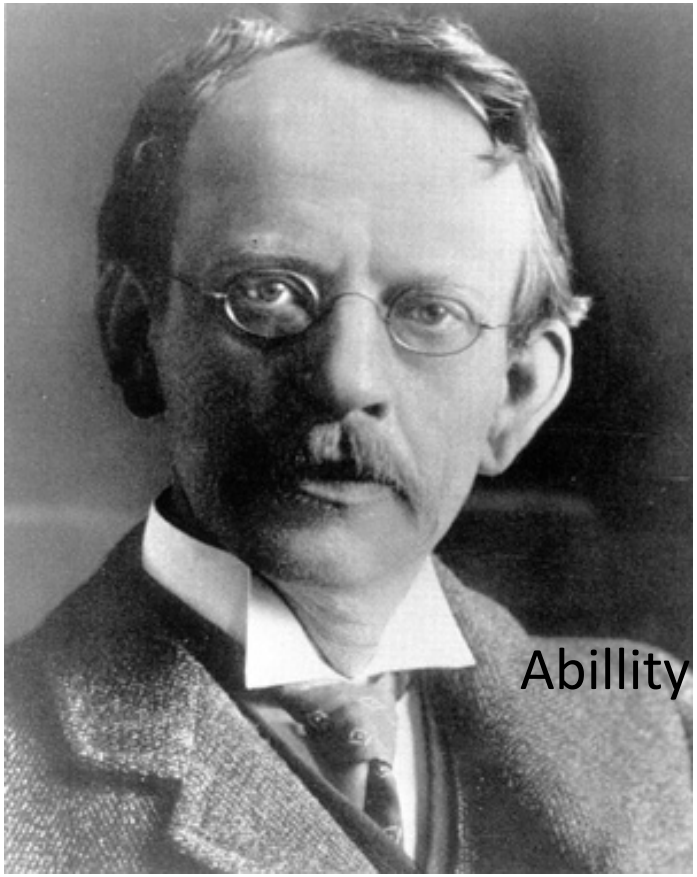
Active Radiative Measurements Using Thomson Scattering



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J.J. Thomson

Motivation:

Abillity to measure inside the core of the plasma!

Contents

- The Thomson scattering phenomenon
- Thomson scattering in a plasma
- Scattering regimes
- Incoherent Thomson scattering
  - Dipole approximation
  - Relativistic discription
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The Thomson Scattering Phenomenon

Classical interpretation for a single charged particle:

EM wave impinges charged particle

$\longrightarrow$ Acceleration of particle + emission of radiation

For

$\hbar\omega \gg mc^2$ Compton Scattering

$\hbar\omega \ll mc^2$ Thompson Scattering

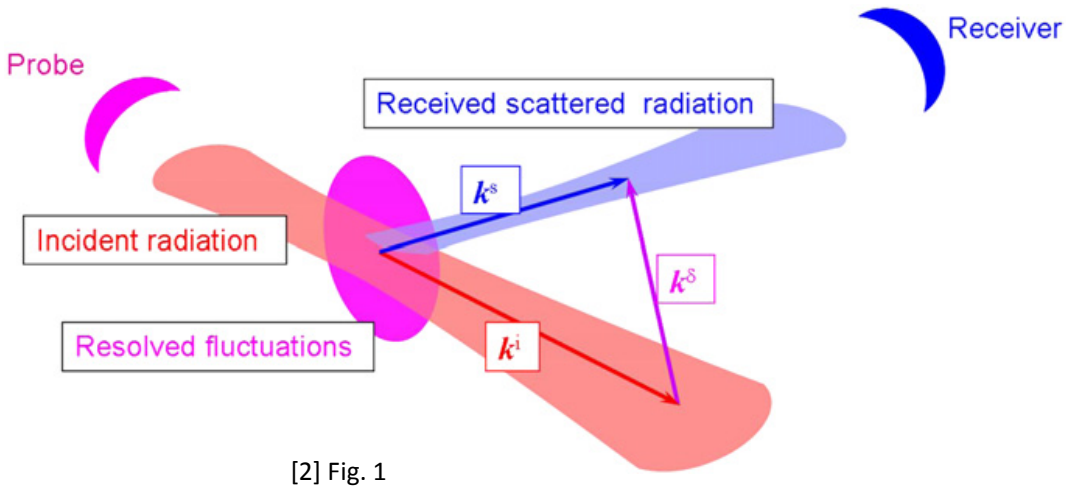
Thomson scattering in a plasma

Many charged particles in a plasma:

Ions and *electrons*

Great mass difference →

Electrons do the scattering



[2] Fig. 1

$$\mathbf{k}^\delta = \mathbf{k}^s - \mathbf{k}^i$$

(1) Scattering regimes

Debye shielding: Lowering of the Coulomb potential due to shielding of opposite charges

- Test electron – shielding cloud of +1 elementary charge consisting of only electrons (absence of electrons)
- Test ion – shielding cloud of:

  ions contribute (absence of ions) with -½ of an elementary charge

  electrons contribute with -½ of an elementary charge

(2) Scattering regimes

The **phase relation,** between the radiation the test electron and it's shielding cloud of electrons emit, is important!

Incoherent scattering: $k^\delta \lambda_D \gg 1$

Phase difference between electron and cloud is great

$\longrightarrow$ random distribution in cloud insures the radiation add up *incoherently*

Coherent scattering: $k^\delta \lambda_D \ll 1$

Phase difference neglectable $\longrightarrow$ radiation from test electron and it's electron cloud add up *coherently* $\longrightarrow$ greatly reduced scattering $\longrightarrow$ total scattered power are from ion-clouds , i.e. Collective Thompson scattering

(3) Scattering regimes

Incoherent scattering:

-You can analyze the frequency spectrum

→ Electron temperature and density

$$T_e \quad n_e$$

Coherent scattering / CTS

-You can analyze the frequency spectrum

→ Ion temperature and density

$$T_i \quad n_i$$

(1) Incoherent scattering

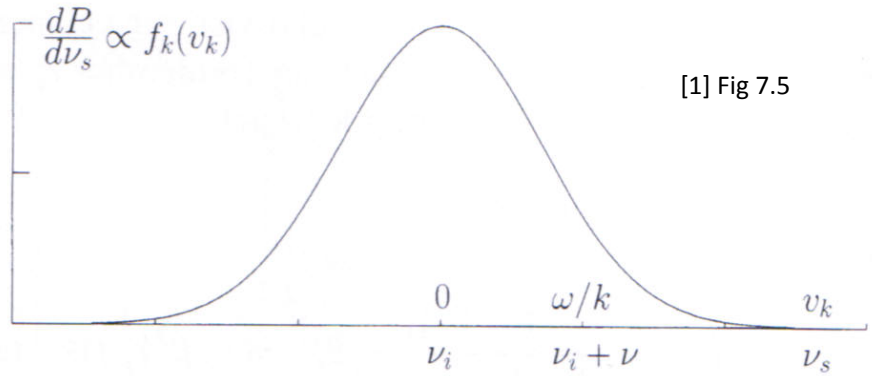
The nonrelativistic dipole approximation:

- Consider plasma with no applied B-field -straight line travel
- Dipole approximation: Assume the E-field of incident wave to be constant in space $\longrightarrow$ emission as from a osc. dipole

Measure Power Spectra:

$\frac{dP}{d\nu_i}$ Power spectral density

$f_k(v_k)$ Velocity distribution along k



[1] Fig 7.5

- The scattered spectrum is directly proportional to 1-dimentional velocity distribution

- Data processing: Signal-to-noise limitation require fit to specific curve , Maxwell distribution, where we can determine n_e T_e

