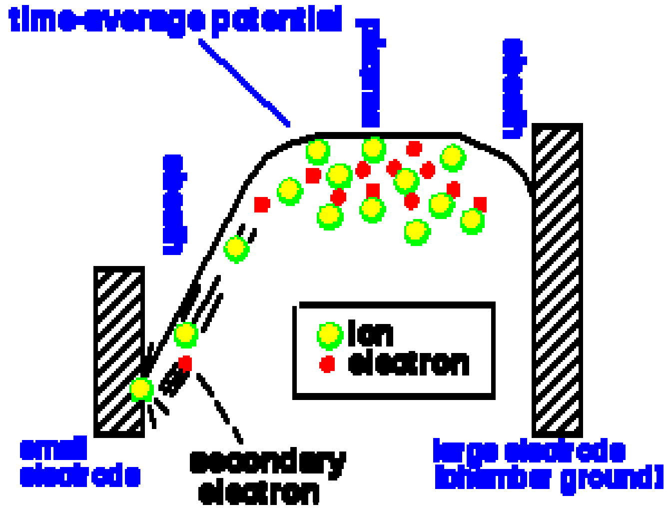
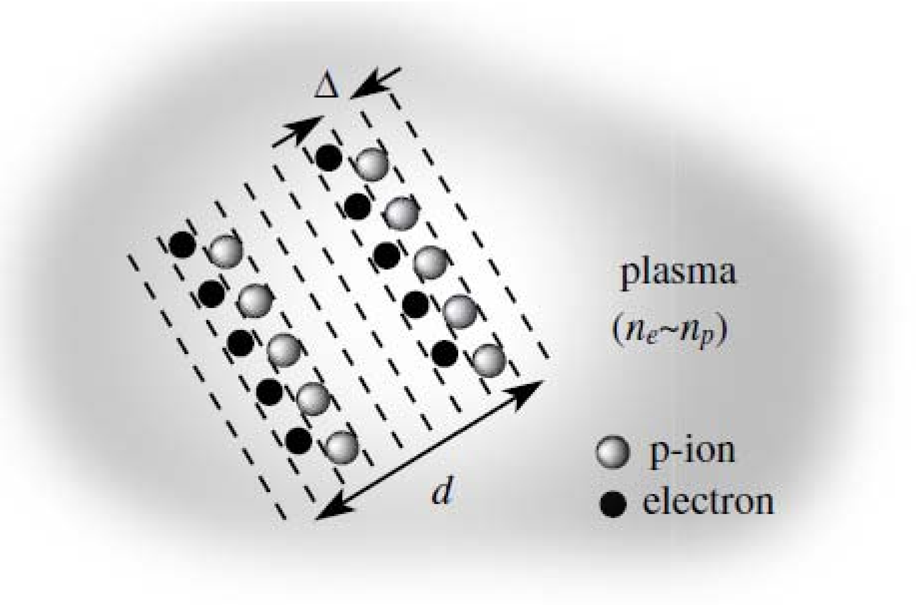


等离子体宏观特性

- 空间电荷分离

  - 空间扰动引起电荷分离
  - 电荷分离的空间尺度
    - 德拜长度/德拜半径
    - 大于德拜半径的尺度里，维持电中性
  - 德拜半径的推导



简化条件：
1. 一维近似下（形成两个电荷层）
2. 无碰撞等离子体（要维持分离，带电粒子的电势能应小于热能

$$E = \frac{en\Delta}{\varepsilon_0} \quad \text{and} \quad V = \frac{en\Delta d}{\varepsilon_0}$$

$$e\frac{en\Delta d}{\varepsilon_0} < kT_e,$$

$\Delta \sim d$

$$d < \left\{\frac{\varepsilon_0 k T_e}{ne^2}\right\}^{1/2} \equiv \lambda_D.$$

无碰撞等离子体（简化情况）的德拜长度 λ_D

等离子体宏观特性

- 空间电荷分离

练习题（参考书Exercise 3.3.1）

若无碰撞等离子体的密度和电子温度分别为$10^{16}m^{-3}$和3eV，请计算其德拜长度

Exercise 3.3.1

Calculate the Debye length when plasma density and electron temperature in a collisionless plasma are 10^{16} m^{-3} and 3 eV, respectively.

$$\lambda_D = \left\{\frac{\varepsilon_0 k T_e}{ne^2}\right\}^{1/2} \sim 7.43 \times 10^3 \times \left(\frac{kT[\text{eV}]}{n[\text{m}^{-3}]}\right)^{1/2} [\text{m}]. \qquad (3.4)$$

That is,

$$\lambda_D = 7.43 \times 10^3 \times \left(\frac{3}{10^{16}}\right)^{1/2} = 1.29 \times 10^{-4} [\text{m}].$$

注意"温度"的单位

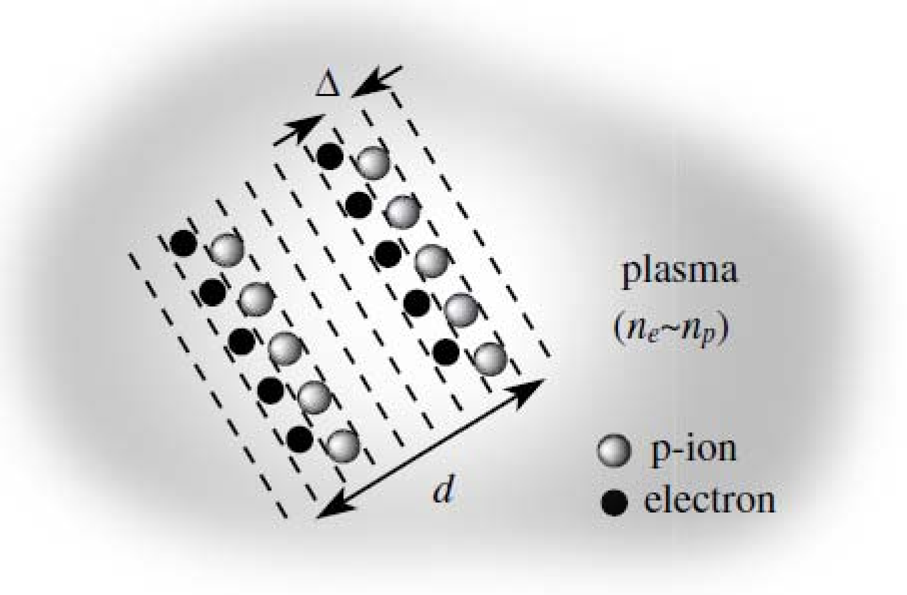
等离子体宏观特性

● 空间电荷分离

□ 电荷分离的时间尺度

■ 电子等离子体振荡/Langmuir振荡

■ 库仑力作用下，电子层在离子层附近来回振荡



$$m\frac{d^2}{dt^2}\Delta(t) = -\frac{e^2 n}{\varepsilon_0}\Delta(t). \Rightarrow \omega_e = \left(\frac{e^2 n}{m\varepsilon_0}\right)^{1/2} \sim 56.4\,(n[\mathrm{m}^{-3}])^{1/2}\ [\mathrm{s}^{-1}],$$

