Lecture 6:

Plasma Physics 1

APPH E6101x
Columbia University

Outline

- Collisions and mobility
  - Low-temperature plasma are “weakly” ionized
- Spitzer resistivity: “fully” ionized plasma
- Conductivity in a magnetized plasma
- (“Classical”) Diffusion of plasma and magnetic field

Electron-Impact Cross Sections for Ionization and Excitation Database

NIST Standard Reference Database 107

Last Update to Data Content: August 2004 | Version History | Disclaimer | **DOI:** https://dx.doi.org/10.18434/T4KK5C

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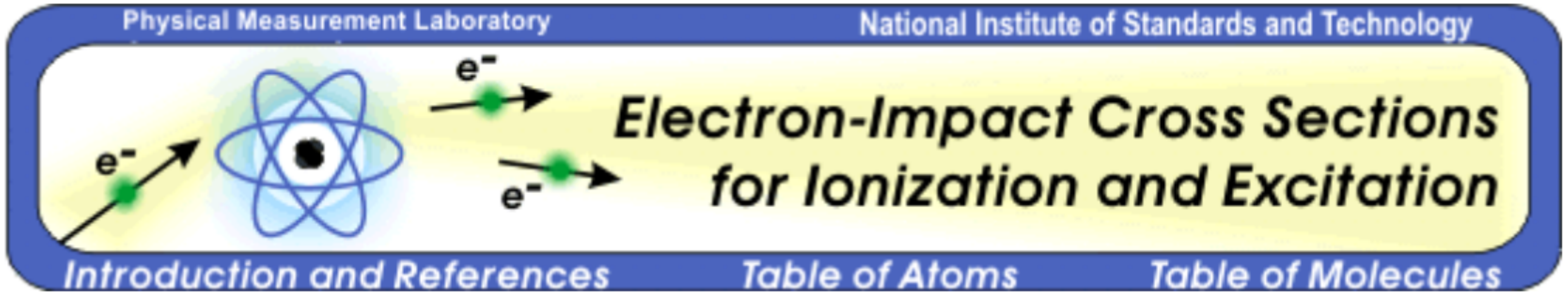
This is a database primarily of total ionization cross sections of molecules by electron impact. The database also includes cross sections for some atoms and energy distributions of ejected electrons for H, He, and H_2. The cross sections were calculated using the Binary-Encounter-Bethe (BEB) model, which combines the Mott cross section with the high-incident energy behavior of the



Holdings for Hydrogen

Symbol: H
Atomic Weight: 1.00794(7)
Ionization Energy: 13.5984 eV
Ground-state Configuration: 1s
Ground-state Level: $^{2}S_{1/2}$

Neutral	
Ionization	**Excitation**
Total Differential	1s -> 2p 1s -> 3p 1s -> 4p 1s -> 5p 1s -> 6p 1s -> 7p 1s -> 8p 1s -> 9p 1s -> 10p

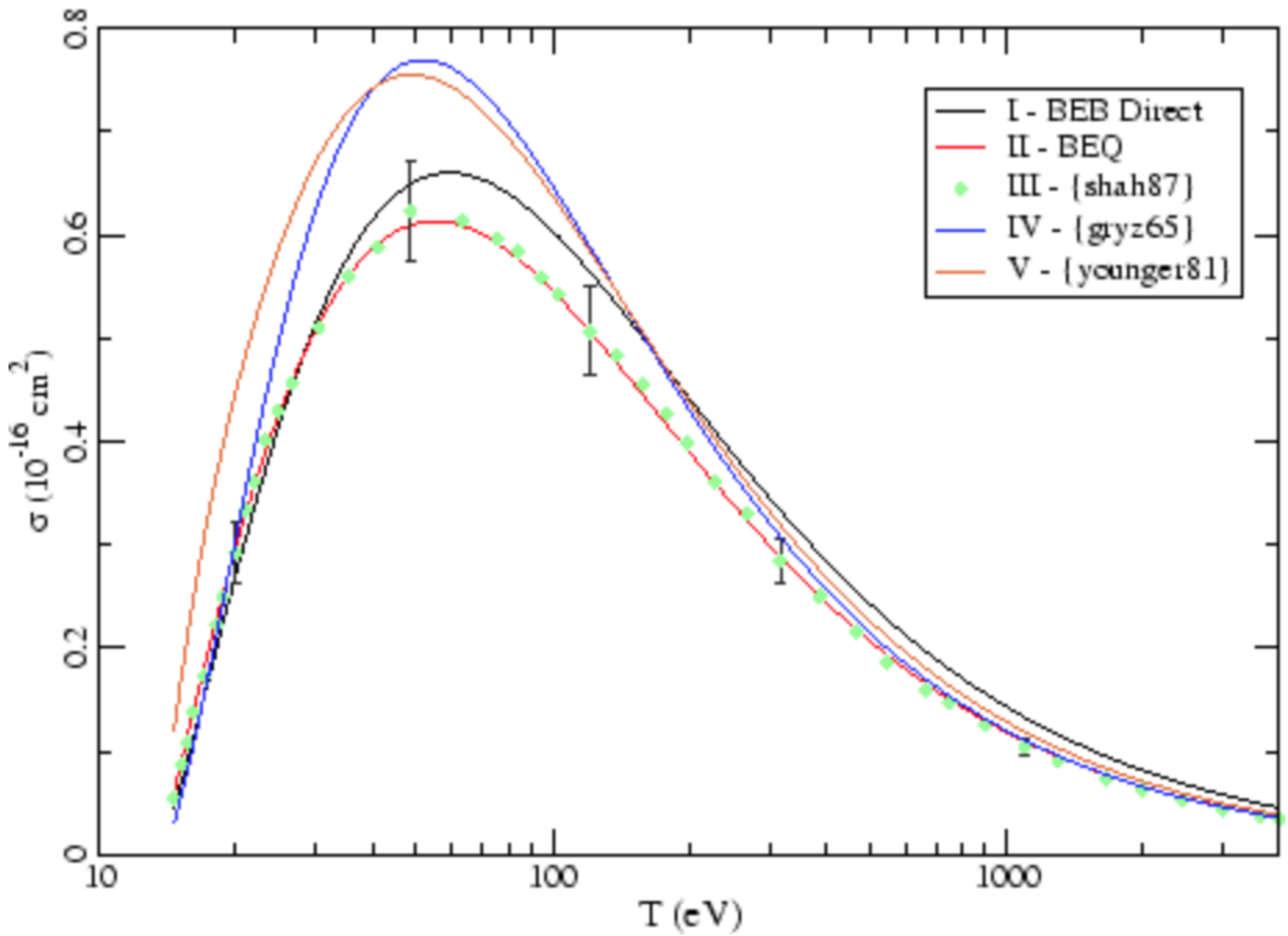
Excitation Energies (E) in eV	
Excitation	**E**
1s-2p	10.1988
1s-3p	12.0875
1s-4p	12.7485
1s-5p	13.0545
1s-6p	13.2207
1s-7p	13.3209
1s-8p	13.3860
1s-9p	13.4306
1s-10p	13.4625

Physical Measurement Laboratory | National Institute of Standards and Technology

Electron-Impact Ionization Cross Sections

Introduction and References | Table of Atoms | Table of Molecules

Neutral Hydrogen Total Ionization Cross-Section



Total Ionization Cross Section

Incident electron energy, **T** = ____ eV

Calculate Cross Section

I - BEB Direct II - BEQ	Y.-K. Kim and M.E. Rudd, Phys. Rev. A **50**, 3954 (1994).(T)
III - shah87	M. B. Shah, D. S. Elliott, and H. B. Gilbody, J. Phys B **20**, 3501 (1987).(E)
IV - gryz65	M. Gryzinski, Phys. Rev. **138**, A305, A322, A336 (1965).(T)
V - younger81	S. M. Younger, J. Quant. Spectrosc. Radiat. Transfer **26**, 329 (1981).(T)

Table of Ionization Cross Sections at Specific Energies (tab-delimited ASCII)

Atomic Orbital Constants for BEB Calculation of the Direct Cross Section

All cross sections are in $\mathbf{10^{-16}\ cm^2}$ unless otherwise specified.

Topic Areas

- Analytical Chemistry
- Atomic and Molecular Physics
- Biometrics
- Biotechnology
- Chemical and Crystal Structure
- Chemical Kinetics
- Chemistry
- Construction
- Environmental Data
- Fire
- Fluids
- International Trade
- Law Enforcement
- Materials Properties
- Mathematical Databases, Software and Tools

NIST Standard Reference Database 64

NIST Electron Elastic-Scattering Cross-Section Database: Version 3.2

No Charge.

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Version 3.2 of this databaseprovides values of differential elastic-scattering cross sections, totalelastic-scattering cross sections, phase shifts, and transport cross sectionsfor elements with atomic numbers from 1 to 96 and for electron energies between50 eV and 300 keV (in steps of 1 eV). The cross sections in the database were provided by Prof. F. Salvatusing relativistic theory.Knowledge ofelastic-scattering effects is important for the development of theoreticalmodels for quantitative analysis by AES, XPS, electron microprobe analysis, andanalytical electron microscopy. The software package is designed to facilitatesimulations of electron transport for these and similar applications in whichelectron energies from 50 eV to 300 keV are utilized. An analysis of availableelastic-scattering cross-section data has been published by A. Jablonski, F.Salvat, and C. J. Powell J. Phys. Chem. Ref. Data 33, 409 (2004)].