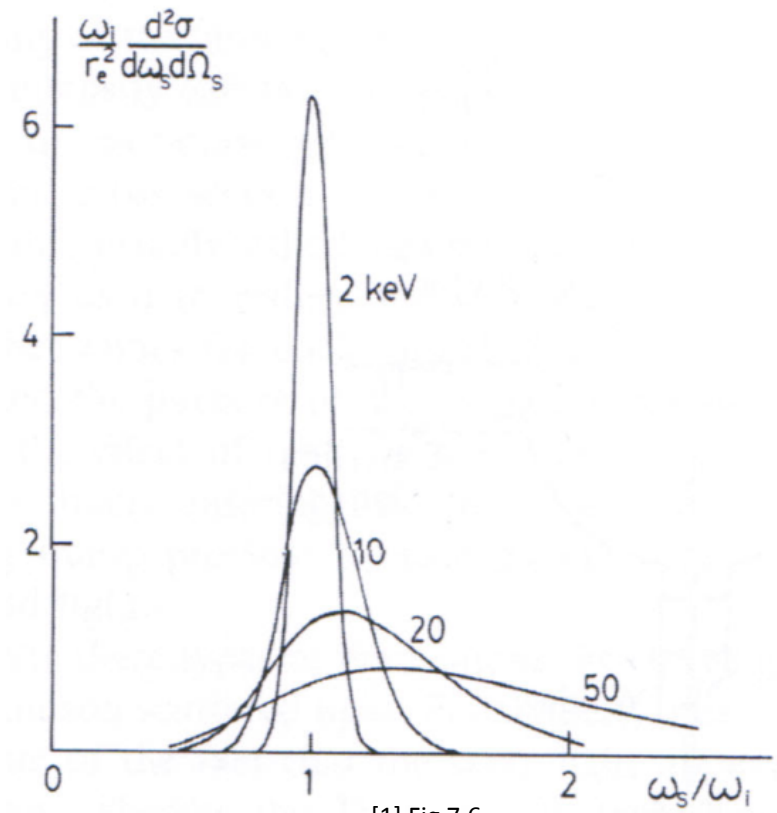
(2) Incoherent scattering

Relativistic discription: When consider high-temperature plasmas

We observe greater <u>intensity</u> of electrons moving towards us, than away from us.

Arises from:
The Relativistic Headlight Effect

Y-axis is proportional to the Power Spectral Density



[1] Fig 7.6

(3) Incoherent scattering

When a magnetic field is applied:

- Consider only scattering during time interval $T \ll 1/\omega_c$

  → An electron rotates only a small fraction of the gyro orbit

  → The electron travels approximately in a straight line.

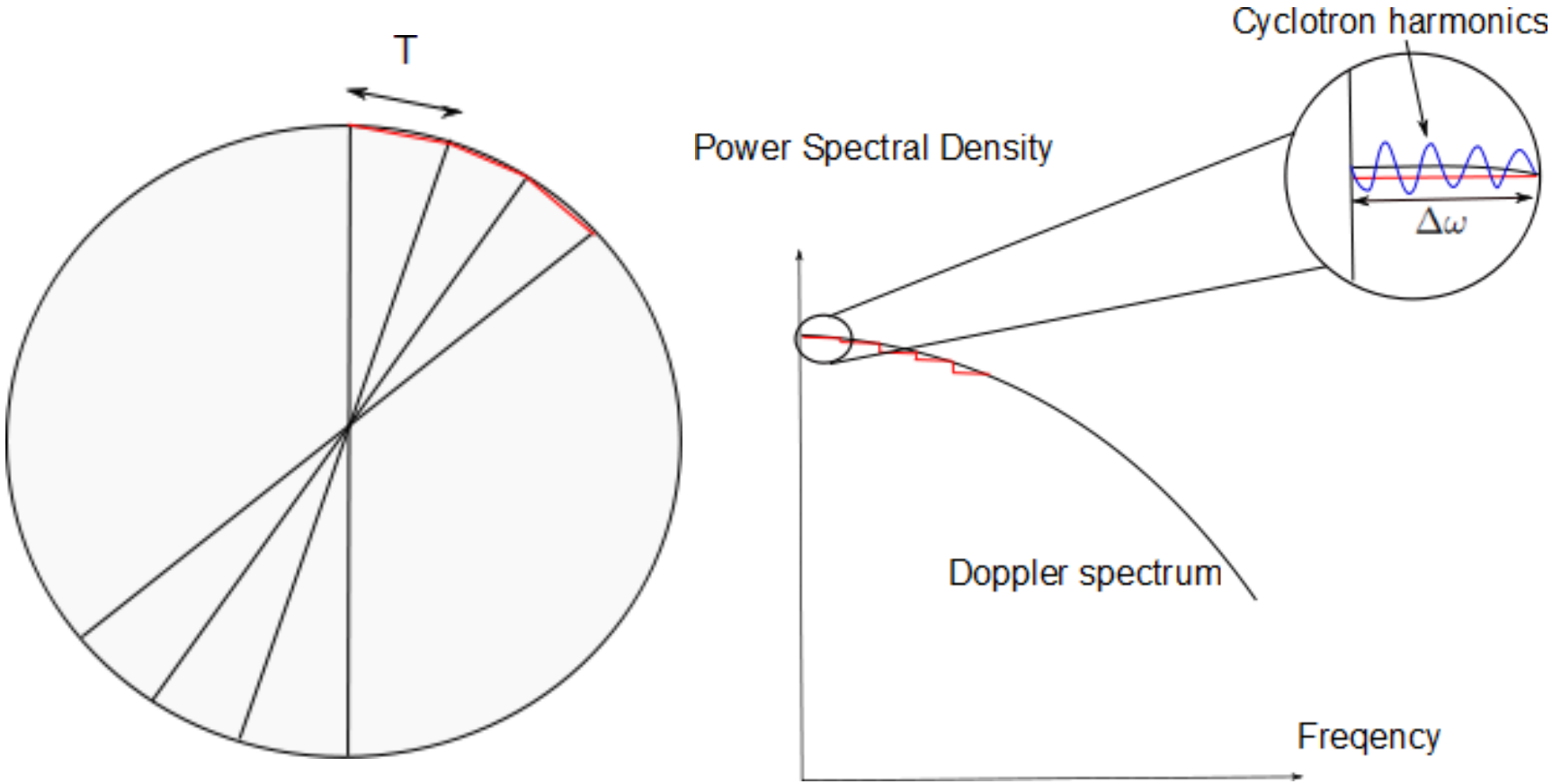
  → The freqency resolution in such a time periode: $\Delta\omega \sim 1/T$