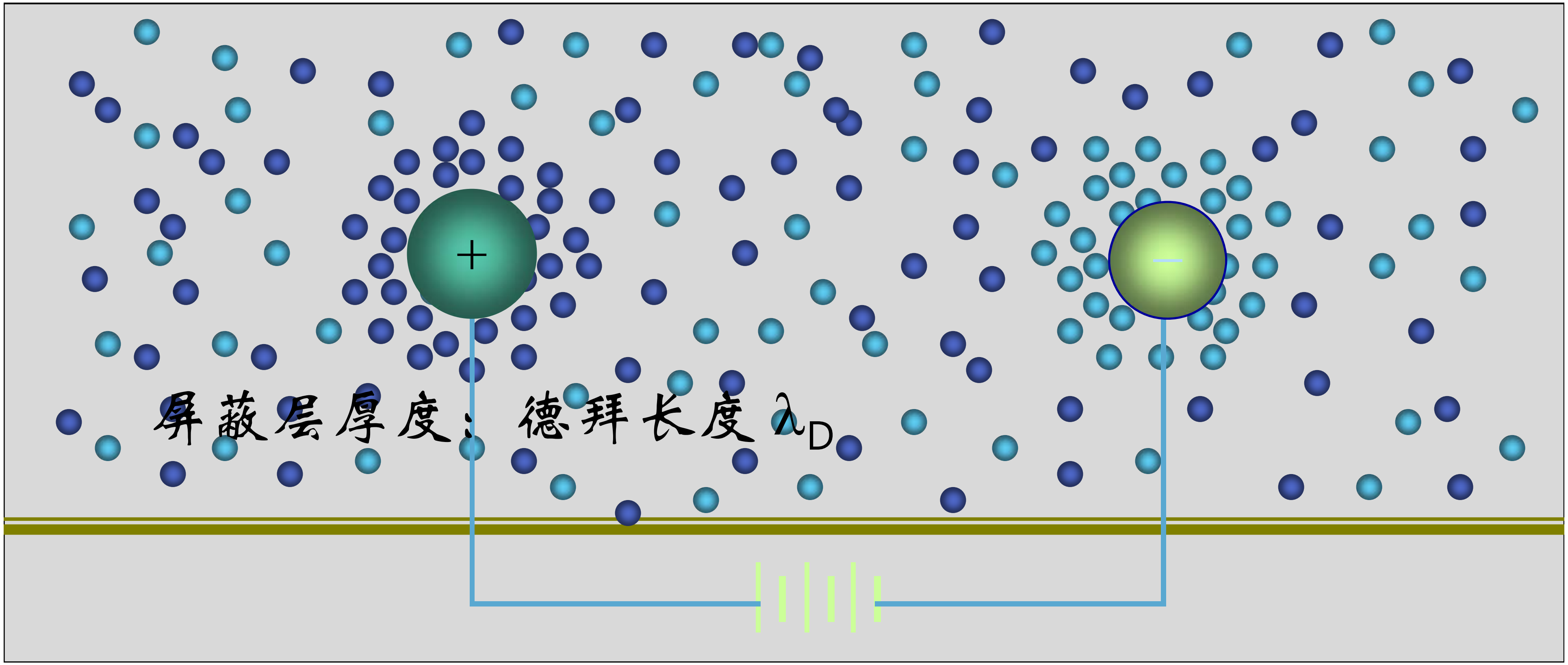
$$\tau_{es} = \frac{1}{\omega_e} \Rightarrow \frac{\lambda_D}{\tau_{es}} = \left(\frac{kT_e}{m_e}\right)^{1/2} \approx V_e,$$

- ω_e: 电子等离子体频率
- τ_{es}: 电荷分离的时间尺度
- V_e: 电子的热速度

等离子体宏观特性

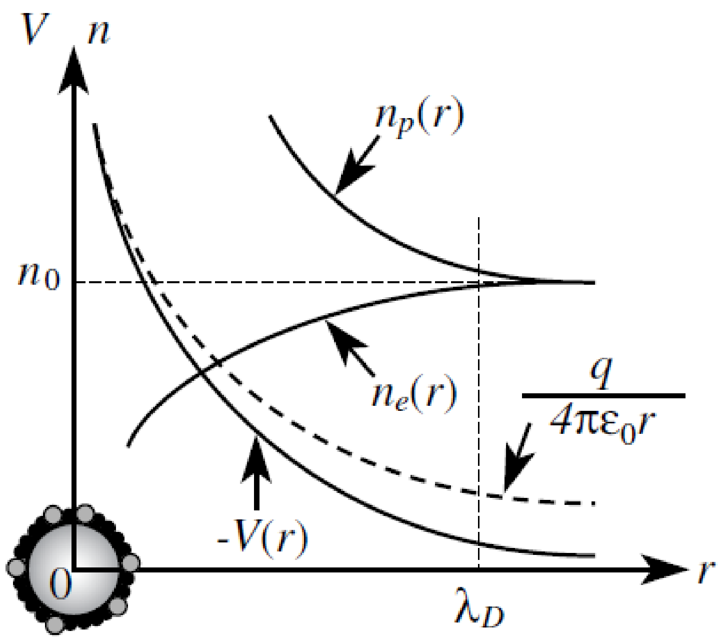
- 等离子体屏蔽

  - 等离子体屏蔽：当材料（金属/介质）被放入等离子体中时，等离子体中的电子和离子会迅速移动到表面，而产生屏蔽



等离子体宏观特性

- 等离子体屏蔽
  - 金属球附近的电位分布
  - 球坐标系下的泊松方程



$$\nabla^2 V(r) = \frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dV(r)}{dr}\right) = -\frac{e}{\varepsilon_0}(n_p - n_e)$$