Following features:

- graphical display of differential elastic-scattering cross sections in different coordinate systems
- graphical display of the dependence of transport cross sections on electron energy

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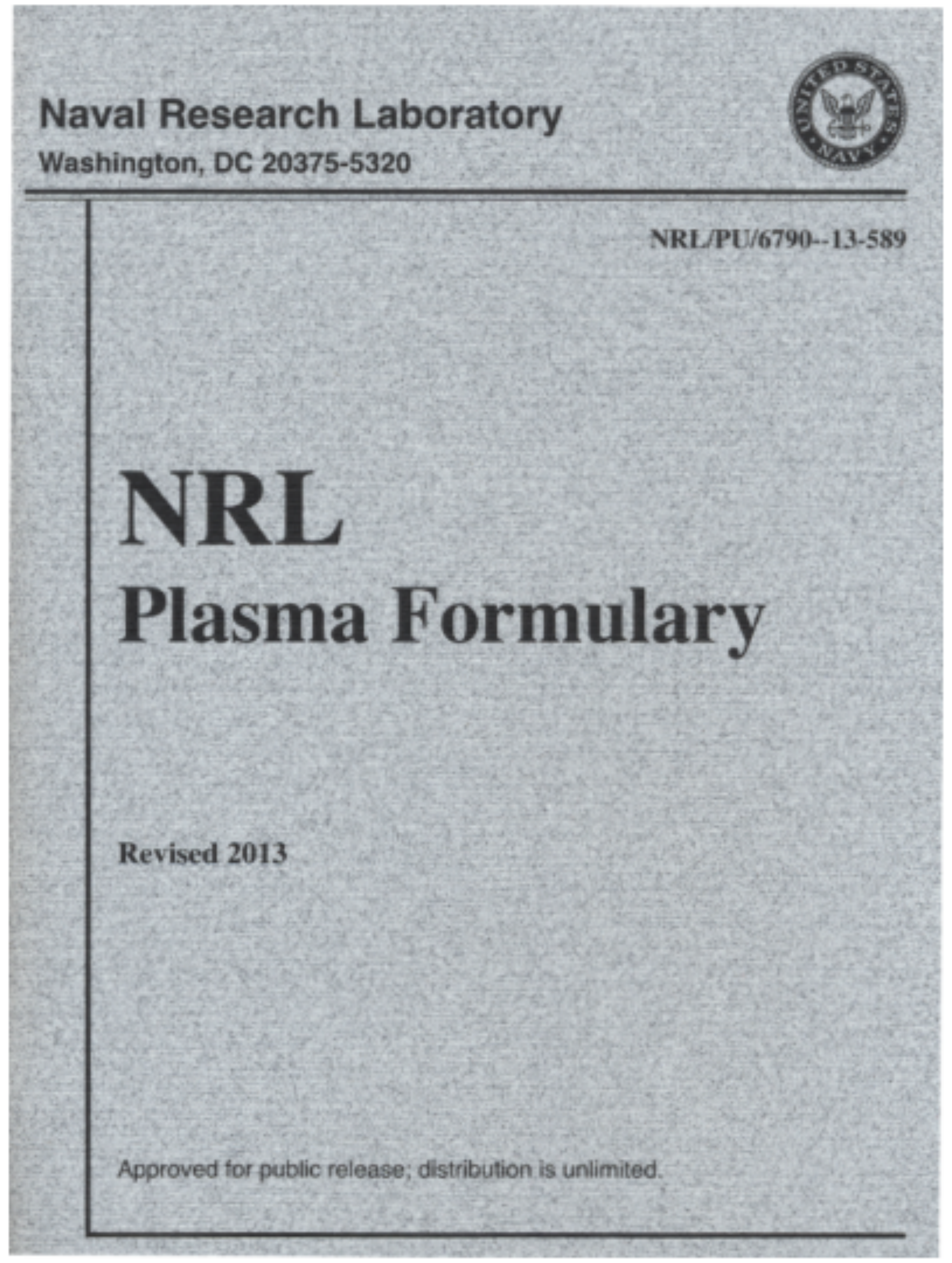


http://www.nrl.navy.mil/ppd/content/nrl-plasma-formulary

Weakly Ionized Plasmas

Collision frequency for scattering of charged particles of species α by neutrals is

$$\nu_\alpha = n_0 \sigma_s^{\alpha|0} (kT_\alpha/m_\alpha)^{1/2} \quad = V_{th}/\lambda_{mfp}$$

where n_0 is the neutral density and $\sigma_s^{\alpha\backslash 0}$ is the cross section, typically $\sim$ $5 \times 10^{-15}\ \mathrm{cm}^2$ and weakly dependent on temperature.

The elastic scattering of electrons on atoms is almost isotropic [68]. Therefore, on average, the electron loses its mean momentum $m_\mathrm{e}\bar{\mathbf{v}}_\mathrm{e}$ and we can write the equation of motion for an *average electron*

$$m\dot{\bar{v}} = -eE - m\bar{v}\nu_\mathrm{m}\,. \tag{4.25}$$

This average electron now moves in $-E$-direction. The quantity $\nu_\mathrm{m} = 1/\tau_\mathrm{coll}$ is the effective collision frequency for momentum transfer.

$$v_{\mathrm{d}} = -\frac{e}{m\nu_{\mathrm{m}}}E = -\mu_{\mathrm{e}}E$$

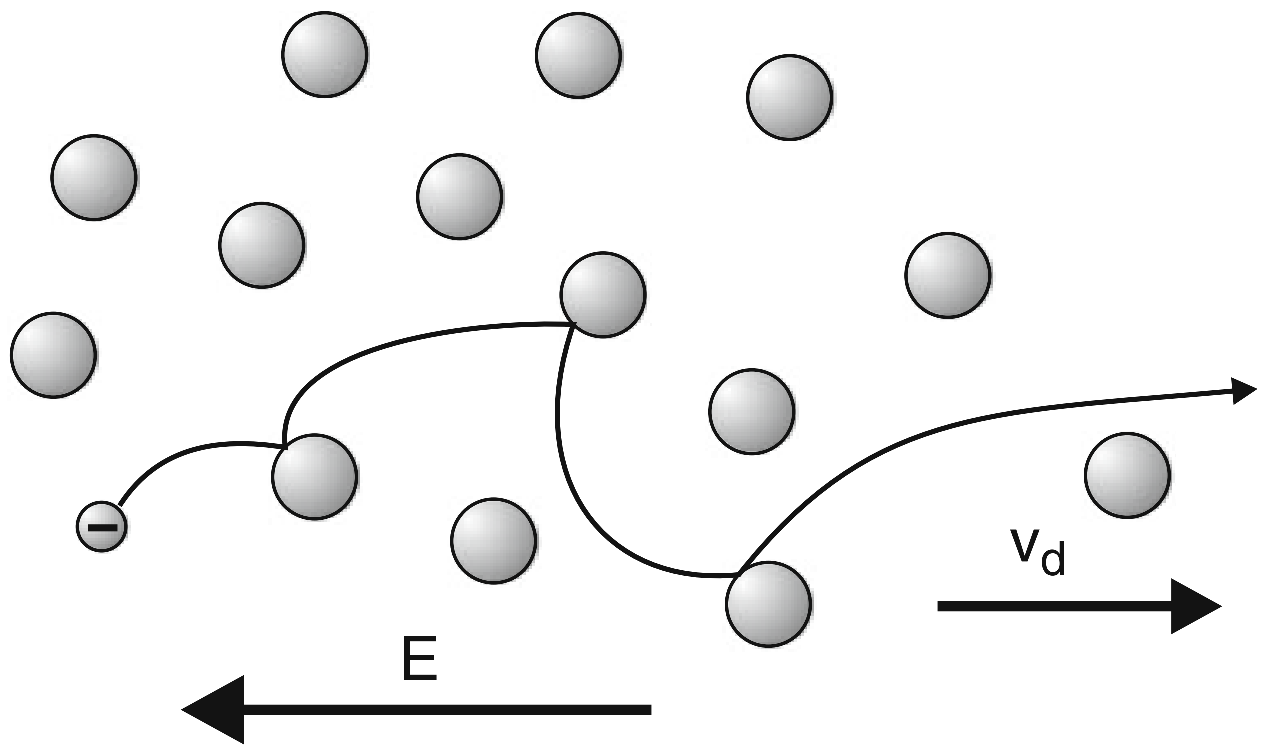
The mobilities of electrons and ions are defined as

$$\mu_{\mathrm{e}} = \frac{e}{m_{\mathrm{e}}\nu_{\mathrm{m,e}}} \quad ; \quad \mu_{\mathrm{i}} = \frac{e}{m_{\mathrm{i}}\nu_{\mathrm{m,i}}} \, .$$

Electrical Conductivity

$$j = j_{\mathrm{e}} + j_{\mathrm{i}} = n[(-e)v_{\mathrm{de}} + e v_{\mathrm{di}}] = ne(\mu_{\mathrm{e}} + \mu_{\mathrm{i}})E = \sigma E$$

$$\sigma_{\mathrm{e,i}} = ne\mu_{\mathrm{e,i}} = \frac{ne^2}{m_{\mathrm{e,i}}\nu_{\mathrm{m}}}$$