  → Broad resolution $\Delta\omega \gg \omega_c$, where we can average over harmonic structure

  → An average over all orbit angles results in the same scattering from electrons flying in straight lines

Requirement: $\omega \gg \Delta\omega \gg \omega_c$

(4) Incoherent scattering



(5) Incoherent scattering

Experimental challanges:

For a typical setup one will only detect a fraction of the incident photons corresponding to about 10^{-13}

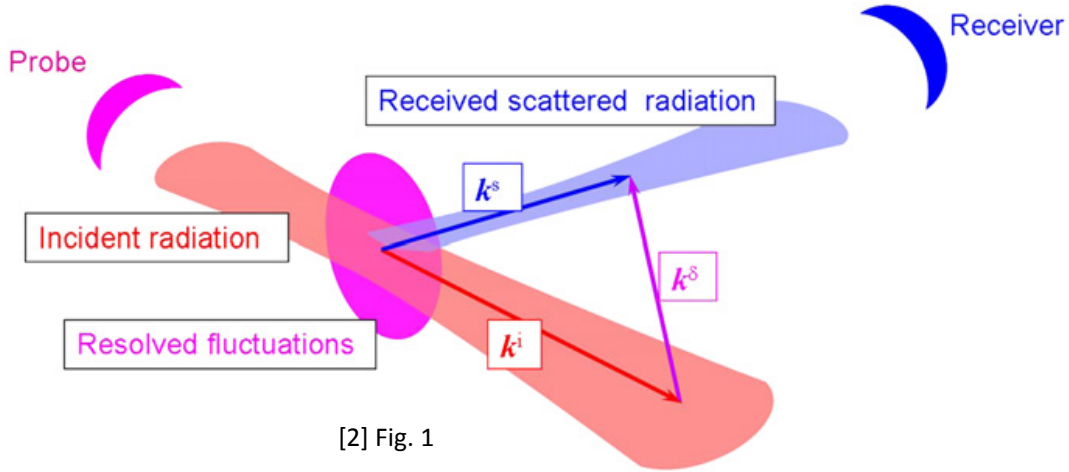
Requirements:

- High power and energy $\rightarrow$ Intense radiation source (pulsed laser)
- Avoid straylight from vacuum windows $\rightarrow$ Use baffles + avoid input-light frequency in our Doppler spectrum
- Minimize noise from detection equipment
- Filter out line radiation $\rightarrow$ Make a spectral survey of what lines exist in frequency spectrum due to plasma composition. You can then design a grating to exclude lines from being transmitted.
- Subtract the background average Bremsstrahlung recorded just before scattering pulse is subtracted from the total signal.

