Overview of Plasma Diagnostics at General Fusion

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Magnetized Target Fusion

- General Fusion (GF) is working towards building a prototype magnetized target fusion reactor in Vancouver, BC (Howard et al., 2009).
- Magnetized plasma (spheromak) is formed and accelerated into a compression chamber.
- Plasma is compressed by a liquid lithium lead shockwave created by pistons impacting the outside of the chamber.

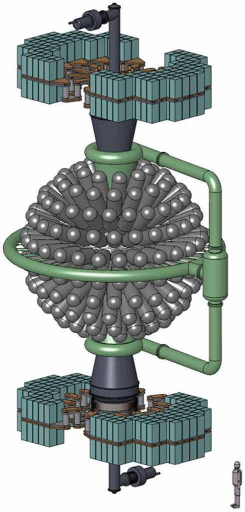


Figure: GF reactor concept.

Spheromaks

- A spheromak is a special plasma configuration that is compact and generates its own magnetic field that insulates it from the walls (Bellan, 2000; Jarboe, 2005).
- Spheromak magnetic field follows a helical path, which is nearly parallel to the current.

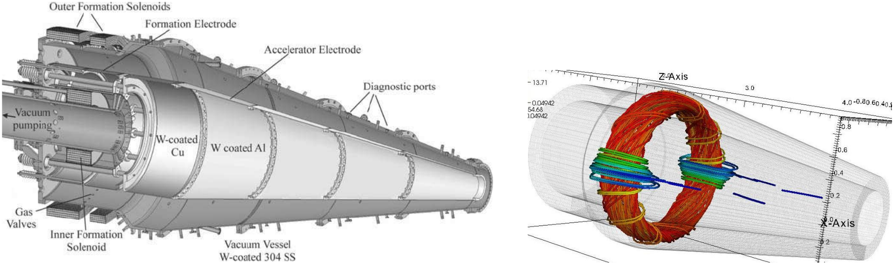
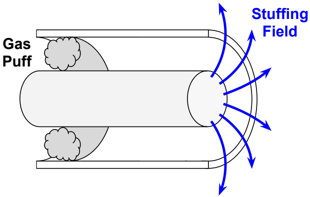


Figure: (Left) GF plasma injector. (Right) Simulated spheromak.

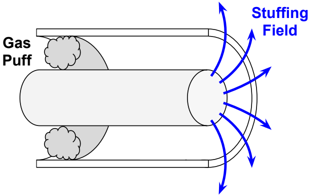
Spheromak Formation (Kornack, 1998)

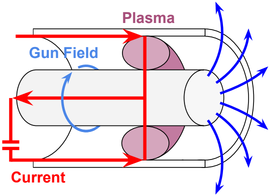
- Generate stuffing field, puff gas into injector vacuum.



Spheromak Formation (Kornack, 1998)

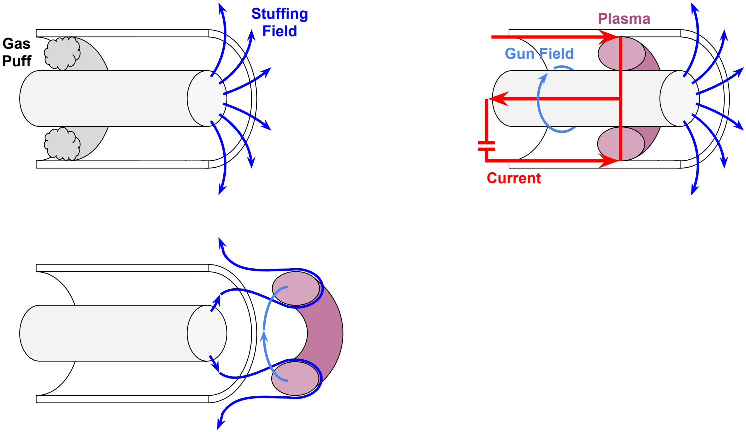
- Voltage applied, plasma formed, current creates gun field.