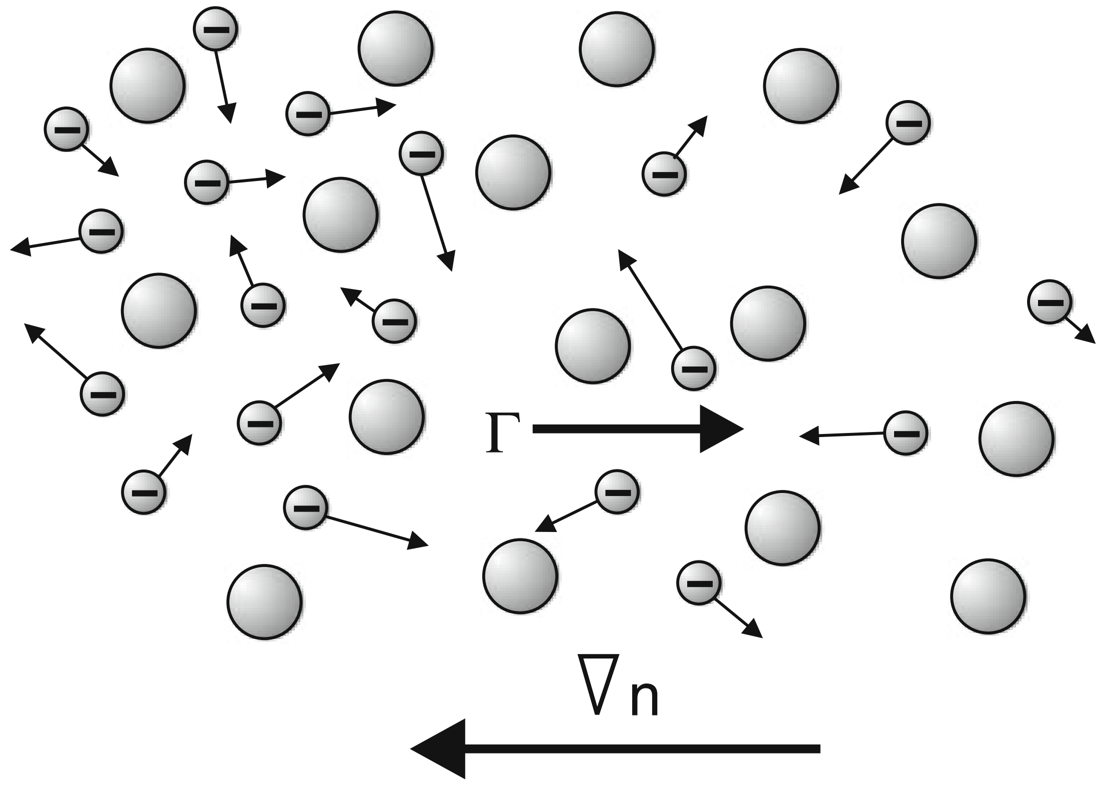


Collisional Diffusion

$$\boldsymbol{\Gamma}_{\mathrm{e,i}} = n_{\mathrm{e,i}}\bar{\mathbf{v}}_{\mathrm{e,i}} = -D\nabla n_{\mathrm{e,i}}$$

$$\frac{D}{\mu} = \frac{k_{\mathrm{B}}T}{e} \qquad \mu_{\mathrm{e}} = \frac{e}{m_{\mathrm{e}}\nu_{\mathrm{m,e}}}$$

$$D = V_{th}^2/\nu_m = \lambda_{mfp}^2/\tau_m$$



Einstein relation is an unexpected result of Brownian motion from 1904-5.

PHYSICAL REVIEW VOLUME 89, NUMBER 5 MARCH 1, 1953

Fully Ionized Plasma

Transport Phenomena in a Completely Ionized Gas*

LYMAN SPITZER, JR., AND RICHARD HÄRM
Princeton University Observatory, Princeton, New Jersey

(Received November 10, 1952)

The coefficients of electrical and thermal conductivity have been computed for completely ionized gases with a wide variety of mean ionic charges. The effect of mutual electron encounters is considered as a problem of diffusion in velocity space, taking into account a term which previously had been neglected. The appropriate integro-differential equations are then solved numerically. The resultant conductivities are very close to the less extensive results obtained with the higher approximations on the Chapman-Cowling method, provided the Debye shielding distance is used as the cutoff in summing the effects of two-body encounters.

$$\eta_S = \frac{\pi e^2 m_e^{1/2}}{(4\pi\varepsilon_0)^2 (k_B T)^{3/2}} \ln \Lambda$$

Log $[12\pi N_D]$
Plasma parameter

$\eta_{\parallel} = \frac{1}{2}\eta_{\perp}$

transverse Spitzer resistivity

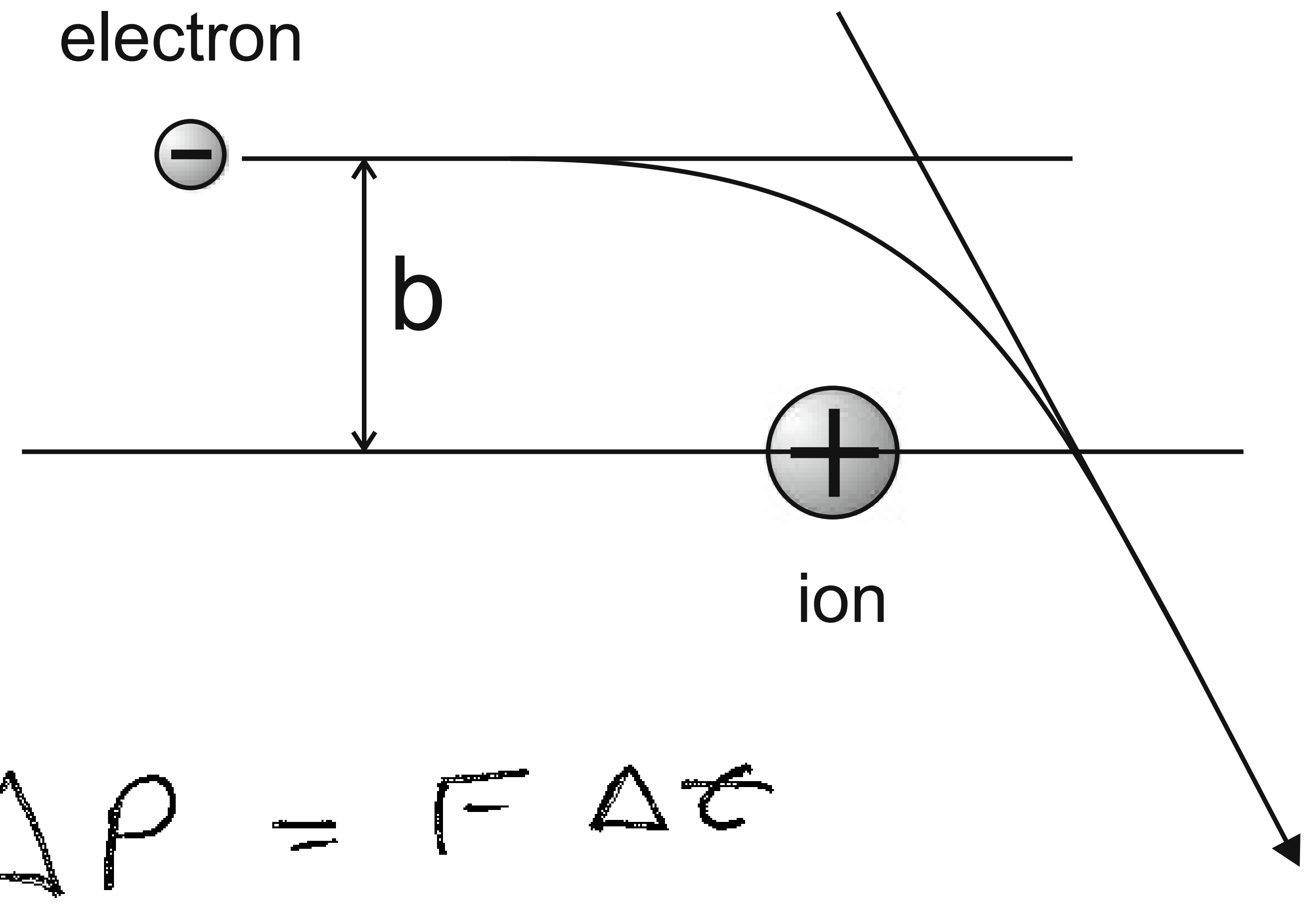
$$\eta_{\perp} = 1.15 \times 10^{-14} Z \ln \Lambda T^{-3/2} \text{ sec}$$
$$= 1.03 \times 10^{-2} Z \ln \Lambda T^{-3/2}\ \Omega\,\text{cm}$$