(1) Coherent scattering (CTS)

Critirion: $k^\delta \lambda_D \ll 1$ $\longrightarrow$ The received radiation carries informtion of the ion dynamics

Ion moving with velocity $\mathbf{v_i}$
Will cause a Doppler shift
giving $\omega^s \approx \omega^i + \mathbf{v_i}(\mathbf{k^s} - \mathbf{k^i})$



[2] Fig. 1

I.e. the CTS diagnostic resolve
Full $\mathbf{v_i}$ - distribution in
scattering volume projected
along $\mathbf{k}^\delta$:

$$g(u) = \int \delta(u - \mathbf{k}^\delta \cdot \mathbf{v} / \mid \mathbf{k}^\delta \mid) \mathbf{f}(\mathbf{v}) \mathbf{dv}$$

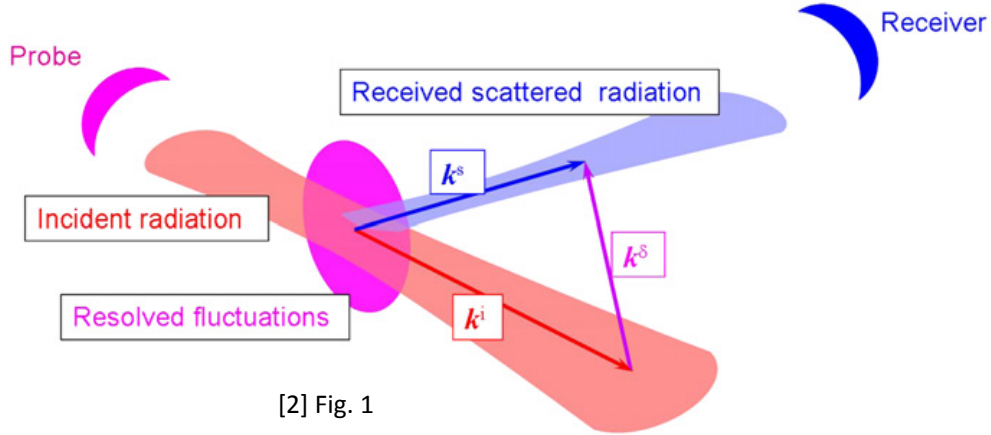
$g(u)$: 1D projection of full velocity distribution $f(\mathbf{v})$
where u is the velocity component along $\mathbf{k}^\delta$

Angle between $\mathbf{k}^\delta$ and the main confining magnetic field is of significant importance

(2) Coherent scattering (CTS)

Scattering geometry limitations:

- The restriction, $k^{\delta}\lambda_D \ll 1$, limits the options of the scattering angle
- Far infrared sources
  → Limit scattering angle to $\sim 1^{\circ}$
- Using gyrotrons
  → (100 GHz)



[2] Fig. 1

Limitation on scattering angle is in most cases absent

Drawback: gyrotrons is in the range of Electron Cyclotron Emission

(3) Coherent scattering (CTS)

The input/output relation:

The transfer function for a CTS diagnostic system is given by:

$$\frac{\partial P^s}{\partial \nu^s} = P^i O_b \lambda_0^{i2} r_e^2 n_e \frac{1}{2\pi} \Sigma$$

$\frac{\partial P^s}{\partial \nu^s}$ Spectral power density

ν_s Frequency of scattered radiation

O_b Beam overlap between probe and receiver beam

λ_0^i Vacuum wave length of incident probe radiation

r_e Classical electron radius

n_e Electron density

Σ Scattering function: Accounts for spectral variation and spectral response due to microscopic fluctuations

(4) Coherent scattering (CTS)

Experimental importances:

- $\frac{\partial P^s}{\partial \nu^s}$ is dependent of injected probe power:

  For sufficient signal to noise ratio of CTS diagnostic:

  100 kW – 1MW
- Sensitivity of CTS receiver needs to be in the order of nW
- A key component is a narrow band notch filter blocking stray light:

  Notch filter: Narrow enough to obtain bulk ion spectral distribution

  Broad enough to block straylight

(5) Coherent scattering (CTS)

Measurement of fast the ion distribution:

Experiment at ASDEX Upgrade:

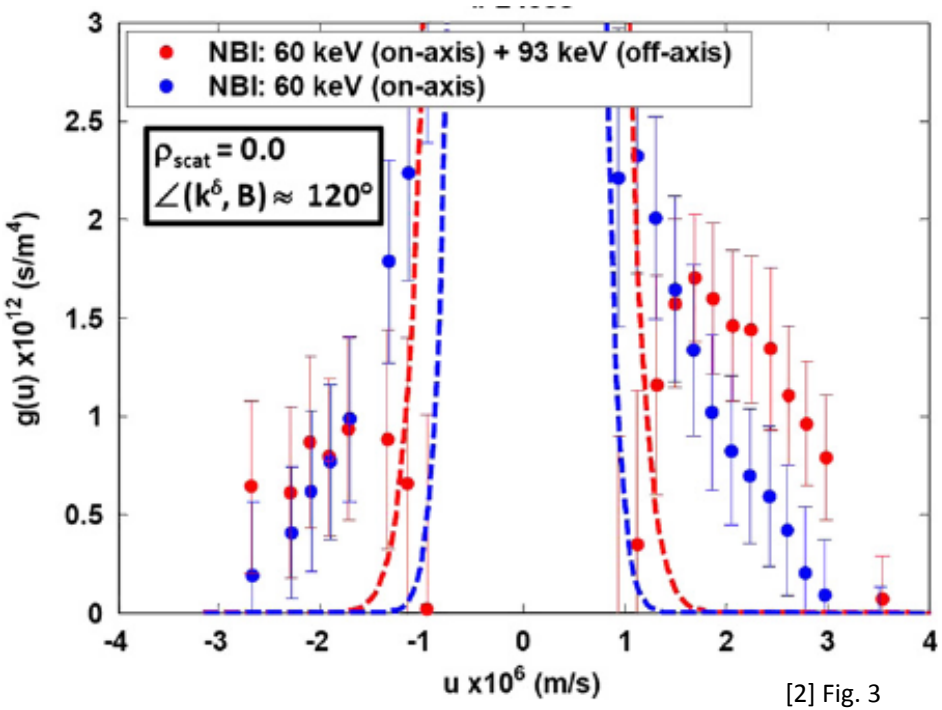
$$n_e(0) = 6 \times 10^{19} \mathrm{m}^{-3}$$
$$B_t = 2.6\,\mathrm{T}$$
$$\angle(\mathbf{k}^\delta, \mathbf{B}) \approx 120^\circ$$

Heating configurations:

Red – two NBI sources

Blue – one NBI source

Dashed lines represent models



[2] Fig. 3

Each source provides the power of 2.4 MW

(6) Coherent scattering (CTS)

Possible measurements using CTS diagnostics:

- The bulk ion temperature
  - Fitting the maxwellian part of the ion velocity distribution.
- The toroidal and poloidal bulk ion rotations
  - You need a setup so you can resolve $\mathbf{k}^{\delta}$ along the toroidal and the poloidal axis respectively
- Measurement of the fuel ion ratio (tritium-deuterium density ratio)
  - Having $\mathbf{k}^{\delta}$ close to perpendicular in relation to main magnetic field
    - → The CTS spectrum becomes sensitive to Ion **Bernstein waves**
    - → Dependent of ion species and densities
- Measurements of the localized bulk ion density changes/values
  - Fitting the maxwellian part of the ion velocity distribution

Summary

- What defines Thomson scattering
- The central role the Debye shielding plays
- The differences between incoherent and coherent Thompson scattering
- Incoherent Thomson scattering: Dipole approximation, relativistic effects, applying a magnetic field, experimental challanges
- Coherent Thomson scattering: Geometry limitations of setup, theoretical input/output relations, experimental importances, measure of fast ions, alternative use of CTS diagnostics

References

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