$$n_p = n_0 \exp\left(-\frac{eV(r)}{kT_p}\right),$$

$$n_e = n_0 \exp\left(\frac{eV(r)}{kT_e}\right),$$

$$V(r) = \frac{A}{r}\exp\left(-\frac{r}{\lambda_D}\right),$$

$q_0/4\pi\epsilon_0 r$

边界条件，金属球表面电位

$$V(r) = \frac{q_0}{4\pi\varepsilon_0 r}\exp\left(-\frac{r}{\lambda_D}\right)$$

$$\lambda_D^2 = \frac{\varepsilon_0 k T_p T_e}{e^2 n_0 (T_p + T_e)}.$$

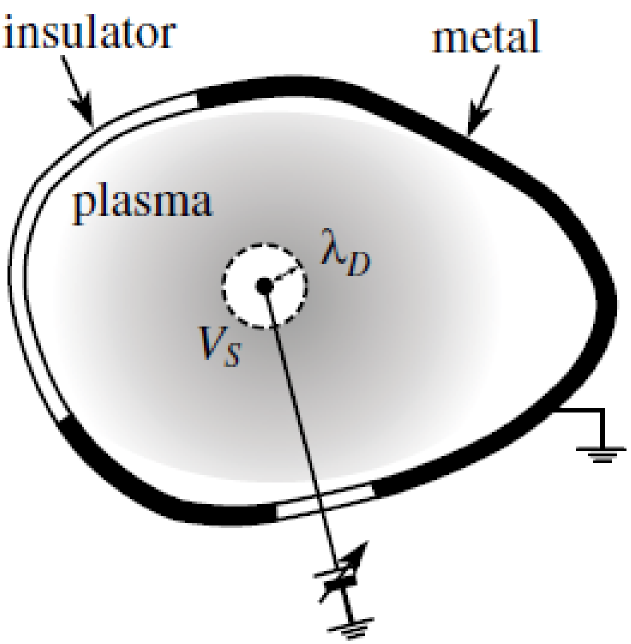
有碰撞热平衡等离子体（简化情况）的德拜长度 λ_D

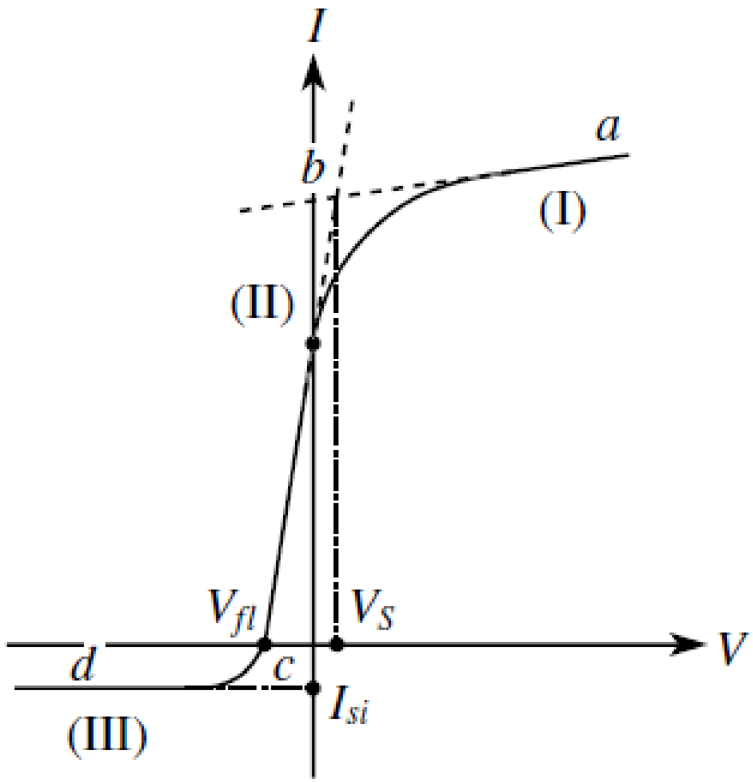
等离子体宏观特性

- 等离子体屏蔽-鞘层-探针

  - 等离子体中的金属探针
  - 探针I-V特性

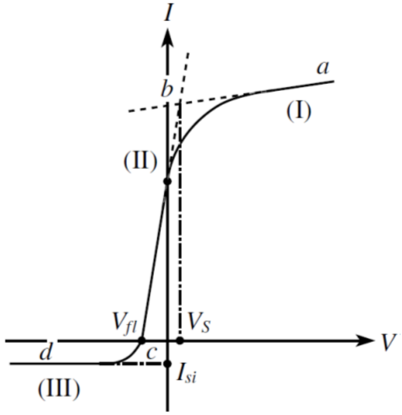
> - V_s: 等离子体电位
> - V_{fl}: 悬浮电位（I=0）





等离子体宏观特性

- 等离子体屏蔽-鞘层-探针
  - 等离子体中的金属探针
    - 等离子体参数诊断



$$V_p = Vs - V$$

$$I(V) = en_e S \int_{v_x=-\infty}^{\infty} \int_{v_y=-\infty}^{\infty} \int_{v_z=\sqrt{\frac{2e|V_p|}{m}}}^{\infty} v_z \left(\frac{m}{2\pi k T_e}\right)^{3/2} \times \exp\left\{-\frac{m(v_x^2+v_y^2+v_z^2)}{2kT_e}\right\} dv_x dv_y dv_z$$

$$= en_e S \left(\frac{m}{2\pi k T_e}\right)^{3/2} \int_{-\infty}^{\infty} \exp\left(-\frac{mv_x^2}{2kT_e}\right) dv_x \int_{-\infty}^{\infty} \exp\left(-\frac{mv_y^2}{2kT_e}\right) \times dv_y \int_{v_z}^{\infty} v_z \exp\left(-\frac{mv_z^2}{2kT_e}\right) dv_z$$

$$= en_e S \left(\frac{m}{2\pi k T_e}\right)^{3/2} \frac{2\sqrt{\pi}}{2\sqrt{\frac{m}{2kT_e}}} \frac{2\sqrt{\pi}}{2\sqrt{\frac{m}{2kT_e}}} \frac{1}{\frac{m}{kT_e}} \exp\left(-\frac{eV_p}{kT_e}\right),$$

特性曲线bc段

$$I(V) = \frac{en_e\langle v_e\rangle}{4} S \exp\left(\frac{V - V_s}{kT_e}\right)$$

由ln(I)-V特性斜率和$n_e\langle v_e\rangle$计算得到T_e

（忽略运动过程中的碰撞）

特性曲线ab段

$$I = \frac{en_e\langle v_e\rangle}{4} S.$$

根据饱和电流计算$n_e\langle v_e\rangle$

等离子体宏观特性

- 等离子体屏蔽-鞘层-探针

Exercise 3.4.1 朗缪尔探针法用bc曲线估算等离子体温度的气压条件（适用范围）

Discuss the pressure condition that the electron temperature T_e is estimated from the curve in region (II) in bc in Figure 3.3.