electrical conductivities

$$\sigma_{\|} = 1.96\sigma_{\perp};\ \sigma_{\perp} = ne^2\tau_e/m_e$$

$\nu_m = \frac{1}{\tau_m}$

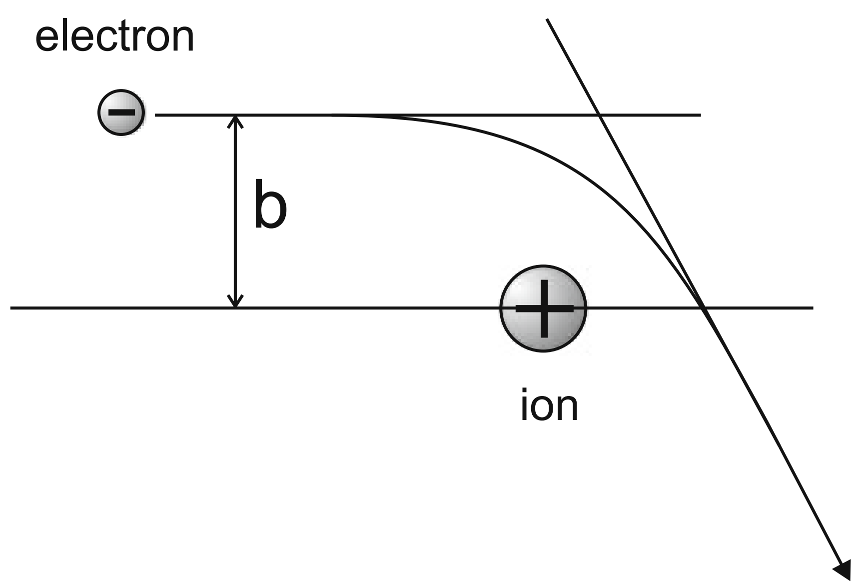
Coulomb Collisions



$\Delta p = F \Delta t$

$$m_e v = \frac{e^2}{4\pi\varepsilon_0 b^2}\left(\frac{b}{v}\right)$$

Coulomb Collisions



$$m_e v = \frac{e^2}{4\pi\varepsilon_0 b^2}\left(\frac{b}{v}\right)$$

$$\nu_{ei} = n\sigma_{\pi/2} v = \frac{ne^4}{16\pi\varepsilon_0^2 m_e^2 v^3}$$

× Log λ

Coulomb Log.

BUT THE RUTHERFORD SCATTERING CROSS SECTION/RATE DIVERGES FOR SMALL (MANY) ANGLE COLLISIONS

$$\Delta\theta_{min} \sim \frac{e^2}{m V_{th}^2 \lambda_D}$$

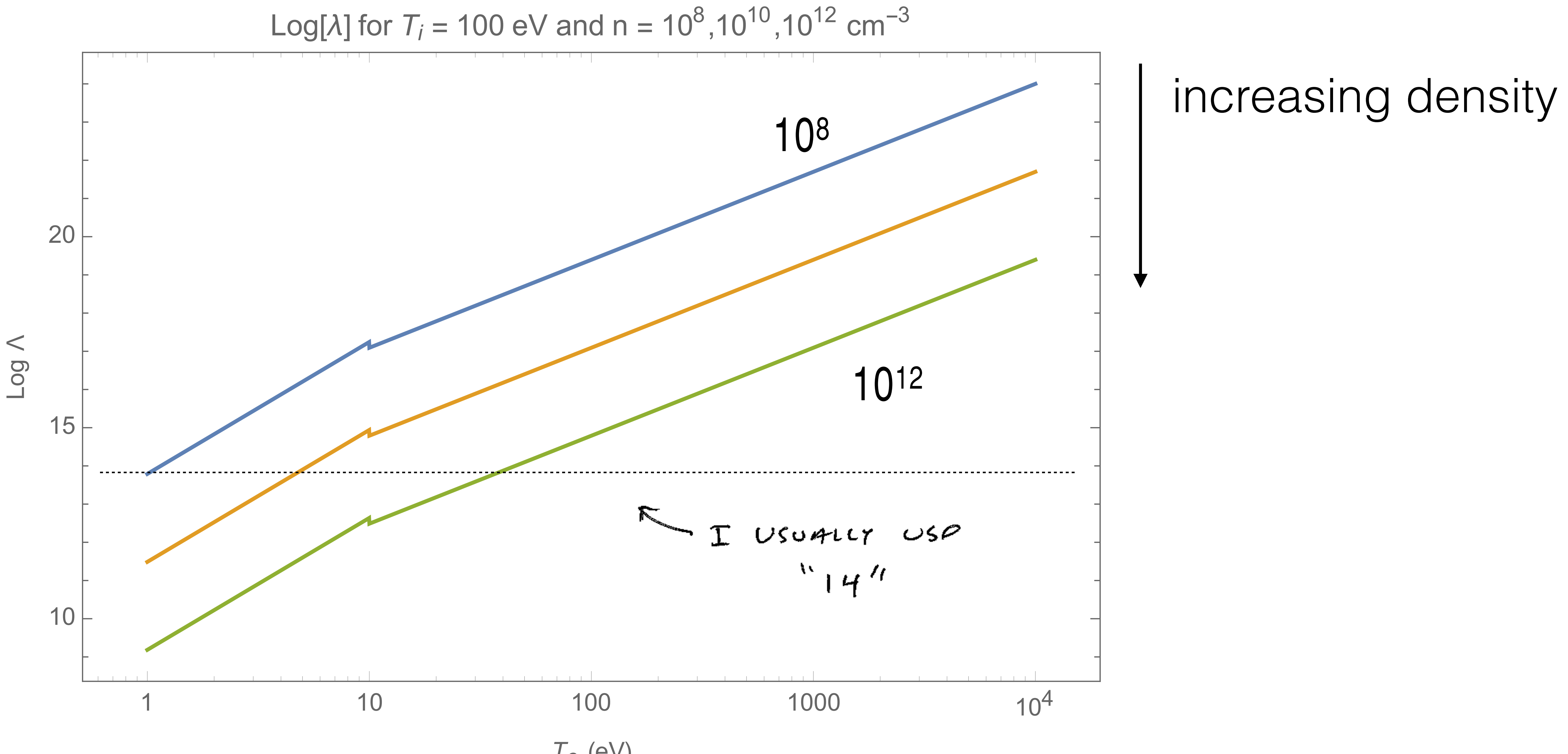
Coulomb Logarithm

(b) Electron–ion collisions

$$\lambda_{ei} = \lambda_{ie} = 23 - \ln\left({n_e}^{1/2} Z T_e^{-3/2}\right), \qquad T_i m_e/m_i < T_e < 10Z^2 \text{ eV};$$

$$= 24 - \ln\left({n_e}^{1/2} T_e^{-1}\right), \qquad T_i m_e/m_i < 10Z^2 \text{ eV} < T_e$$

$$= 30 - \ln\left({n_i}^{1/2} {T_i}^{-3/2} Z^2 \mu^{-1}\right), \qquad T_e < T_i Z m_e/m_i.$$

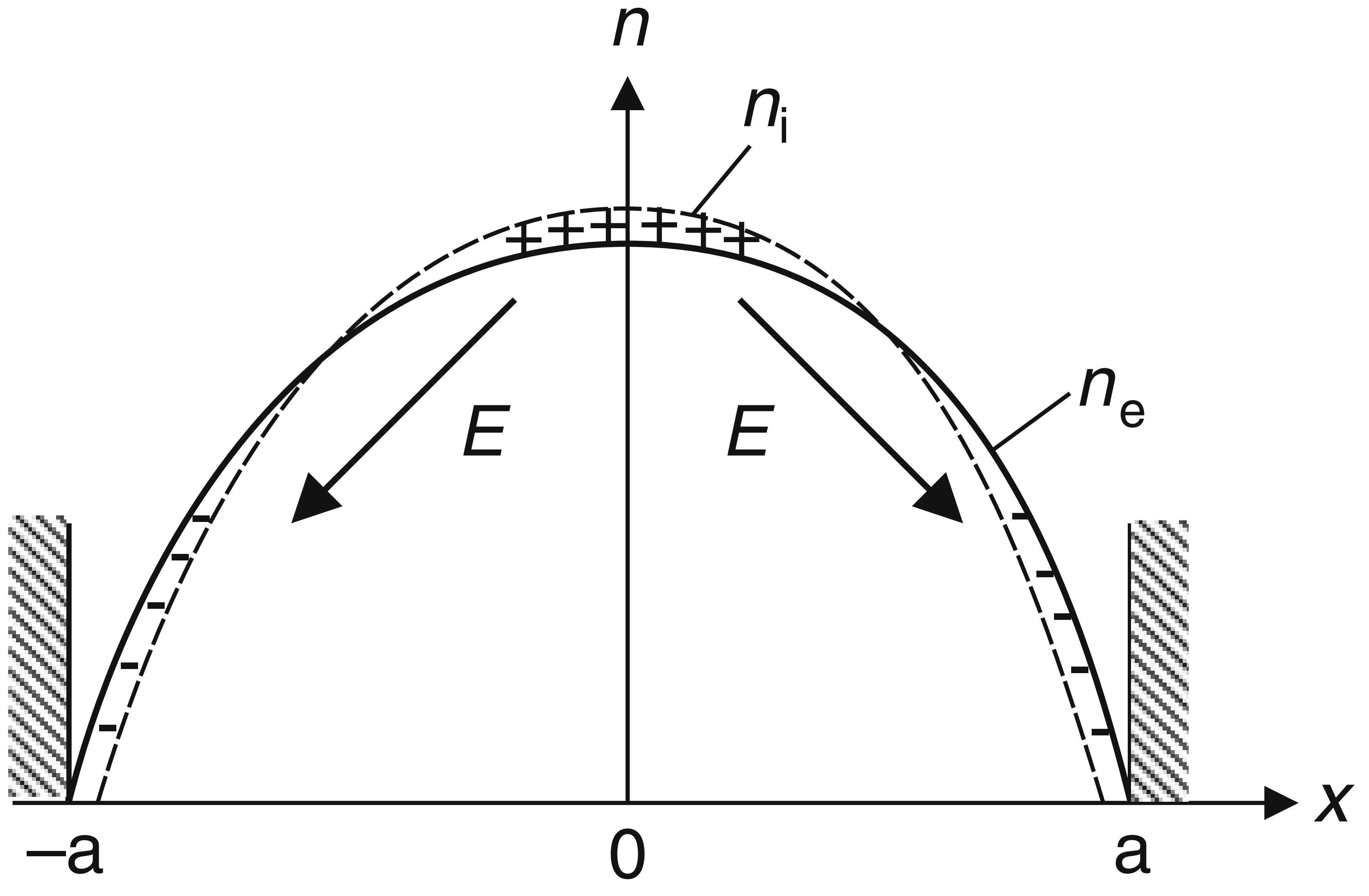


Ambipolar Diffusion

$$\mu_e = \frac{e}{m_e \nu_{m,e}} \quad ; \quad \mu_i = \frac{e}{m_i \nu_{m,i}}$$