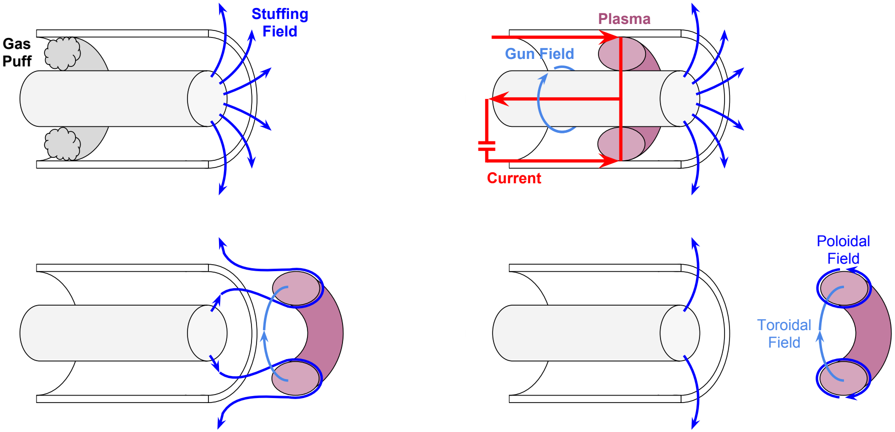
Spheromak Formation (Kornack, 1998)

- Gun field pushes plasma out, stretching stuffing field.

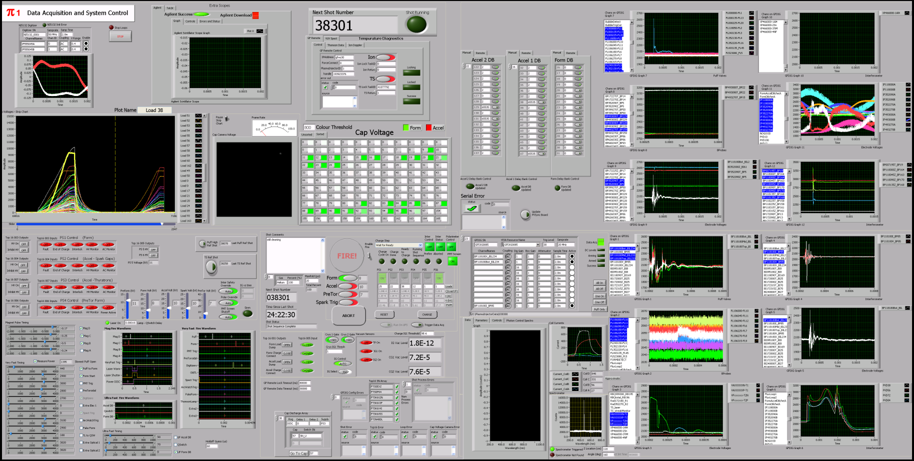


Spheromak Formation (Kornack, 1998)

- Stuffing field reconnects, and spheromak plasma formed.



Control plasma with this:



Plasma Diagnostics

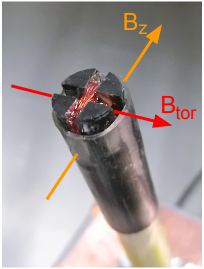
- Some of the key parameters we would like to measure are density, temperature, lifetime and magnetic field.
- GF is using or has attempted to used the following diagnostics:
  - Magnetic coil probes
  - Hall-effect probes
  - Rogowski coils
  - Interferometry
  - Thomson scattering
  - Spectroscopy
  - Scintillator/Photomultiplier tubes
  - Bubble detectors
  - Polarimetry
  - Langmuir probes
  - X-ray photodiodes
  - Bolometer
  - High-speed imaging

Magnetic Coil (B-dot) Probes

- Change in magnetic flux through loop of wire induces voltage:

$$V(t) = NA\frac{\mathrm{d}B}{\mathrm{d}t}$$

- Voltage signal must be integrated over time to give magnetic field.
- Most probes are located on the surface of the machine, giving readings of the spheromak's poloidal field.