As a typical plasma we assume, $n_e = 10^{15}\ \mathrm{m}^{-3}$, $kT_e = 3.0\ \mathrm{eV}$. Then, the Debye length is

$$\lambda_e = 7.43 \times 10^3 \times \left(\frac{kT_e[\mathrm{eV}]}{n_e[\mathrm{m}^{-3}]}\right)^{1/2} = \frac{7.43 \times 10^3 \times \sqrt{3}}{\sqrt{10} \times 10^7} = 4.07 \times 10^{-4}\ [\mathrm{m}].$$

The mean speed of electrons is

$$\langle v_e \rangle = (8kT_e/\pi m)^{1/2} = 6.71 \times 10^7 \times \sqrt{kT_e\ [\mathrm{eV}]} \approx 1.16 \times 10^6\ [\mathrm{ms}^{-1}].$$

The collision rate R is roughly approximated at $10^7 p[\mathrm{Pa\ s}^{-1}]$, and the flight time of the electron in the static sheath in front of the probe is

$$\frac{\lambda_e}{\langle v_e \rangle} \approx \frac{4.07 \times 10^{-4}}{1.16 \times 10^6} \approx 3.51 \times 10^{-10} \ll \frac{1}{R} \left(\approx \frac{1}{10^7 p}\right).$$

Therefore, the collisionless condition is obtained as

无碰撞条件

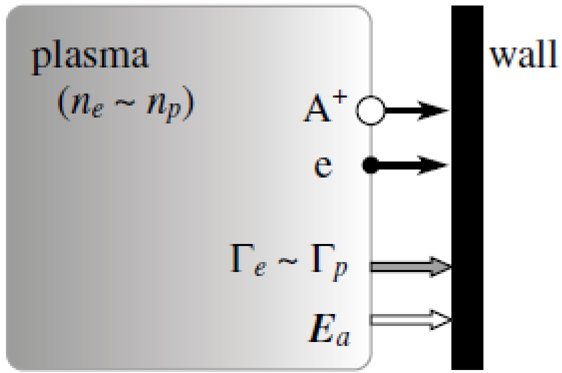
$$p \ll \frac{1}{10^7} \times \frac{1}{3.51 \times 10^{-10}} \approx 2.85 \times 10^2\ [\mathrm{Pa}].$$

等离子体宏观特性

- 鞘层-粒子扩散

  - 器壁附近的双极扩散

  - 稳态时，电子和离子扩散到器壁的流量相等 $\Gamma_e \approx \Gamma_p$



$$\Gamma_e = n_e \langle v_e \rangle = n_e v_{de} - D_e \frac{dn_e}{dr},$$

$$\Gamma_p = n_p \langle v_p \rangle = n_p v_{dp} - D_p \frac{dn_p}{dr},$$

$$v_a = -D_a \frac{1}{n}\frac{dn}{dr},$$

$$D_a = \frac{\mu_p D_e + \mu_e D_p}{\mu_p + \mu_e},$$

$$D_a = \frac{D_p\left(1 + \frac{T_e}{T_p}\right)}{\left(1 + \frac{\mu_p}{\mu_e}\right)}.$$

$$D_a = D_p \frac{T_e}{T_p}. \qquad T_e \gg T_p,$$

$$D_a = 2D_p. \qquad T_e = T_p,$$

等离子体宏观特性

- 鞘层-玻姆判据
  - 玻姆判据：稳定等离子体鞘层的形成条件
    - 在鞘层和主等离子体之间存在一个过渡层——预鞘层(加速离子的区域)
    - 离子在预鞘层-鞘层边界达到玻姆速度
    - 形成稳定鞘层时，电子流和离子流达到平衡

David Joseph Bohm (1917–1992)

- 推导玻姆判据的近似条件：
  - 鞘层和预鞘层中无碰撞（离子的平均自由程>鞘层厚度）
  - 电子温度满足玻尔兹曼分布，离子温度为0
  - 鞘层(正离子鞘层)内：$n_i > n_e$
  - 预鞘层内：$n_i \approx n_e < n_0$
  - 等离子体区： $n_i \approx n_e = n_0$
  - 等离子体与预鞘层边界： 电位$\varphi=0$
  - 预鞘层与鞘层交界处：电位$\varphi= \varphi_s$
  - 容器壁处： $\varphi= \varphi_w$

