Sensors
Plasma Diagnostics

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NRL Formulary
MIT Formulary

www.psfc.mit.edu/library1/catalog/reports/2010/11rr/11rr013/11rr013_full.pdf

Lectures will be posted on Canvas and on my website.

Topics-Plasma physics

- Introduction to plasma physics and its applications
- Macroscopic measurements
- Probes and sheaths
- Wave propagation/Interferometry
- Laser scattering
- Radiation from free electrons/Electron cyclotron emission
- Atomic physics relevant to plasmas
- Plasma spectroscopy
- Particle measurements
- Digital signal processing

General reference-<u>Principles of plasma diagnostics</u> by Ian Hutchinson (1987) Cambridge University Press

Plasmas

- A plasma is a gas of charged particles -- Generally ionized atoms

  Gas: potential energy of a typical particle due to its nearest neighbor is much smaller than its kinetic energy (Compared with condensed matter).
- Fourth state of matter -- Classical gas but E-M dominated
  - Binding energies
  - 99% of known universe (25% of total mass) is in plasma state
- Usually consider plasmas to be quasi-neutral

  $n_e \sim Zn_i$ (or sum over ion mixture, both positive and negative if present)
- How would you tell difference between a hot gas and plasma?
- What is the difference in interparticle forces in gas and plasmas?
- Conceptual simplicity belies complex phenomenology:
  many dimensionless parameters; few useful approximations

First Plasma Parameter

- Kinetic energy* 3kT/2 >> Mean potential energy* $\frac{e^2}{4\pi\varepsilon_o n^{-1/3}}$

$$6\pi \frac{\varepsilon_o T n^{-1/3}}{e^2} >> 1$$

In plasma physics, T is always kT
Energy units generally **eV**

- Conventional dimensionless form to 3/2 power as

$$n\left(\frac{\varepsilon_o T}{ne^2}\right)^{3/2} (6\pi)^{3/2} >> 1 \qquad \lambda_D \equiv \sqrt{\frac{\varepsilon_o T}{ne^2}}$$

where constants in Debye length λ_D from elsewhere

- First dimensionless parameter is number of particles in Debye sphere

$$\Lambda_D = \frac{4}{3}\pi n \lambda_D^3 >> 1$$

- Thus Λ_D>>1 ~ Thermal energy >> Coulomb potential energy
"Collisionless"