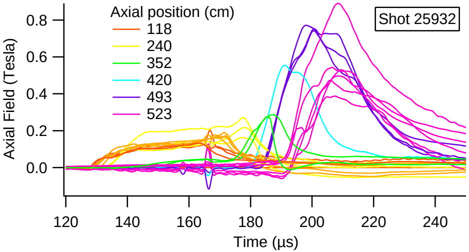
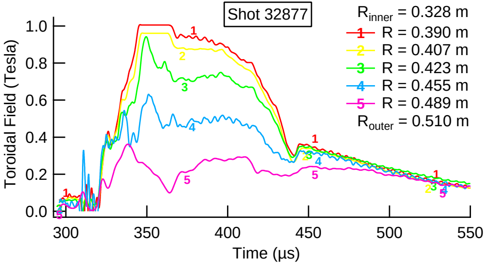


Figure: (Left) B-dot probe. (Right) Probes show plasma moving down injector.

Magnetic Probe Array

- Array of probes in a protective ceramic tube can be inserted into plasma to measure magnetic fields in the plasma core.
- Immersed probes could contaminate and disturb the plasma, so should only be used at low-temperature, low-density locations.



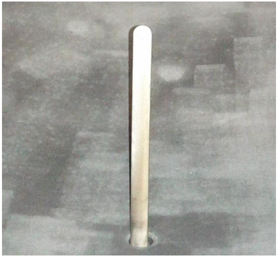
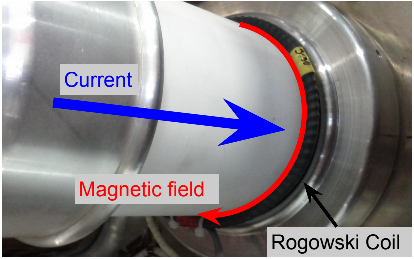


Figure: (Left) Probe array shows toroidal field radial profile inside plasma. (Right) Probe array inside injector.

Rogowski coils

- Rogowski coils measure current entering/exiting injector.
- Useful for measuring input power and machine efficiency.
- As plasma accelerates down injector, inductance of machine increases, which alters current going into machine.



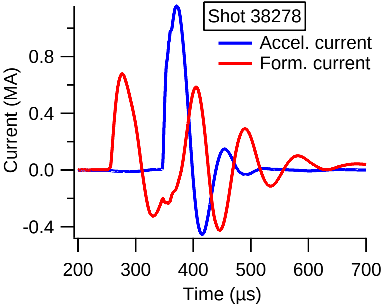


Figure: (Left) Rogowski coil on current feedthrough. (Right) Current measured.

Plasma Interferometry

- Plasma index of refraction changes with electron density.
- Beam through plasma is phase shifted (Hutchinson, 2002, p116).

$$\phi_n[\mathrm{rad}] = 2.82 \times 10^{-15} \lambda \int n_e dl$$

- Interferometer measures phase shift to determine density.

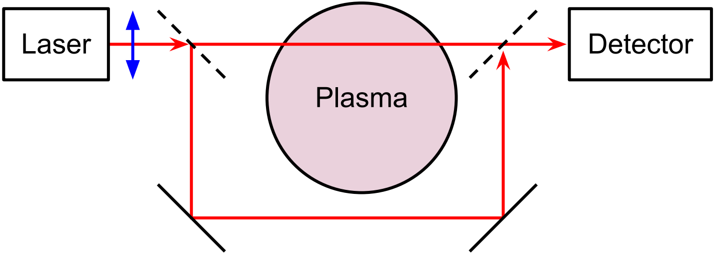
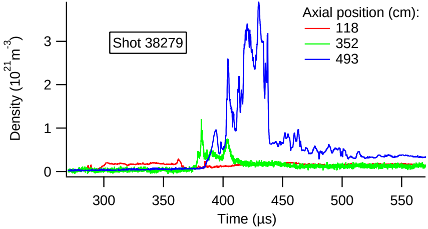


Figure: Mach-Zehnder interferometer.

Interferometer Density Measurements

- Density is important because:
  - Basic parameter required for economical fusion power.
  - Affects maximum temperature achievable in plasma (less density, higher temperature).
  - Very low density (eg after gettering) can cause sudden crashes.



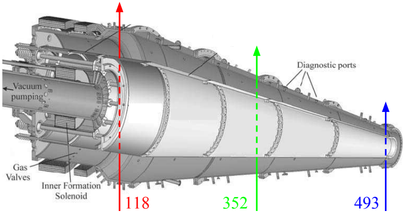


Figure: (Left) Interferometers show plasma being compressed as it travels down injector. (Right) Interferometer positions.