等离子体宏观特性

- 鞘层-玻姆判据

离子被预鞘层加速：

$$u_s = \sqrt{-2e\phi_s / m_i}$$

电子在鞘层-预鞘层边界处的密度为（离子密度与此相等）：

$$n_s = n_0 e^{e\phi_s / kT_e}$$ 玻尔兹曼分布

设鞘层内离子密度和速度分别为n_i和u_i，由通量的连续性有

$$n_i u_i = n_s u_s$$

$$u_i = \sqrt{-2e\phi / m_i}$$

⟹

$$n_i = n_s u_s / u_i = n_s \sqrt{\phi_s / \phi}$$

$$n_e = n_s e^{e(\phi - \phi_s)/kT_e}$$

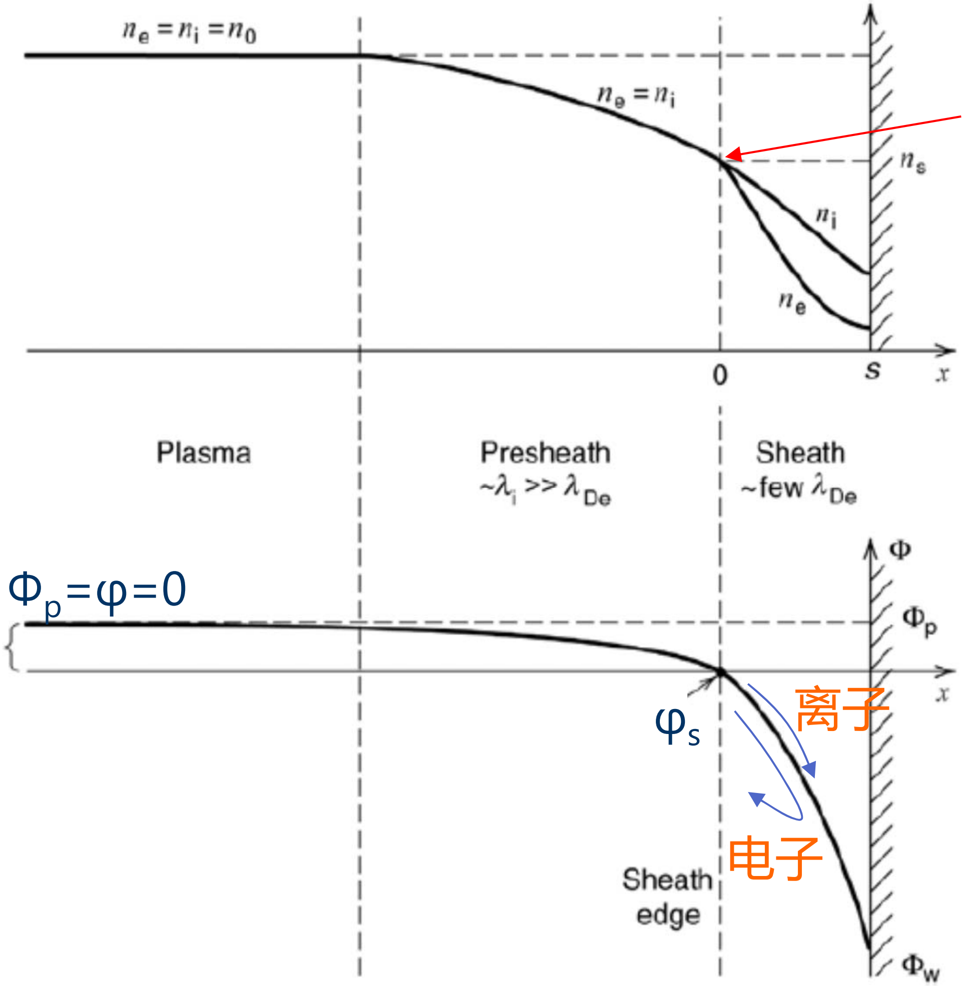
⟹ 鞘层的净空间电荷：

$$n_i - n_e = n_s \left\{ \sqrt{\frac{\phi_s}{\phi}} - e^{e(\phi-\phi_s)/kT_e} \right\}$$

近似展开：$\sqrt{\frac{\phi_s}{\phi}} \approx 1 + \frac{1}{2}\frac{\Delta\phi}{\phi_s}, \quad e^{e(\phi-\phi_s)/kT_e} \approx 1 - \frac{e\Delta\phi}{kT_e}$ 鞘层边界开始偏离电中性

等离子体宏观特性

- 鞘层-玻姆判据



$$n_i - n_e = n_s \left\{ \sqrt{\frac{\phi_s}{\phi}} - e^{e(\phi-\phi_s)/kT_e} \right\}$$

$$\sqrt{\frac{\phi_s}{\phi}} \approx 1 + \frac{1}{2}\frac{\Delta\phi}{\phi_s}, \quad e^{e(\phi-\phi_s)/kT_e} \approx 1 - \frac{e\Delta\phi}{kT_e}$$

要使： $n_i - n_e \geq 0$ ⇒ $\frac{1}{2}\frac{\Delta\phi}{\phi_s} + \frac{e\Delta\phi}{kT_e} \geq 0$ ⇒ $e|\phi_s| \geq kT_e/2$

等离子体宏观特性

- 鞘层-玻姆判据

$$u_s = \sqrt{-2e\phi_s / m_i}$$

$$e|\phi_s| \geq kT_e / 2 \Rightarrow u_s \geq \sqrt{kT_e / m_i}$$

物理意义

定义：玻姆速度 $u_B = \sqrt{kT_e / m_i}$

形成正离子鞘层的离子通量不依赖于容器壁的电位，而是由于等离子体密度n_0、电子温度T_e以及离子质量m_i共同决定

鞘层边界处的电位至少比等离子体电位低 $\phi_s \leq -kT_e / 2e$

鞘层边界处的密度至少下降到 $n_s = n_0 e^{-1/2} = 0.605 n_0$

鞘层边界处的离子通量(玻姆通量) $\Gamma_i = n_s u_B = 0.605 n_0 \sqrt{kT_e / m_i}$

电子通量计算(由玻尔兹曼分布)

$$\Gamma_e = \int_{v_0}^{\infty} w_x f_e(w_x) dw_x = \frac{n_0 < v_e >}{4} e^{e\phi_w / kT_e}$$

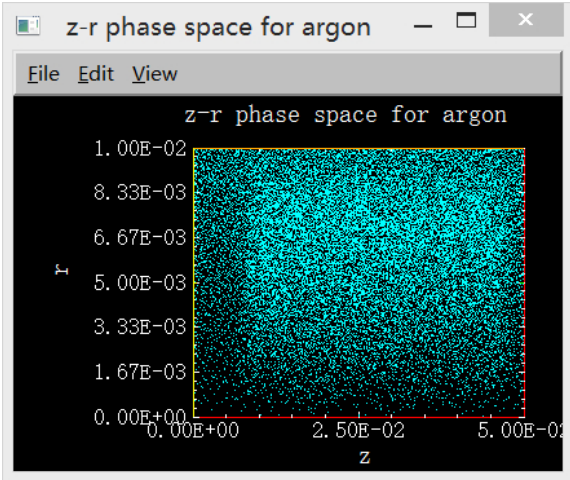
其中克服φ_w最小速度v_0和平均速度$\langle v_e \rangle$为

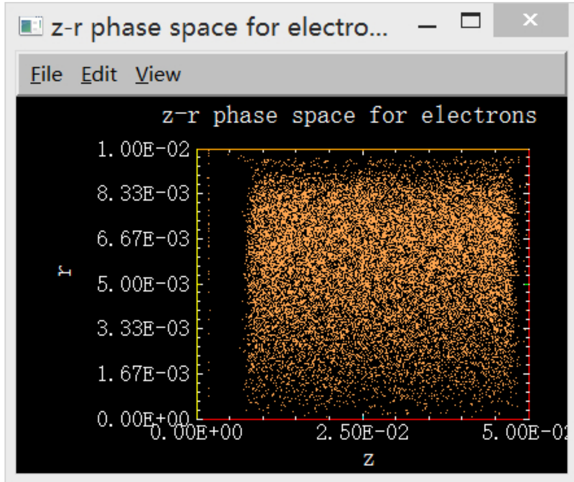
$$v_0 = \sqrt{\frac{-2e\phi_w}{m_e}}, < v_e > = \sqrt{\frac{8kT_e}{\pi m_e}}$$

