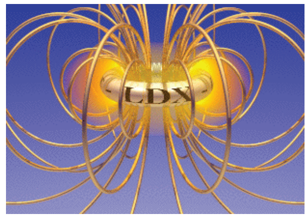

Multi-Color Soft X-ray Diagnostic Design for the Levitated Dipole Experiment (LDX)

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Abstract

We present a design for a new diagnostic to measure the warm plasma electron temperature on LDX using a ‘multi-color’ soft X-ray diode array. The challenge is to select thin-film coatings that allow detection of soft X-rays while minimizing the signals from the more energetic, 20-60 keV, trapped electrons created by electron cyclotron resonance heating [Garnier, et al., *Phys. Plasmas*, **13** (2006) 056111]. The soft X-ray detector array presented here is designed to be sensitive to 0.5-5 keV bremsstrahlung emitted by the warm temperature of the higher density bulk plasma electrons. The array employs the ‘two-foil’ method in which filters are used such that different detectors observe different parts of the bremsstrahlung spectrum. We present conceptual design plans for the LDX diagnostic and also present results from an existing soft X-ray diode array installed to measure the electron temperature of the dipole-confined plasma diagnostic in the Collisionless Terrella Experiment (CTX).
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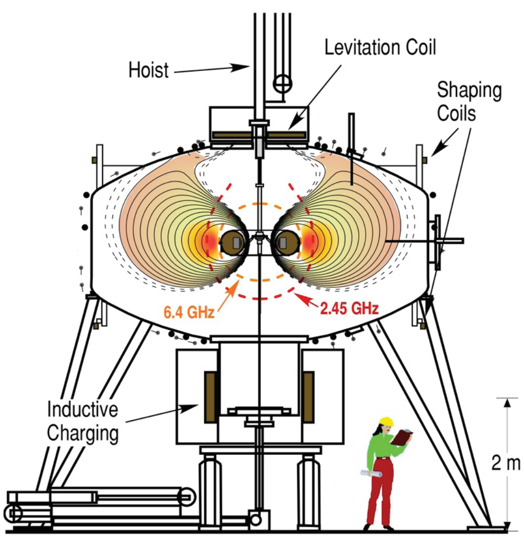
Levitated Dipole Experiment

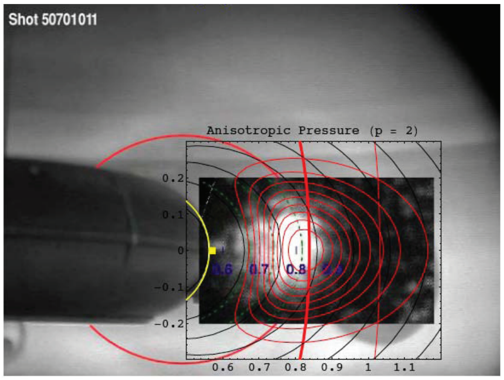
Levitated Dipole Experiment



Internal super-conducting coil can operate either mechanically supported or magnetically levitated in the chamber.

Plasmas are created using multi-frequency electron cyclotron resonance heating (ECRH).

Hot Electrons up to 60 keV



Measurements of X-rays have been used on LDX to deduce the temperature of the heated, high-energy electron population[1].

The temperature of the hot electrons is 20-60 keV.

[1] J. L. Ellsworth

Power from Bremsstrahlung as function of frequency and electron temperature

$$P_{brem}(\nu, T_e) = N_e N_i Z^2 \left(\frac{e^2}{4\pi\epsilon_o}\right)^3 \frac{32\pi^2 g}{3\sqrt{3}m^2c^3}\sqrt{\frac{2m}{\pi T_e}}\; e^{\frac{-h\nu}{T_e}}$$

$$\propto N_e N_i Z^2 \sqrt{\frac{1}{T_e}}\; e^{\frac{-h\nu}{T_e}}$$

Power from Recombination as function of frequency and electron temperature

$$P_{recon}(\nu, T_e) = N_e N_i Z^2 \left(\frac{e^2}{4\pi\epsilon_o}\right)^3 \frac{32\pi^2 g}{3\sqrt{3}m^2c^3}\sqrt{\frac{2m}{\pi T_e}}\; e^{\frac{-h\nu}{T_e}} \left[\frac{Z^2 R_y}{T_e}\frac{2G_n}{n^3}\; e^{Z^2 R_y/n^2 T_e}\right]$$

$$\propto \frac{N_e N_i Z^4}{n^3 T_e^{3/2}}\; e^{\frac{h\nu - |E_n|}{T_e}}$$

Estimating the Temperature

We compare probe measurements of the electron temperature at the edge of the LDX plasma to profile models to calculate an estimate of the peak warm electron temperature.