Faraday Rotation and Polarimetry

- Faraday rotation of a linearly polarized beam's polarization plane by a magnetized plasma.
- Amount of Faraday rotation depends on plasma magnetic field and density (Chen, 1984, p136):

$$\phi_f[\text{deg}] = 1.5 \times 10^{-11}\lambda^2 \int n_e B_{\|} dl$$

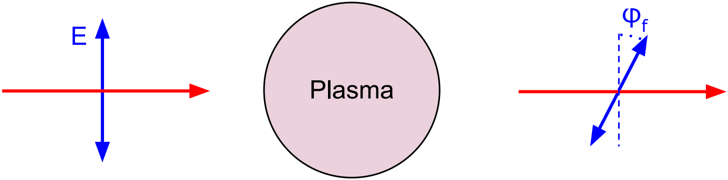


Figure: Faraday rotation of a beam of light in a plasma.

Three-Beam Heterodyne Polarimetry

- Polarimeter measures Faraday rotation to give information on density and inner magnetic field of plasma.
- Does not disturb plasma, unlike magnetic probe array.
- GF polarimeter uses three beams of slightly different frequencies to carry information (heterodyning).

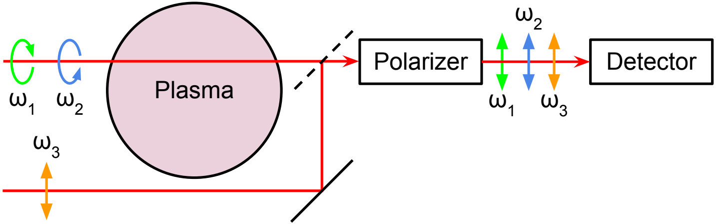
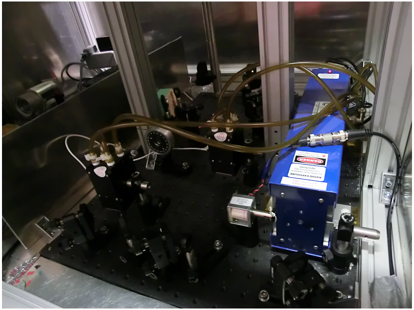


Figure: Three-beam heterodyne polarimeter.

Polarimeter at GF

- Uses a $\mathrm{CO_2}$ laser ($10.6\mu\mathrm{m}$) that produces a sufficiently high frequency beam to avoid reflection off plasma.
- Acousto-optic modulators frequency shift beams by 25MHz and 40MHz to allow for heterodyning.



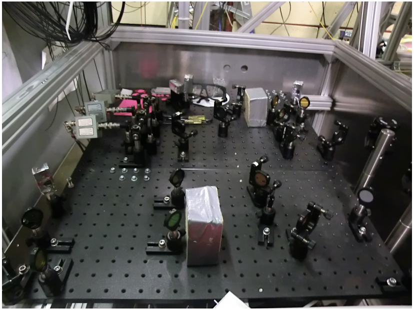


Figure: Polarimeter at GF: (Left) bottom level, (Right) top level.

Polarimeter Data

- Must calibrate polarimeter to have well-circularly polarized, highly collinear beams.
- Results agree well with expected Faraday rotation from model based on magnetic probe measurements (Carle et al., 2013) .

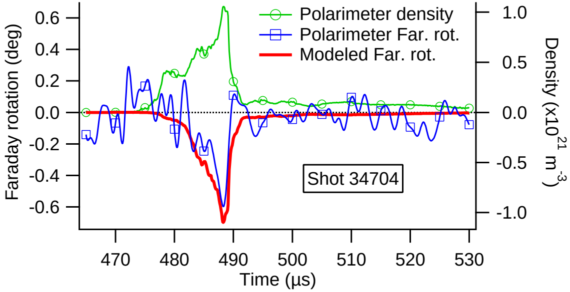


Figure: Polarimeter measurements compared to probe model.

Spectroscopy

- Spectrometer spreads observed light into its component colours with a diffraction grating.
- Excited atoms emit light at specific wavelengths (line radiation).
- Spectroscopy can give information on flow velocity, temperature, density and impurities.
- Impurities usually undesirable since they radiate power out of plasma.