等离子体宏观特性

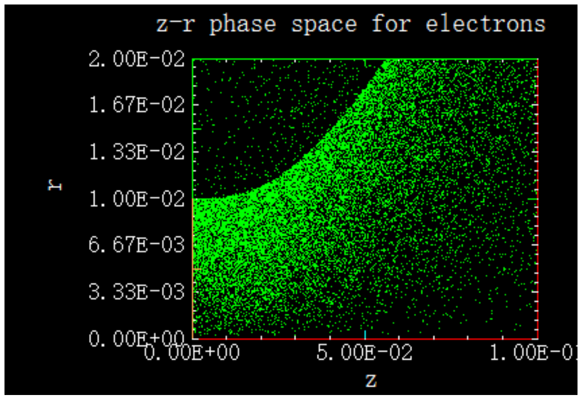
- 粒子模拟软件OOPIC Pro演示

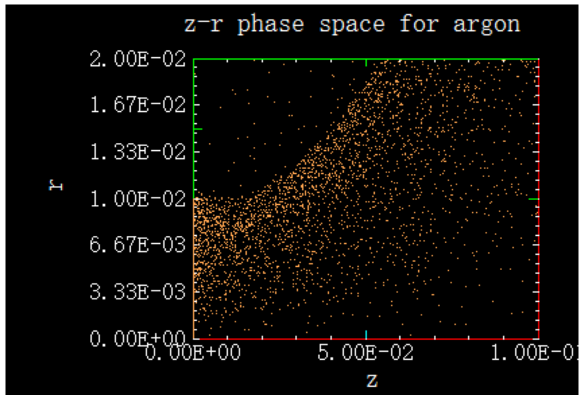
  - ☐ 鞘层形成（dcdis.inp）





  - ☐ 氩气放电(gas.inp)





等离子体宏观特性

- OOPIC Pro简介

Physics kernel (OOPIC) developed at UC Berkeley, circa 1992-1995; now in version 3.0

XOOPIC = OOPIC + XGrafiX

owned/maintained by UCB Plasma Simulation Group

runs on Linux

Source codes at

http://langmuir.nuc.berkeley.edu/pub/codes/xoopic/

After several SBIR cycles, there is currently an available commercial product:

OOPICPro = OOPIC + Qscimpl

maintained and distributed by Tech-X Corp. (w/ UCB license)

Windows and Linux $commercial version 1.0

目前：开发者J P Verboncoeur已转到Michigan state university
OOPIC Pro 已被Tech-X公司终止研制和发售（2.0版后）

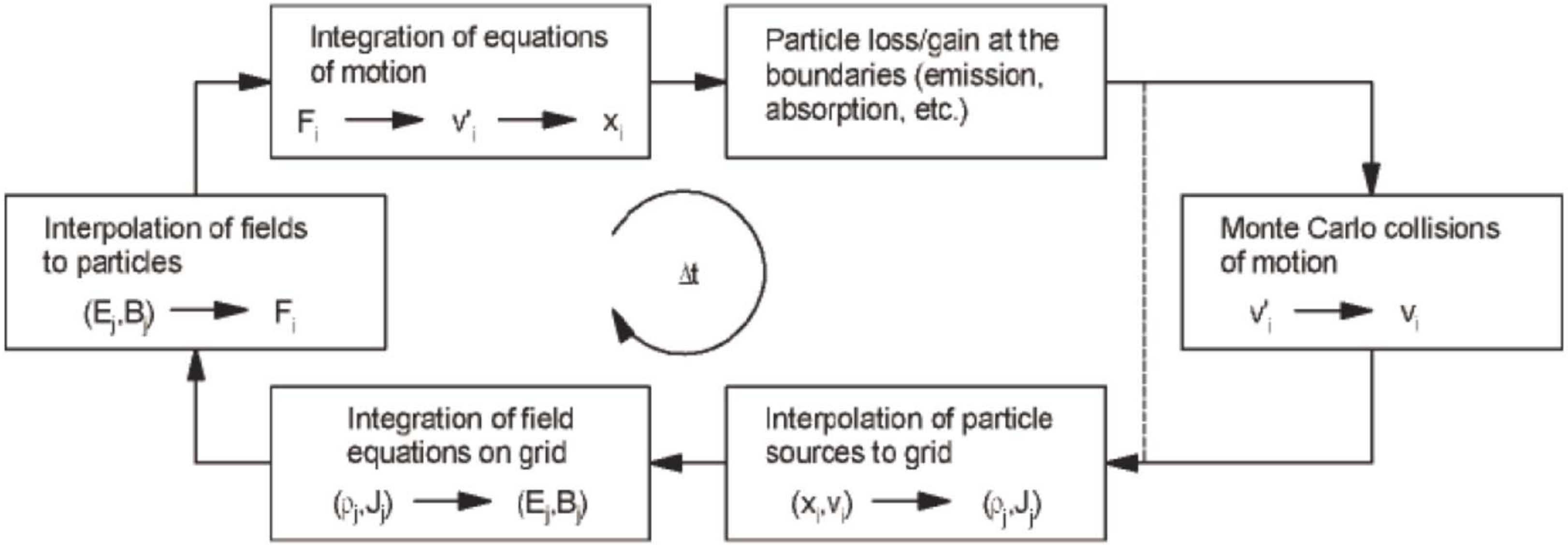
等离子体宏观特性

- OOPIC Pro简介

CHARLES KENNEDY BIRDSALL

等离子体宏观特性

- OOPIC Pro简介



1. Verboncoeur J P, Langdon A B and Gladd N T 1995 An object-oriented electromagnetic PIC code, *Comput. Phys. Commun.* **87** 199–211.
2. Verboncoeur J P, 2005 Particle simulation of plasmas: review and advances, Plasma Phys. Control. Fusion **47** A231–A260.

等离子体宏观特性

- OOPIC Pro简介

  - Grid
  - Spatial regions
  - Fields
  - Particle groups—can be different species or e.g. beam vs. plasma electrons
    - Each group has a list and definition
  - Boundaries
    - Ports
    - Symmetry planes
    - "Dielectrics" (actually includes all materials)
      - "Conductor", includes insulators; can absorb particles
      - Emitter, produces particles by some rule

等离子体宏观特性

- OOPIC Pro简介

- 2-dimensional orthogonal grid
  - Cartesian (x,y) or cylindrically symmetric (r,z)
  - Nonuniform grids in both dimensions possible
  - **Moving window**
- Plasma and beam emission / interaction
  - Boundary interactions (absorption, reflection)
  - Secondary emission from boundaries
  - Monte Carlo scattering between species; ionization
  - Time-dependent current injection
  - **Tunneling ionization**
- Full e.m. field solve
  - **Linear Polarized Electromagnetic Field Launcher**
  - Can do wakefields in cylindrical geometry
  - Obvious choice for PWFA and LWFA

等离子体宏观特性

- OOPIC Pro简介

An input file is a series of blocks denoted by heading + brackets

Parameters are defined inside the blocks   // is a comment marker

Example:

```
Grid  // rest of line commented out
{
J = 10  // these are parameters
x1s = 0.00
x1f = 0.05
K = 10
x2s = 0.00
x2f = 0.05
}  // end of block
```