$$\boldsymbol{\Gamma}_{e,i} = \pm n \mu_{e,i} \mathbf{E} - D_{e,i} \nabla n$$

$$\frac{D}{\mu} = \frac{k_B T}{e}$$



$$\Gamma_e = \Gamma_i$$

$$-n\mu_e E - D_e \nabla n = n\mu_i E - D_i \nabla n$$

OR

$$E = -\frac{1}{n} \nabla n \left(\frac{D_e - D_i}{\mu_e + \mu_i} \right)$$

$$\approx -\frac{kT}{e} \frac{\nabla n}{n}$$

$$= +\mu_e \left(\frac{D_e - D_i}{\mu_e + \mu_i} \right) \nabla n - D_e \nabla n$$

$$= -\left[\frac{D_e \mu_i}{\mu_e + \mu_i} + \frac{\mu_e D_i}{\mu_e + \mu_i} \right] \nabla n$$

$$\simeq -\left[2 D_i \right] \nabla n$$

Collisional Drift Velocity in (E,B) Field

$$\bar{J} = q n \bar{v} = \bar{\bar{\sigma}} \cdot \bar{E}$$

FIND AVERAGE DRIFT WITH STATIC
E, B AND COLLISIONS

$$\left.\begin{aligned} \frac{d\bar{v}}{dt} \simeq 0 &\simeq \frac{q}{m}\bar{E} + \omega_c \bar{V}_\perp \times \hat{b} - \nu_m \bar{V}_\perp \\ 0 &\simeq \frac{q}{m}\bar{E} \times \bar{B} - \omega_c \bar{V}_\perp B - \nu_m \bar{V}_\perp \times \bar{B} \end{aligned}\right\} \perp B$$

$$\left. 0 \simeq \frac{q}{m} E_\parallel - \nu_m V_\parallel \right\} \parallel B$$

$$\bar{V}_\perp - \left(\frac{\omega_c}{\nu_m}\right) \bar{V}_\perp \times \hat{b} = \frac{q}{m\nu_m} \bar{E}_\perp$$

$$\left(\frac{\omega_c}{\nu_m}\right)^2 \left[\bar{V}_\perp + \left(\frac{\nu_m}{\omega_c}\right) \bar{V}_\perp \times \hat{b} = \frac{q}{m\nu_m} \frac{\bar{E} \times \hat{b}}{\omega_c} \right]$$

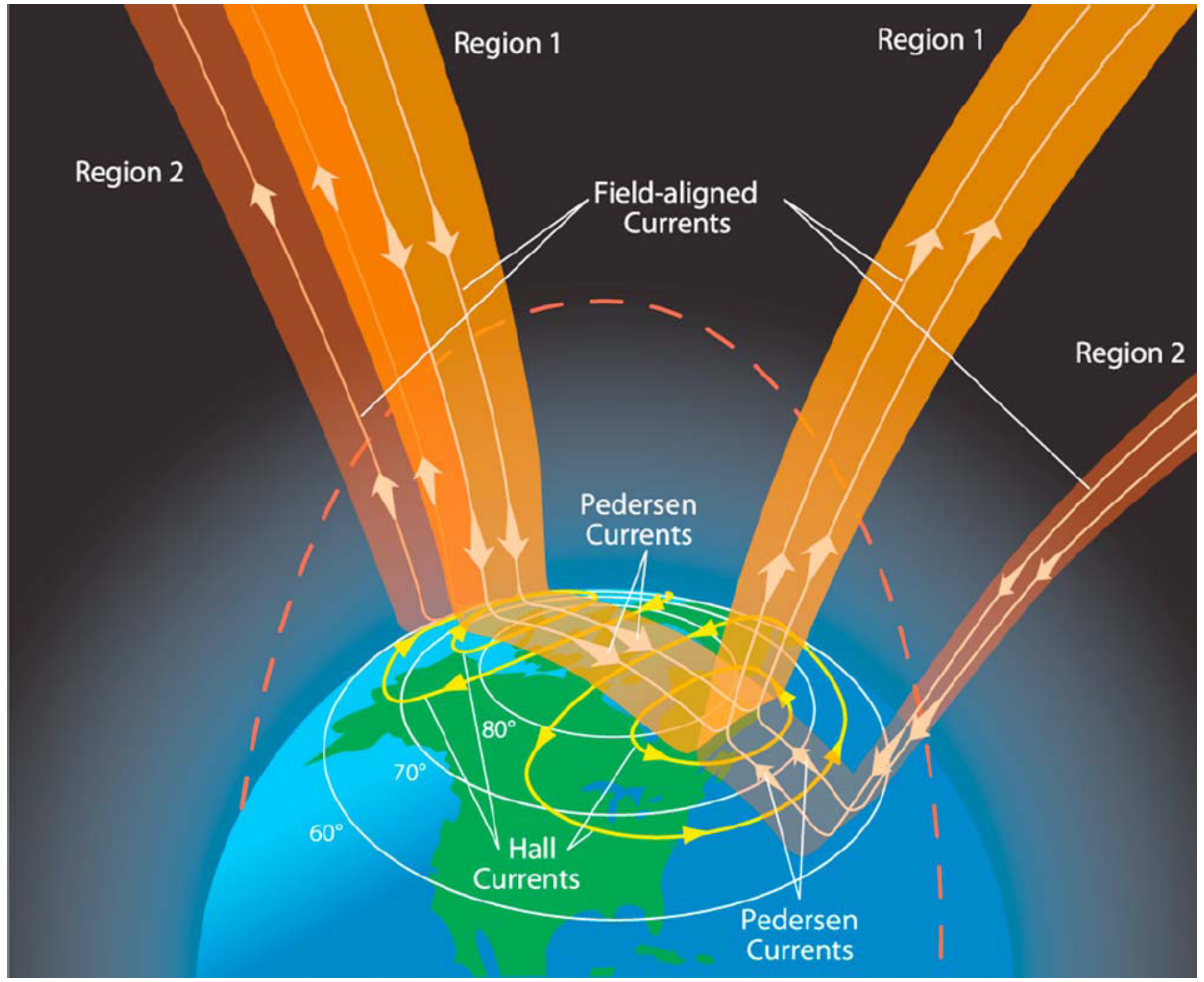
$$\left(1 + \left(\frac{\omega_c}{\nu_m}\right)^2\right) \bar{V}_\perp = \frac{q}{m\nu_m} \bar{E}_\perp + \frac{q}{m\nu_m} \left(\frac{\omega_c}{\nu_m}\right) \bar{E}_\perp \times \hat{b}$$

$$\left\{ V_\perp = \frac{q}{m\nu_m} \begin{pmatrix} \frac{1}{1 + \left(\frac{\omega_c}{\nu_m}\right)^2} & \frac{\frac{\omega_c}{\nu_m}}{1 + \left(\frac{\omega_c}{\nu_m}\right)} \\ \frac{-\omega_c/\nu_m}{(\ )} & \frac{1}{1 + (\ )} \end{pmatrix} \cdot \bar{E}_\perp \right.$$

QED

Conductivity in a Magnetized Plasma

1879 EDWIN HALL
(PHD DISSERTATION)



Pedersen — Hall

$$\begin{pmatrix} j_x \\ j_y \\ j_z \end{pmatrix} = \sigma_i \begin{pmatrix} \frac{1}{1+(\omega_{ci}/\nu_{m,i})^2} & \frac{\omega_{ci}/\nu_{m,i}}{1+(\omega_{ci}/\nu_{m,i})^2} & 0 \\ \frac{-\omega_{ci}/\nu_{m,i}}{1+(\omega_{ci}/\nu_{m,i})^2} & \frac{1}{1+(\omega_{ci}/\nu_{m,i})^2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}$$

$\sigma_i = \frac{q^2 n}{m \nu_m}$

$\omega_c = \frac{qB}{m}$

$\nu_m = v_{TH}/\lambda_{mfp}$

UNMAGNETIZED $\omega_{ci} \ll \nu_m$, $\lambda_{mfp} \ll \rho_c$

$$\bar{J} = \sigma \begin{pmatrix} 1 & \frac{\omega_{ci}}{\nu_m} & 0 \\ -\frac{\omega_c}{\nu_m} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