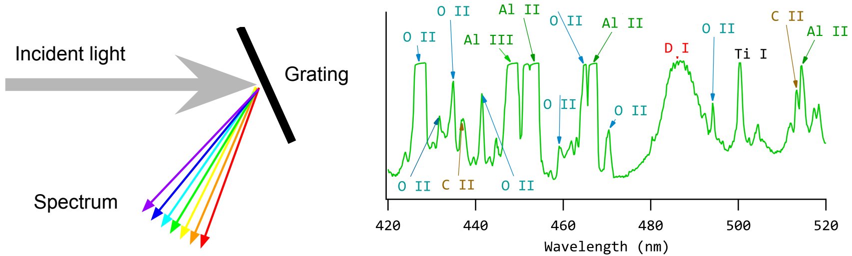
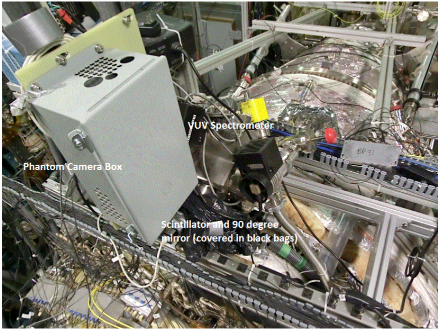


Figure: (Left) Spectrometer illustration. (Right) Segment of visible spectrum measured with spectrometer/camera (by J. McCone)

Vacuum Ultraviolet Spectrometer

- For readings on the hot plasma core, need to go beyond visible wavelengths since highly ionized atoms emit almost exclusively in the ultraviolet (UV).
- Vacuum-UV (VUV) absorbed by air, so need to do VUV spectroscopy inside machine vacuum.



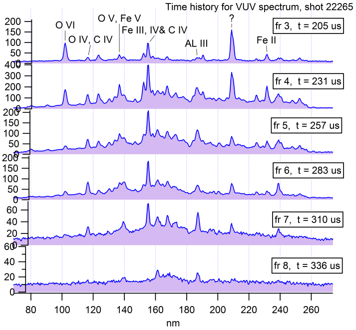


Figure: (Left) VUV spectrometer. (Right) VUV spectrum. (by J. McCone)

Ion-Doppler Line Broadening

- Line radiation emitted from moving ions is Doppler shifted.
- Observe broadened lines due to distribution of ion velocities. Allows for a measurement of ion temperature.
- Must account for Stark broadening, which depends on plasma density.
- Measured Ion-Doppler temperatures at GF sometimes seem too high. Possibly due to energetic reconnection events.

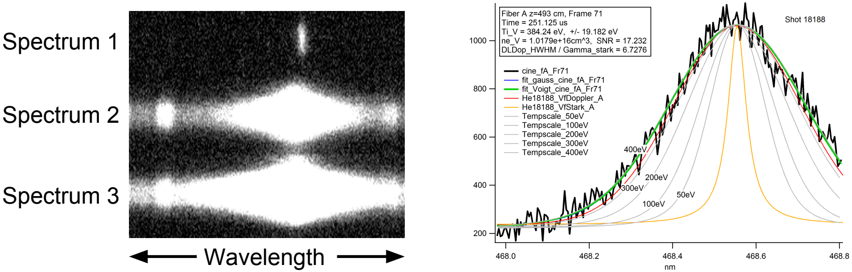


Figure: (Left) Broadened lines give (Right) temperature. (by J. McCone)

Plasma Flow Velocity

- Doppler shift in central wavelength indicates plasma flow.
- Measurements indicate plasma travels down injector at up to 100km/s.
- Observe that plasma is rotating, which might have implications for stability.

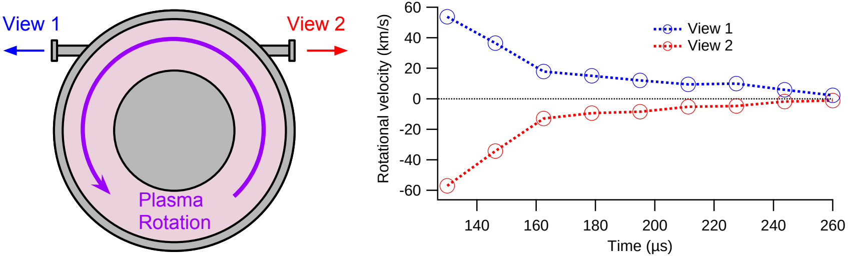
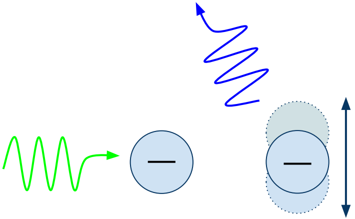