* We shall generally use SI units, but the plasma literature is varied

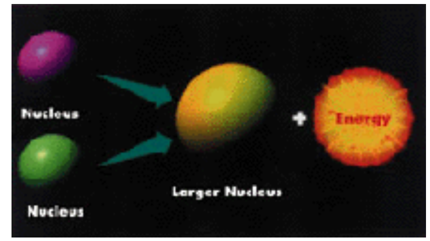
Applications of plasma physics
Fusion

$$^{2}D+^{2}D\Rightarrow^{3}He+^{1}n+3.27\,MeV$$

$$^{2}D+^{2}D\Rightarrow^{3}H+^{1}H+4.03\,MeV$$

$$^{2}D+^{3}T\Rightarrow^{4}He+^{1}n+17.58\,MeV$$

$$^{2}D+^{3}He\Rightarrow^{4}He+^{1}H+18.34\,MeV$$

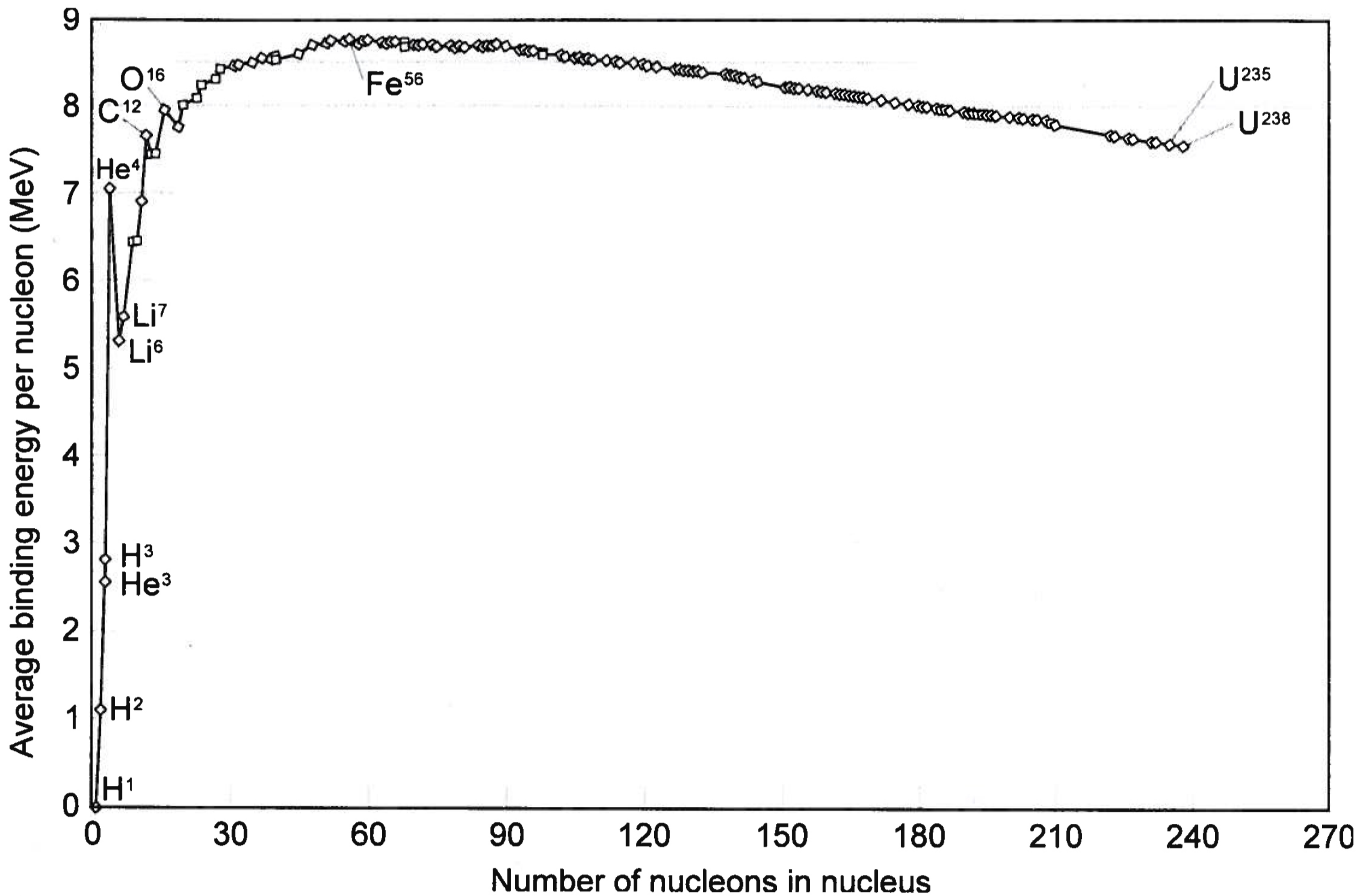


- Lawson criteria
  - Power out > power in
  - Ignition-plasma temperature is sustained by α particle heating
  - Fusion power generated > power loss rate