← SMALL

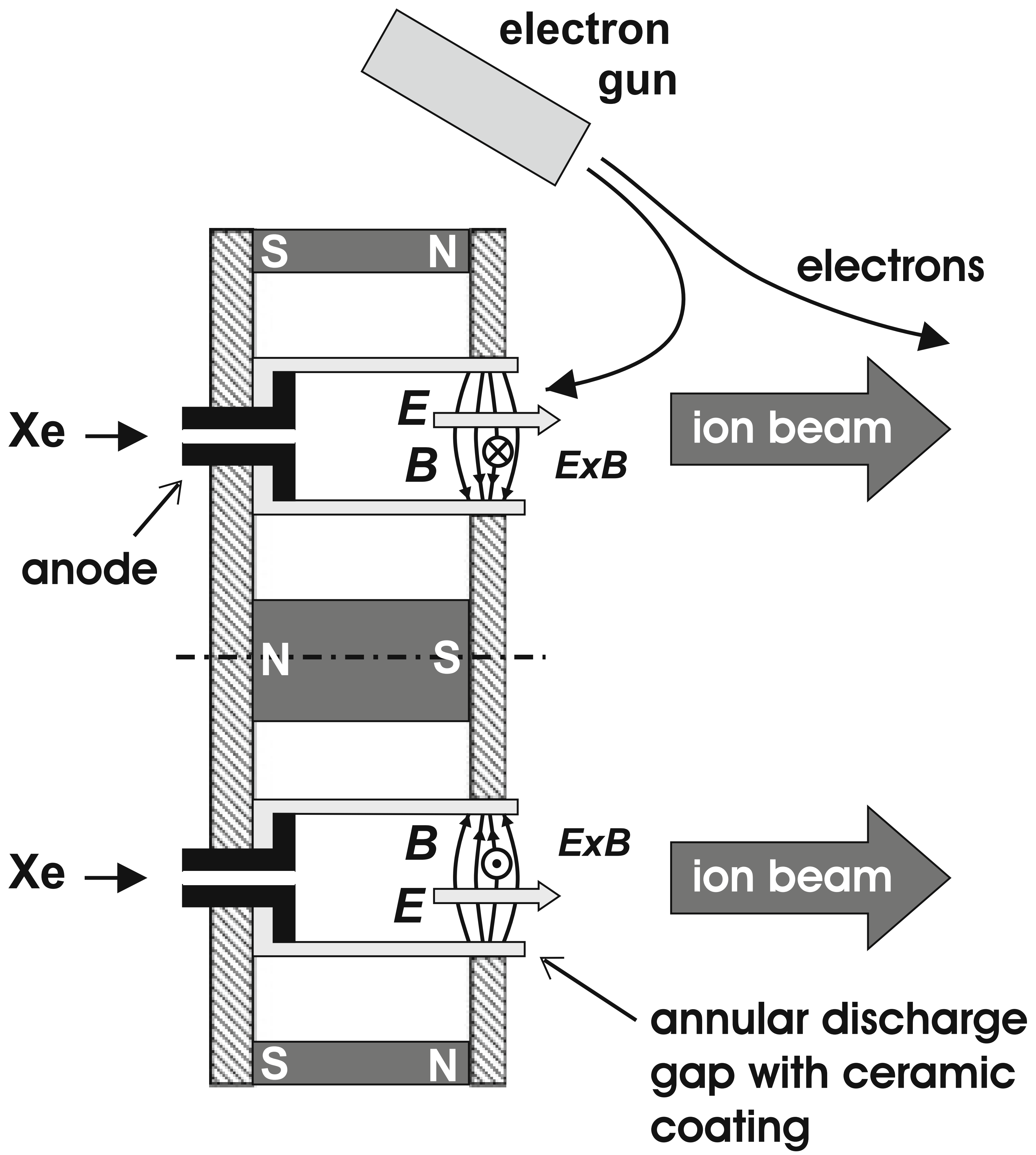
MAGNETIZED $\omega_{ci} \gg \nu_m$, $\lambda_{mfp} \gg \rho_c$

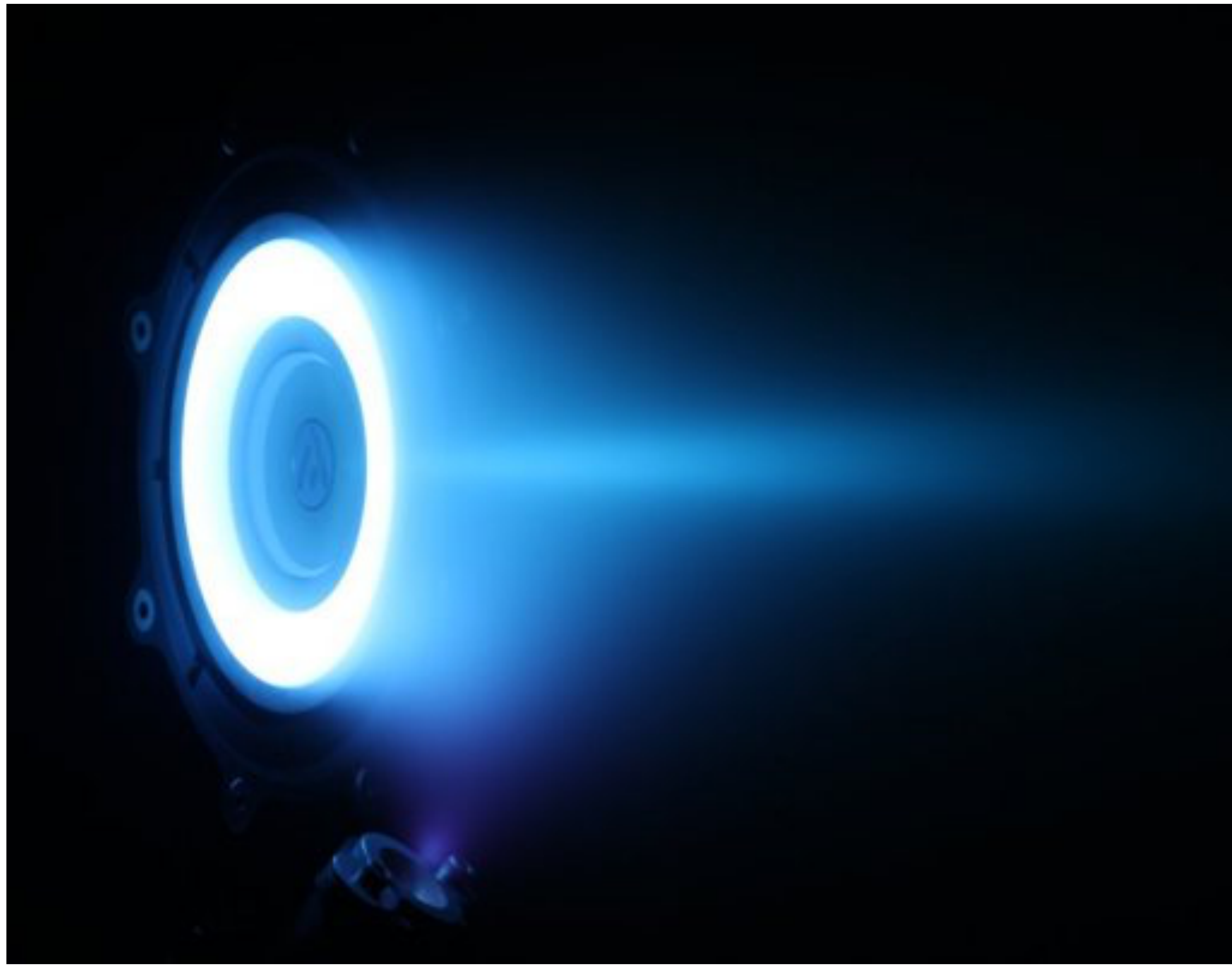
$$\bar{J} = \sigma \begin{pmatrix} 0 & \frac{\nu_m}{\omega_{ci}} & 0 \\ -\frac{\nu_m}{\omega_{ci}} & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\frac{\nu_m \sigma}{\omega_c} = qn\left(\frac{1}{B}\right)$ $(E \times B)$

Hall Effect Thruster

Fig. 4.17 Hall-effect plasma thruster. The plasma channel of the SPT100ML thruster has 69 and 100 mm inner and outer diameter, and 25 mm length. The mean radial magnetic field is $B_r = 160\,\mathrm{mT}$. The discharge is operated at $U_d = 300\,\mathrm{V}$ and $I_d = 4.2\,\mathrm{A}$, giving a thrust of 80 mN. (Reprinted from [69] with permission. © 2004, IOP Publishing Ltd.)