Figure: Spectrometer has measured spheromak rotation (by J. McCone)

Thomson Scattering

- Thomson scattering occurs when incident light accelerates an electron, which re-emits the light.
- Scattered light is Doppler broadened due to velocity distribution.
- Measure electron temperature from broadening, and density from scattered light intensity.



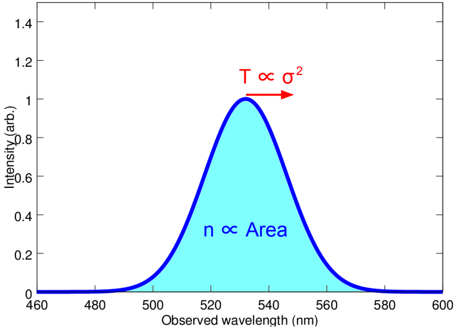


Figure: (Left) Thomson scattering. (Right) Doppler broadened scattered light.

One-Dimensional Thomson Scattering

- Current system measures temperature at one point in space and time.
- With an Intesified-CCD camera, can collect scattered light across entire laser line, giving spatially resolved density and temperature.
- Possibly get temporal resolution by bouncing laser back and forth.

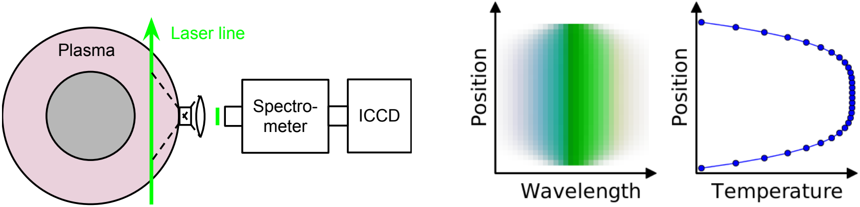


Figure: (Left) 1D Thomson setup. (Right) Simulated 1D Thomson data.

Neutron Detection

- Detection of neutrons during a shot is a sign of fusion.
- Neutron yield increases with temperature, so could potentially use to measure temperature.
- GF detects neutrons primarily with a scintillator/photomultiplier tube, and also has bubble detectors for confirmation of high yield events.

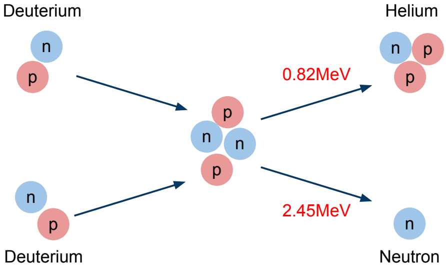


Figure: Deuterium-Deuterium fusion reaction can produce a neutron.

Neutron Data

- Must distinguish between gamma rays and neutron signals.
  - Pulse shape discrimination.
  - Shielding: lead blocks gammas, polyethylene blocks neutrons.
- GF believes it has detected neutrons. Often unclear if they are from thermonuclear fusion or high-energy particle beams.

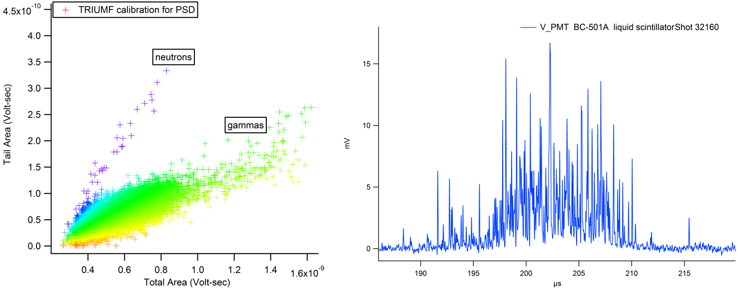
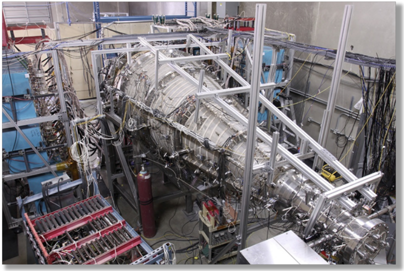


Figure: (Left) Pulse-shape discrimination. (Right) Scintillator detects neutrons. (by S.Howard)

Summary

- Plasmas tend to be complex structures, which are not easily understood.
- Require many different diagnostics to collect pieces of incomplete plasma puzzle.
- Fill in the missing pieces with computer simulations for a better understanding of dynamics.