$$\kappa n^{2} > \frac{nT}{\tau_E} \quad \Rightarrow \quad n\tau_E > constant$$

$$n\tau_E > 1.5\times 10^{20}\ m^{-3}\,s$$

Binding energy



Applications of plasma physics
Plasma processing of materials

Industrial applications

Etching in fabricating chips

Surface treatment for improved film adhesion

Plasma nitriding to harden surface of steel

Plasma enhanced chemical vapor deposition-deposit thin film

Plasma spray deposition of ceramic or metal alloys

Plasma welding and cutting

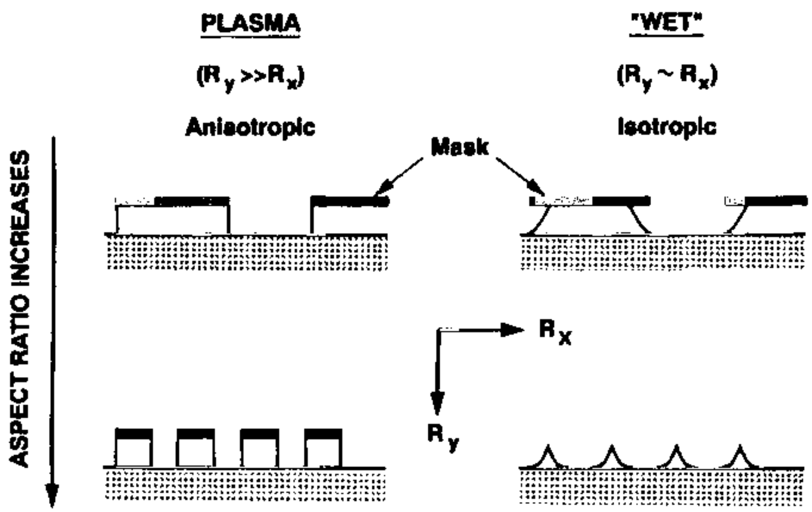
Plasma melting and refining of alloys

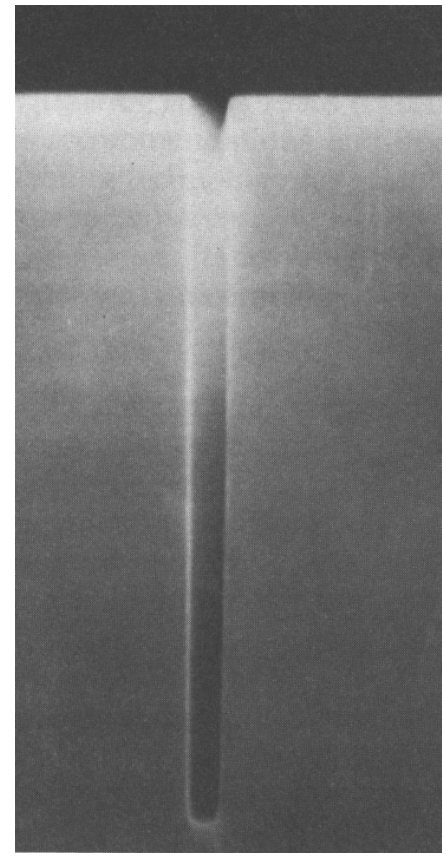
Plasma sputter deposition of magnetic films for memory