Ohm's Law (Part 1)

$$\bar{J} = \bar{J}_i + \bar{J}_e = en(\bar{V}_i - \bar{V}_e)$$

e^-: $0 \simeq -en\bar{E} - en\bar{V}_e \times \bar{B} - m_e n \nu_{ei} \bar{V}_e$

e^+: $0 \simeq +en\bar{E} + en\bar{V}_i \times \bar{B} - M_i n \nu_{ie} \bar{V}_i$

STATIC FORCE BALANCE NO ACCELERATION

ADD: $0 \simeq en(\bar{V}_i - \bar{V}_e)\times\bar{B} - n(M_i \nu_{io}\bar{V}_i + m_e \nu_{eo}\bar{V}_e)$

$0 \simeq \bar{J} \times \bar{B}$ (NO FORCE) — NO NET MOMENTUM

REALLY $\nabla p = J \times B$

SUBTRACT: $0 \simeq 2en\bar{E} + en((\bar{V}_i + \bar{V}_e)\times\bar{B}) - n[M_i \nu_{io}\bar{V}_i - m_e \nu_{ei}\bar{V}_e]$

$\simeq 2en\bar{E} + 2en\bar{V}_\perp \times \bar{B} - \frac{M_i \nu_{io}}{e}\bar{J} - n\bar{V}_e[M_i \nu_{ie} - m_e \nu_{ei}]$, with $n\bar{V}_e[M_i \nu_{ie} - m_e \nu_{ei}] \simeq 0$

$0 \simeq E_\perp \times V_\perp \times \bar{B} - \frac{M_i \nu_{io}}{2en}\bar{J}_\perp$

$$\bar{E} + \bar{V} \times \bar{B} \simeq \eta_\perp \bar{J}$$

Ohm's Law

("Classical") Transport in a Magnetized Plasma

$$\bar{E} + \bar{v} \times \bar{B} = \eta \bar{J}$$

$$\nabla \times \bar{E} = -\frac{\partial B}{\partial t}$$

$$\nabla \times B = \mu \bar{J}$$

$$\nabla \times (\eta J - v \times B) = -\frac{\partial \bar{B}}{\partial t}$$

$$-\nabla \times \left(\frac{\eta}{\mu_0} \nabla \times \bar{B}\right) + \nabla \times (\bar{v} \times \bar{B}) = \frac{\partial \bar{B}}{\partial t}$$

OR

$$\frac{\partial \bar{B}}{\partial t} \doteq \left(\frac{\eta}{\mu_0}\right) \nabla^2 \bar{B}$$

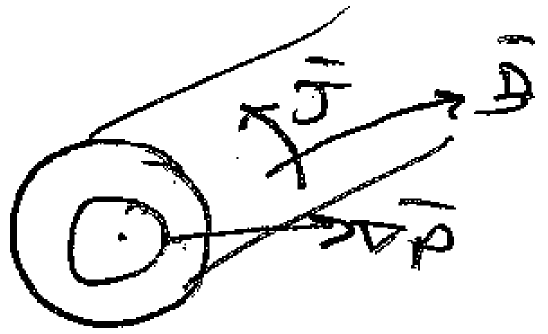
$$D_m = \frac{\eta}{\mu_0}$$

CONCLUSION:
PARTICLES DIFFUSE MORE SLOWLY THAN MAGNETIC FIELD

$$\frac{\partial n}{\partial t} + \nabla \cdot n\bar{v} = 0$$

$$V_\perp = \frac{\eta}{B^2} \bar{J} \times \bar{B} + \frac{\bar{E} \times \bar{B}}{B^2}$$

COLLISIONAL FRICTION



$$\frac{\partial n}{\partial t} + \nabla \cdot \left(\frac{n}{(B^2/\mu_0)} \frac{\eta}{\mu_0} J \times B\right) = 0$$

∇p

$\simeq 2kT \nabla n$

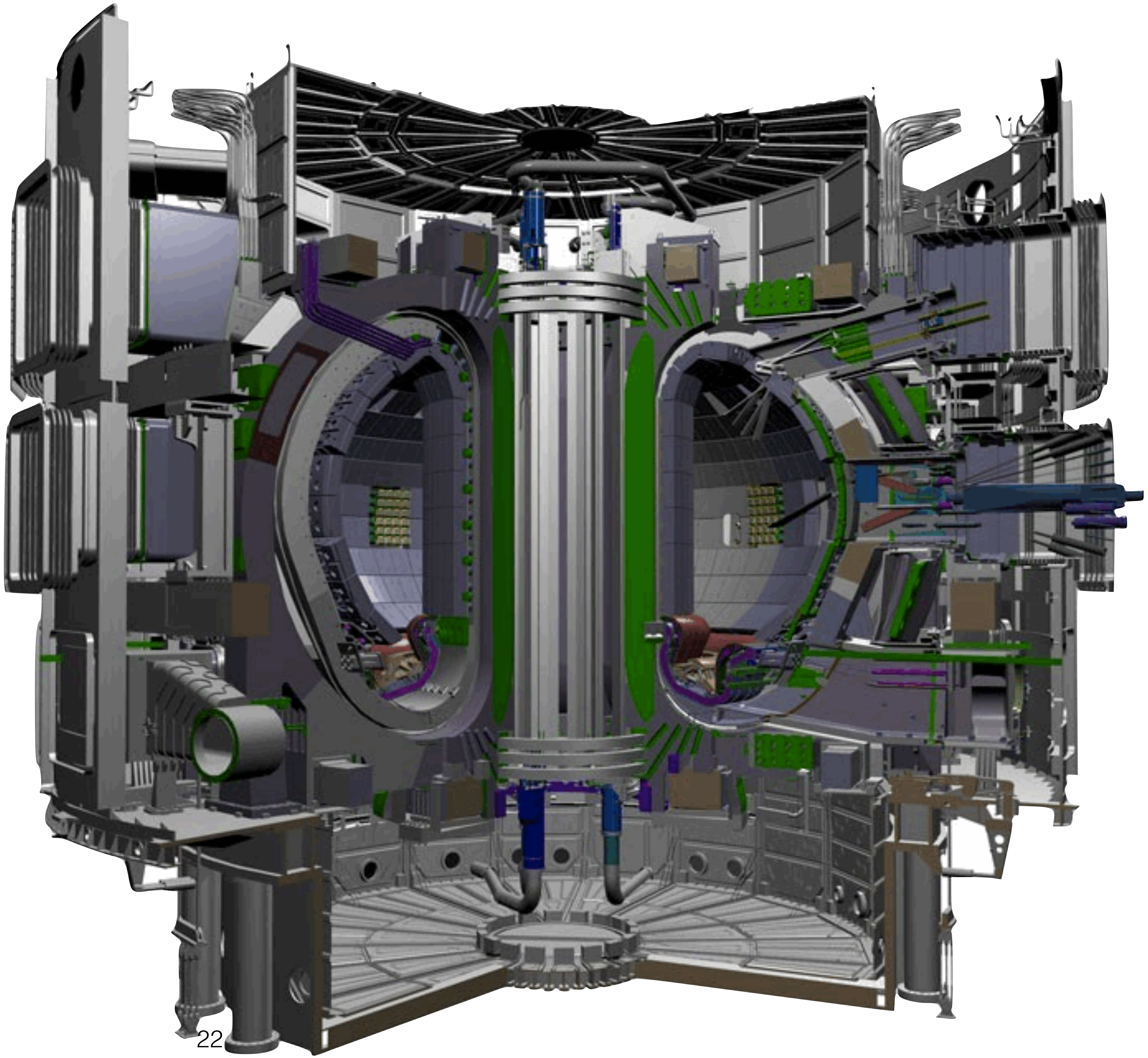
$$\frac{\partial n}{\partial t} + \nabla \cdot \frac{nkT}{(B^2/2\mu_0)} \frac{\eta}{\mu_0} \nabla n = 0$$

$$D_p \sim \frac{1}{2} \beta D_m$$

$$\beta \simeq \frac{2nkT}{B^2/2\mu_0}$$

http://www.iter.org/

- Culmination of 50 years of magnetic fusion research
- 500 MW fusion power for 7 min pulses
- EU, Japan, Russia, China, S Korea, India, USA
- *At least* 22B US$ (14B US$ official), the most ambitious international science project ever
- 23,000 tons (tokamak only), or $1M/ton



$$\mathcal{P}_{\text{Fusion}} \sim 0.08 P^2 \ (\text{MW}\,\text{m}^{-3})$$

P(plasma) = 3 n k T = 4.3 atm

n = 1.0E20 m^3

T = 9 keV

pFusion = 1.5 MW/m^3

B = 5.3 T

P(mag) = 110 atm

β = 4.3/110 ~ 3.9%

τ = 3.7 s

a ~ 2.5 m

Thousands faster than "classical"

Fusion Gain & Ignition

$$\mathrm{D} + \mathrm{T} \longrightarrow \mathrm{He}^4(3.5\,\mathrm{MeV}) + \mathrm{n}(14.1\,\mathrm{MeV})$$