References I

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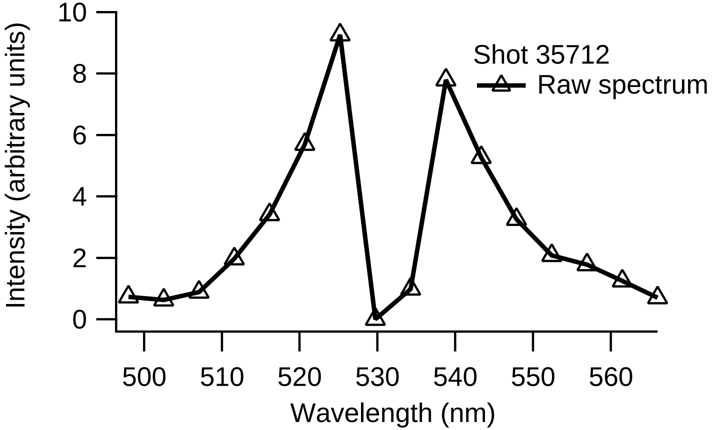
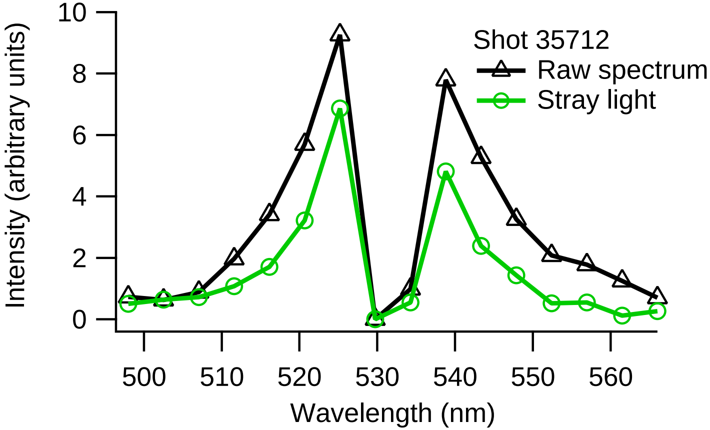
Thomson Data

- Raw data is Thomson scattered light + stray light (+ plasma light).
- Centre wavelength blocked due to very bright stray light.



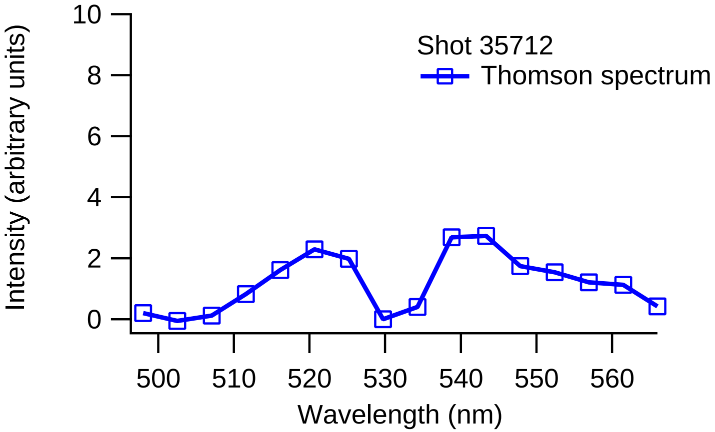
Thomson Data

- Stray light is laser light bouncing off surfaces inside the machine.
- Measured by firing the laser with no plasma and collecting light.



Thomson Data

- Subtract stray light from raw data to get Thomson light.



Thomson Data

- Fit Gaussian to Thomson light data to get temperature measurement.