等离子体宏观特性

- OOPIC Pro简介

Region block

- Parameter groups
  - **Grid**: region dimension and mesh parameters
  - **Control**: simulation parameters, e.g. timestep
  - **Species**: particle characteristics for each particle group
  - **Load** and **VarWeightLoad**: initial spatial distribution for each particle species (Var… for cylindrical coords)
- Boundary conditions
  - Possibilities include **Conductor**, **Dielectric**, **Polarizer**, **DielectricRegion**, **ExitPort**, **CylindricalAxis**, and more

等离子体宏观特性

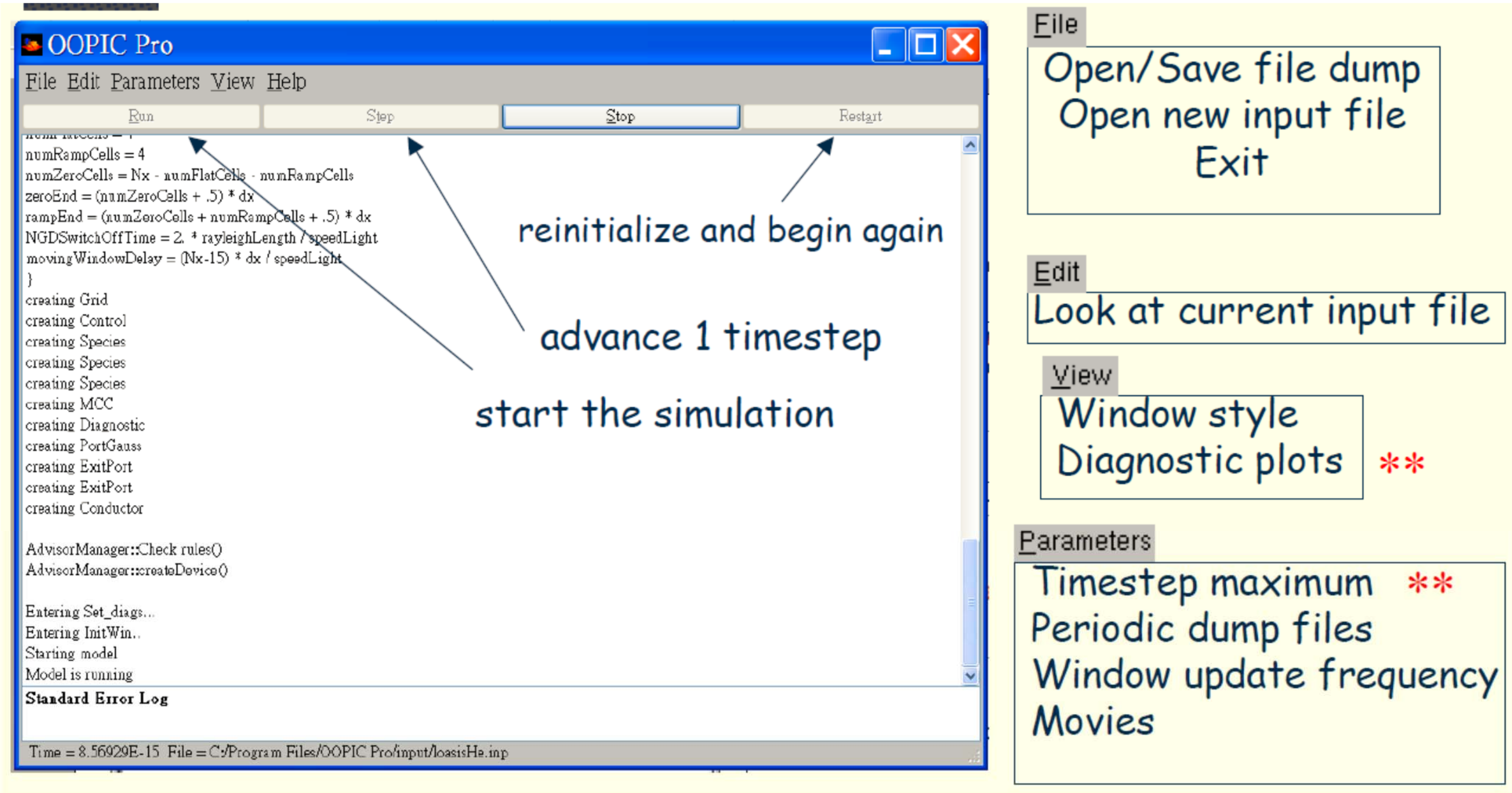
- OOPIC Pro简介

Other useful blocks:

- **Emitters**
  - **BeamEmitter** specifies a boundary which emits a particle beam with given properties, velocity, etc.
  - **PlasmaSource** specifies a rectangular region in which plasma is generated at a constant rate
- **MCC**: collision modeling in the plasma
  - Monte Carlo collision parameters
- **Secondary**: to define secondary emission at a boundary