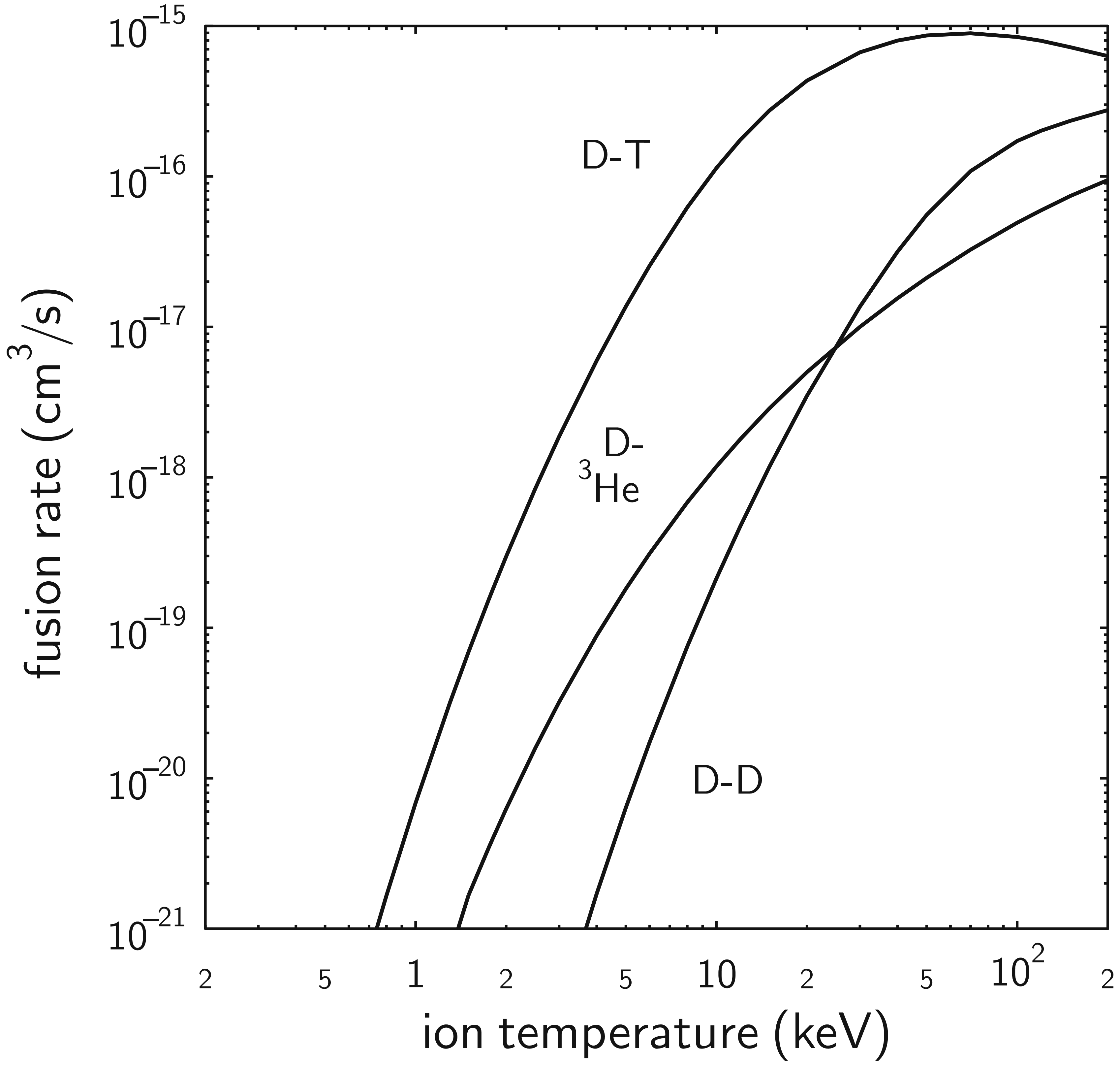
For low energies ($T \lesssim 25\,\mathrm{keV}$) the data may be represented by

$$(\overline{\sigma v})_{DD} = 2.33 \times 10^{-14} T^{-2/3} \exp(-18.76 T^{-1/3})\ \mathrm{cm}^3\ \mathrm{sec}^{-1}$$

$$(\overline{\sigma v})_{DT} = 3.68 \times 10^{-12} T^{-2/3} \exp(-19.94 T^{-1/3})\ \mathrm{cm}^3\ \mathrm{sec}^{-1}$$

where T is measured in keV.

NOTE! <6U> FUNCTION OF T ONLY



Fusion Ignition

$$\mathrm{D} + \mathrm{T} \longrightarrow \mathrm{He}^4(3.5\,\mathrm{MeV}) + \mathrm{n}(14.1\,\mathrm{MeV})$$

$$P_{DT} = 5.6 \times 10^{-13} n_D n_T (\overline{\sigma v})_{DT}\ \mathrm{watt\,cm}^{-3}$$

$n_e^2/4$

Bremsstrahlung from hydrogen-like plasma:[26]

$Z_{EFF} N =$

(30) $$P_{\mathrm{Br}} = 1.69 \times 10^{-32} N_e {T_e}^{1/2} \sum \left[Z^2 N(Z)\right]\ \mathrm{watt/cm}^3$$

where the sum is over all ionization states Z.

$P_{BR} \sim n_e^2 \sqrt{T}\, Z_{EFF}$

Ignition

$P_{atm}\tau_E > 10$ atm · sec
for fusion gain > 10

$f_\alpha P_{FUS} - P_{BR} = 0$
@ T = 5.32 KeV
For D-T

$Q \rightarrow \infty$

$$f_\alpha P_{fus} + Paux = \frac{W}{\tau_E} + P_{brem} + P_{rad}$$

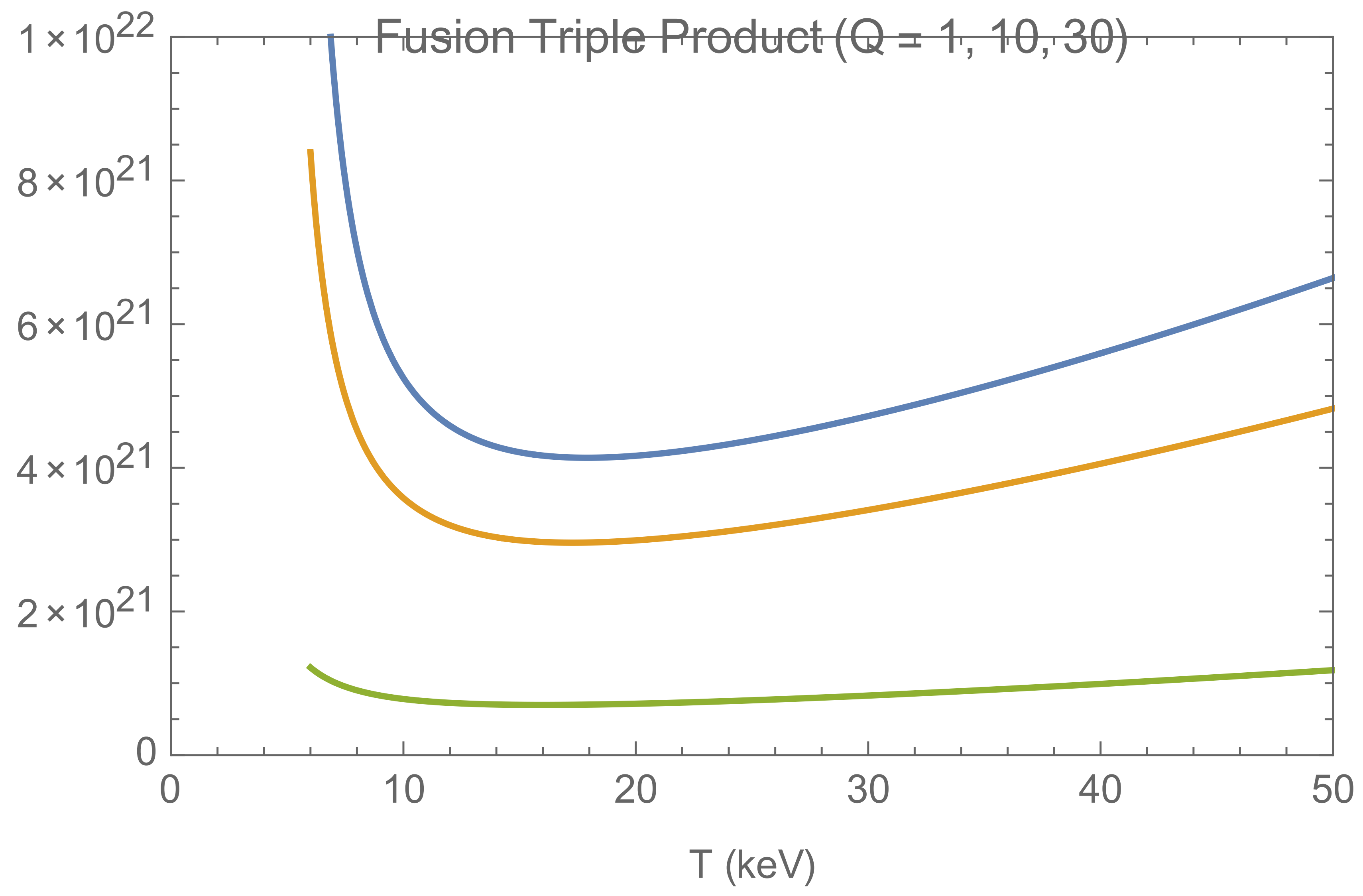
$$Q \equiv \frac{P_{fus}}{P_{aux}}$$

$$P_{fus} \propto P_{brem} \propto P_{rad} \propto n^2$$

$$nT\tau_E = \frac{3\,T^2\,n^2}{(f_\alpha + 1/Q)\,P_{fus} - P_{brem} - P_{rad}}$$

← FUNCTION OF T ONLY

$T_{MIN} \sim 5.32$ KeV ($Z_{EFF} = 1.5$)



but…
Classical Confinement does not describe Magnetized Fusion Plasma

$$D = \beta\,(\eta/\mu_0)$$

$$T = 9\ \text{keV}$$

$$\eta \sim 1.7\text{E-}9\ \text{Ohm-m}$$

$$\eta/\mu_0 \sim 0.001\ \text{m}^2/\text{s}$$

$$\tau \sim 4\,a^2/D \sim 700{,}000\ \text{sec}$$

Homework #4 (Ch. 4)

- Fitzpatrick: Read Chapter 3 about collisions, and discuss the meaning of “Rosenbluth Potentials” and the collision operator in Eq. 3.112
- Piel: All nine problems in Ch. 4 (answers in back of text)

Wednesday's Lecture: "Virtual"

(Prof. Mauel is away at a conference)

- Piel / Chapter 5: "Fluid" Equations
- and the equations describing the large-scale dynamics of plasma