Create nanoparticles

Plasma TV

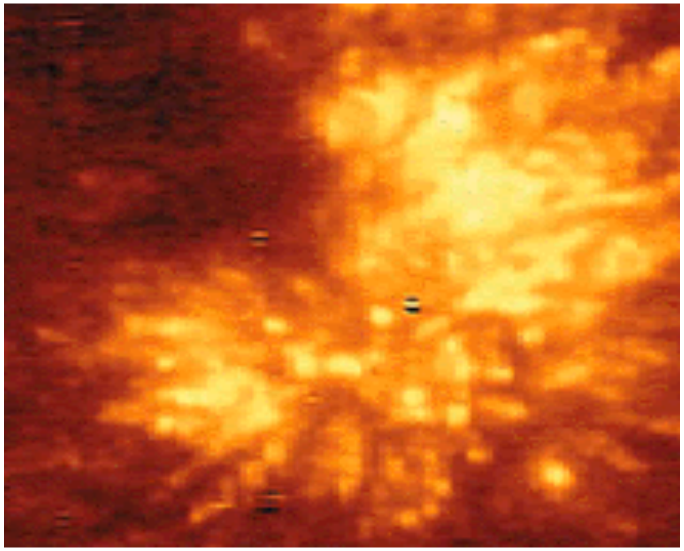
Plasma processing

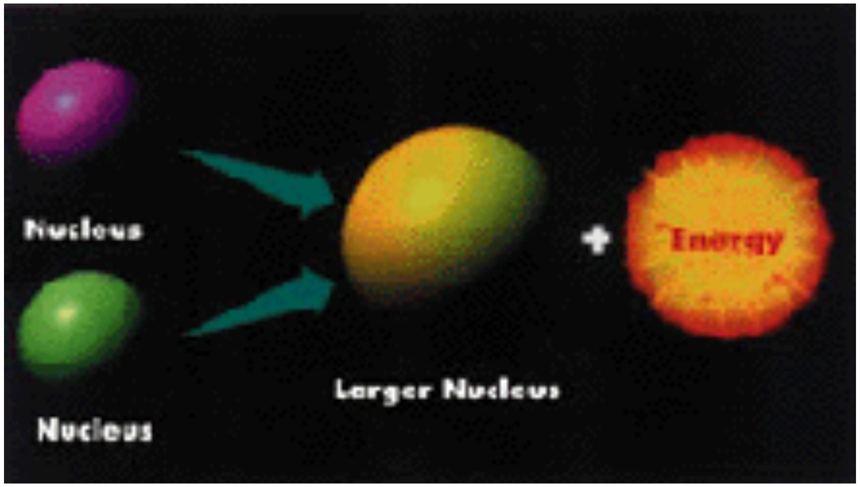


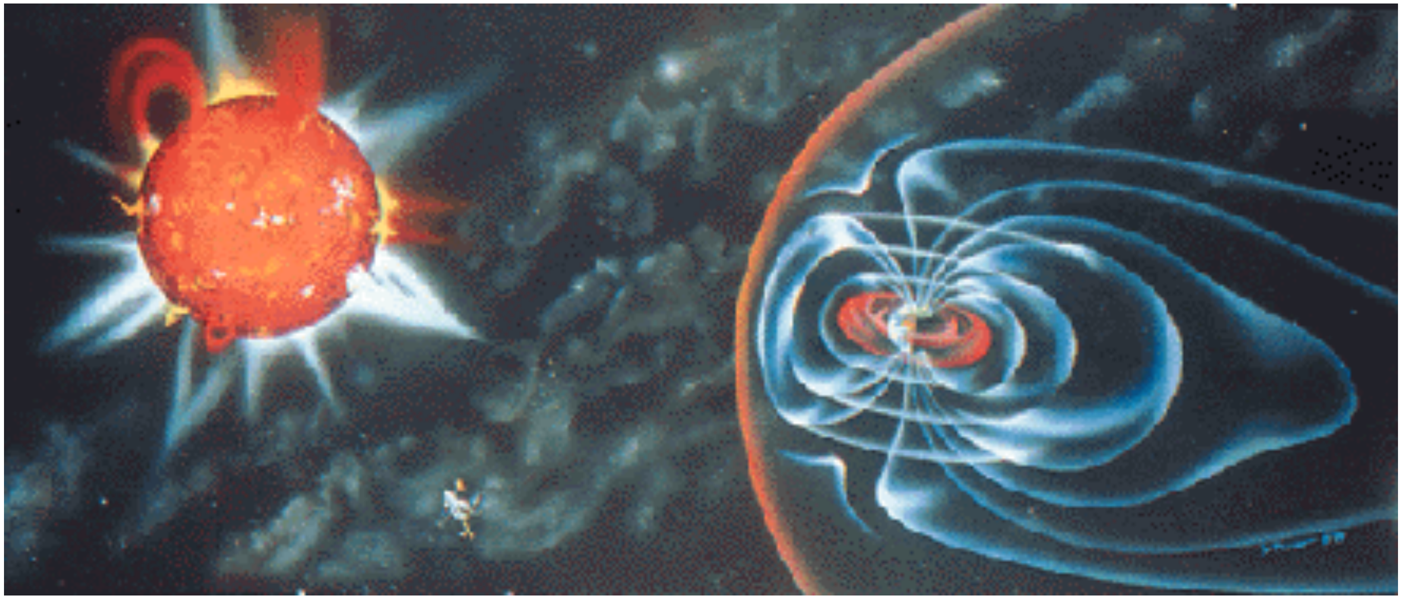


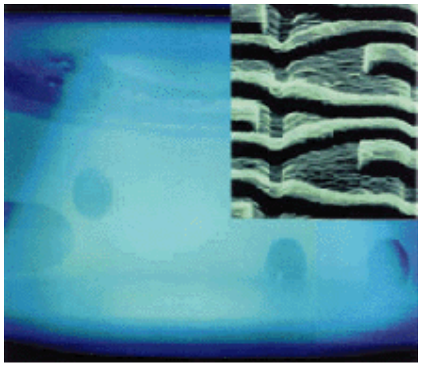
Applications of plasma physics

- Space propulsion
- Industrial applications
  - Lighting
  - Cleaning
- Radiation sources

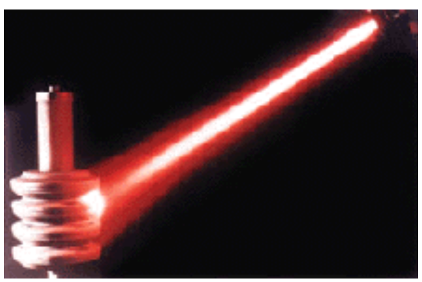



Nucleus
Nucleus
Larger Nucleus
+
Energy

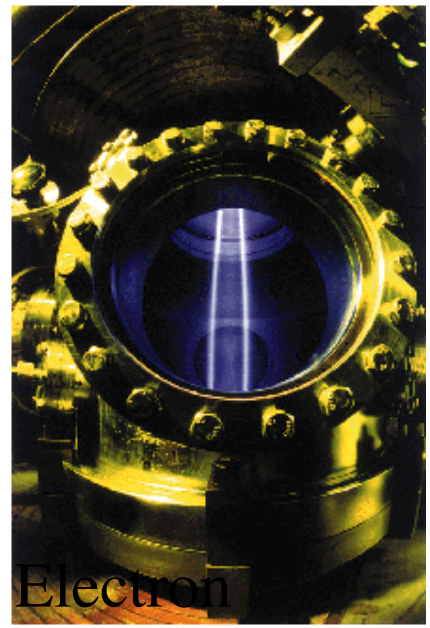




Plasma etching



Plasma spray torches



Electron cyclotron resonance

Description of a plasma

- Collection of single, free charges

  (Most basic model, useful as first approximation for interaction with EM waves)
- Fluid (MagnetoHydroDynamics)
- Two-fluid -- Ion and electron fluids separately
- Kinetic -- Modified Boltzmann Equation for each species

$$\left[\frac{\partial}{\partial t} + \mathbf{v} \bullet \nabla + \frac{q}{m}\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right) \bullet \nabla_v \right] f(\mathbf{r}, \mathbf{v}, t) = \frac{\partial f}{\partial t}\Big|_{coll}$$

- Bewildering combinations of fluid and kinetic (e.g. fluid ions with kinetic electrons, etc. or fluid equations with kinetic corrections, etc.)