等离子体宏观特性

- OOPIC Pro简介



等离子体宏观特性

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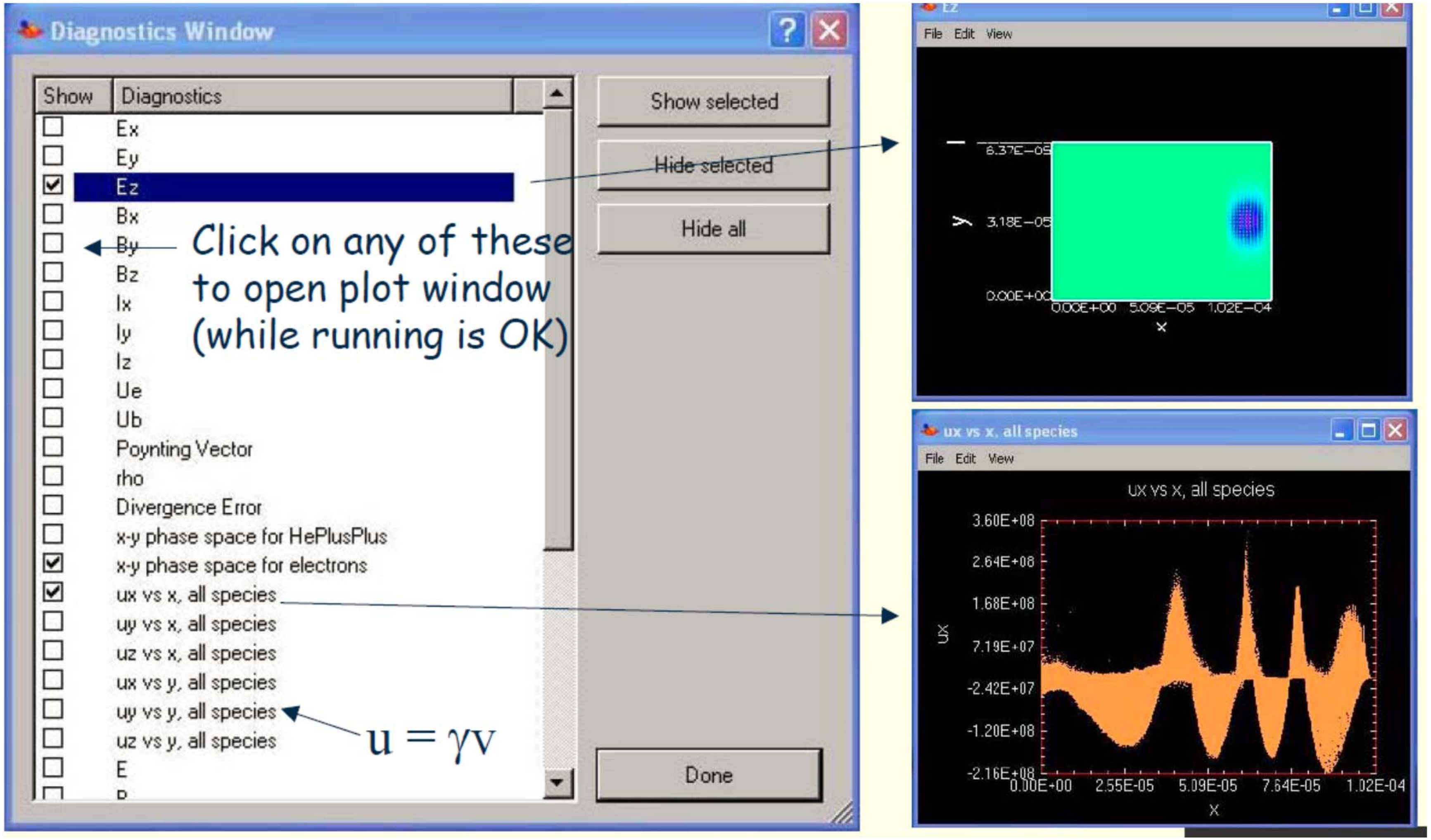

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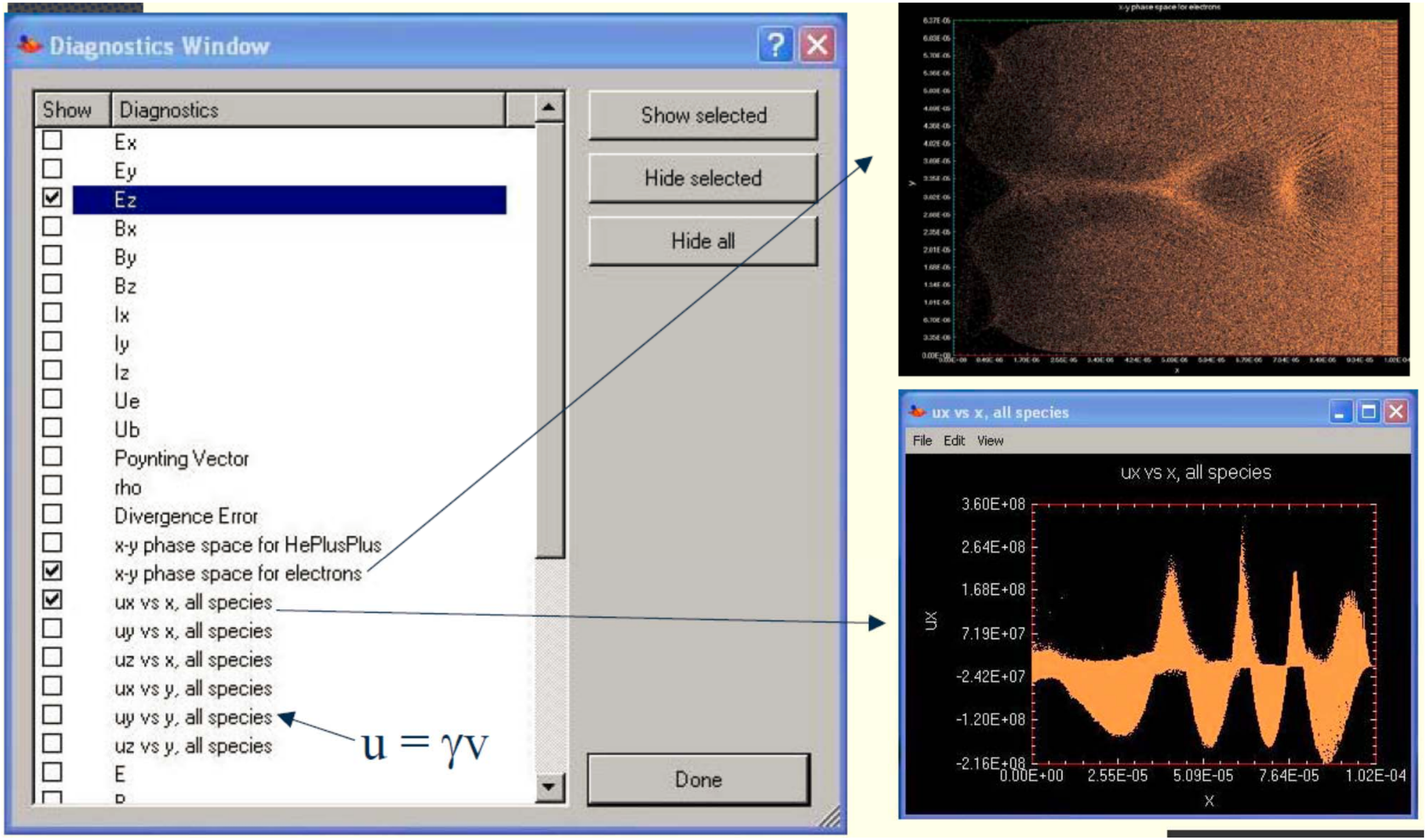

等离子体宏观特性

- OOPIC Pro简介

- 2D particle plots
  - Position (x_2 vs. x_1), velocity coords (u_i vs. x_j); also shows boundaries
- 2D vector plot
  - E, B, or I field directions and magnitudes
- 3D surface plot of scalar field component
  - E_i, B_i, I_i, U, charge density, number density …
- Time history of scalar diagnostic
  - Total and kinetic energy, rms beam parameters, number densities, or user-defined using `Diagnostic` block
- Updating in real time!

《等离子体电子学》

第三章 等离子体宏观特性

本章结束

下一章：气相和表面的基本过程

课件下载：ftp://202.117.18.164/incoming/PE_2015/

（在"幻灯片放映"模式中时单击该箭头）