A Characteristic Time -- Plasma frequency

- Many ways to obtain the expression
- Use standard method to calculate dielectric constant of matter as in every advanced EM text
- Calculate $\varepsilon(\omega)$ assuming electrons bound in harmonic wells
- Plasma is limit with k=0 or $\omega >>$ all ω_o

$$m\frac{dv}{dt} = i\omega m v = eE \qquad v = \frac{e}{i\omega m}E \qquad j = nev$$

$$\nabla \times B = \mu_o\left(j + \varepsilon_o\frac{dE}{dt}\right) \qquad E = \frac{1}{i\omega}\frac{dE}{dt}$$

$$\nabla \times B = \mu_o\left(\frac{ne^2}{-m\omega^2\varepsilon_o} + 1\right)\varepsilon_o\frac{dE}{dt}$$

$$\varepsilon \equiv \left(1 - \frac{\omega_{pe}^2}{\omega^2}\right)\varepsilon_o \qquad \omega_{pe}^2 = \frac{ne^2}{\varepsilon_o m}$$

Electron Plasma Frequency

Note: $v_{characteristic} = \omega_{pe}\lambda_D = v_{thermal}$

Collisions in Plasmas

- Plasmas are conductors, often excellent, but not perfect.
- Collisions are infrequent and may often be neglected, but
- Collisions are process that determines plasma resistivity, as elsewhere.
- Collisions include electron-neutral, but often only the electron-ion "Rutherford" cross-section matters. (Recall the total cross-section diverges. A subtle calculation is required to limit range of 1/r potential and properly treat small-angle scattering that causes minimal resistivity.)
- For a hydrogen plasma, the result is the Spitzer resistivity:

$$\eta = \frac{m\nu_c}{ne^2} = 5.2x10^{-5}\frac{\ln\Lambda}{T_{eV}^{3/2}}\left[\Omega - m\right]$$

$$\ln\Lambda \approx 20$$

Plasmas

I. Low-temperature, highly collisional

- $T_e < 20$ eV, usually $T_e < 10$ eV
- Mechanical support from walls, not plasma
- Neutrals present and physically important
- Atomic physics controls degree of ionization
- Gas discharges, lower ionosphere, plasma processing

II. "High temperature, collisionless"

- True plasma -- requires full equation set, confinement
- Astrophysics, fusion plasmas, hot laboratory plasmas
- *Emphasis of lectures, although some techniques apply to both*

Reference: *Principles of plasma diagnostics* by I. H. Hutchinson.

Plasma as Many-Body System

Minimal Description -- Conducting Fluid, Ideal MHD

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{g} \qquad \mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$$

$$\nabla \times \mathbf{B} = \mu_o \left(\mathbf{j} + \frac{\varepsilon_o \partial \mathbf{E}}{\partial t} \right) \qquad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \bullet \mathbf{B} = 0 \qquad \nabla \bullet \mathbf{E} = \varepsilon_o \rho_q = 0$$

Incompressible: ρ constant
Laboratory: **g**=0
p prescribed externally

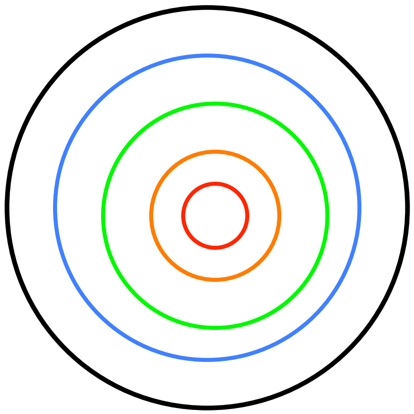
Equilibrium: $\nabla p = \mathbf{j} \times \mathbf{B}$

Real Plasma with n, T ~ p

Equilibrium: $$\nabla p = \mathbf{j} \times \mathbf{B}$$

B lines must lie in isobaric surfaces.
Since $\nabla \bullet \mathbf{B} = 0$, only possible if isobaric surfaces are topological tori. Magnetic field lines must form nested tori.

Equilibrium **must** also be stable. **Much** more complex considerations (Shafronov), establish that the only **stable, toroidally-symmetric** equilibria must have a toroidal plasma **current** in addition to the **toroidal magnetic field**, a tokamak.



Isobars

Note that the magnetic field lines lie in the nested surfaces and will be helices resulting from the combination of toroidal field and the field from the plasma current.