$$\begin{aligned} T_{e(core)} &\sim ?\ \ at\ 0.78\ m \\ T_{e(edge)} &\sim 25\ eV\ \ at\ 2.2\ m \\ N &\propto V^{-1}\ \propto\ r^{-4} \\ pV^{\gamma} &= constant \\ \gamma &= 5/3 \end{aligned}$$

$$p \propto V^{-\gamma},\ N \propto V^{-1}\ \rightarrow\ T_e \propto V^{\gamma-1}$$

$$\frac{T_{e(core)}}{T_{e(edge)}} \propto \left(\frac{V_{edge}}{V_{core}}\right)^{\gamma-1} \propto \left(\frac{R^4_{edge}}{R^4_{core}}\right)^{\gamma-1} \implies T_{e(core)}\ \sim\ 16T_{e(edge)}\ \sim\ 400\ eV$$

Warm and Hot Electron Densities

An important measurement on LDX is to determine the relative densities of the hot, heated (ECRH) electrons and the warm electrons.

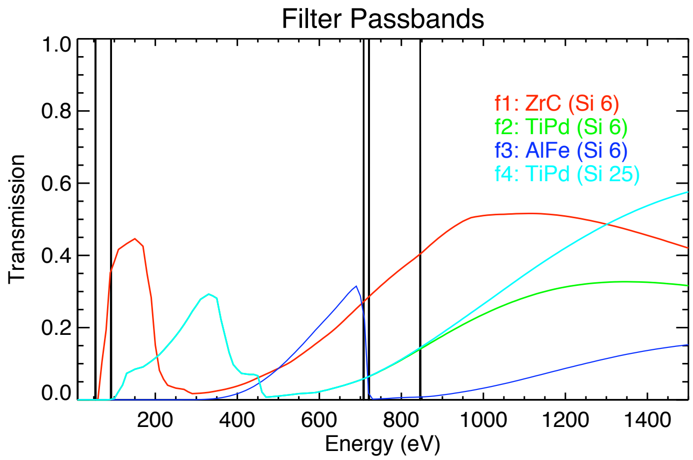
Comparing radiometer[2] measurements of electron cyclotron radiation to diamagnetic current measured by a magnetic loop at the equator gives a ratio of the hot electron pressure to the total electron pressure. This is because the radiometer measurements are a function of the hot electron pressure and the diamagnetic current is a function of the total electron pressure.

$$\frac{radiometer}{diamagnetic} = \frac{p_{e(hot)}}{p_{e(hot)} + p_{e(warm)}} \equiv R \implies \frac{n_h}{n_w} = \frac{RT_w}{T_h - RT_h}$$

$$Example:\ \ T_{e(hot)} \sim 30\ keV\ ,\ T_{e(warm)} \sim 400\ eV\ ,\ R = 0.9 \implies \frac{n_h}{n_w} = 0.12$$

[2] Paul Woskov

Filter Selection



Filter 1:
Zr 200 nm, C 50 nm
(Si 6 microns)

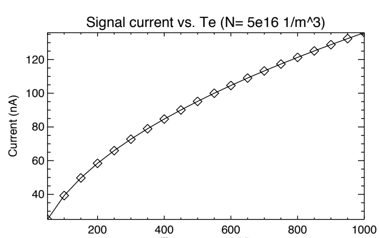
Filter2:
Ti 200 nm , Pd 100 nm
(Si 6 microns)

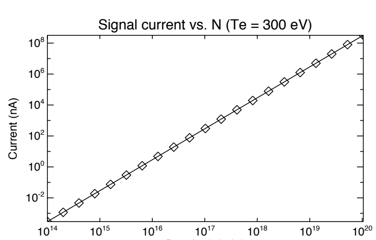
Filter 3:
Al 400 nm, Fe 450 nm
(Si 6 microns)

Filter 4:
Ti 200 nm, Pd 100 nm
(Si 25 microns)

Filter material and thickness determines which frequencies are transmitted to the diode. Multiple filters allow us to view different parts of the spectrum.

Estimating SXR Signal Strength

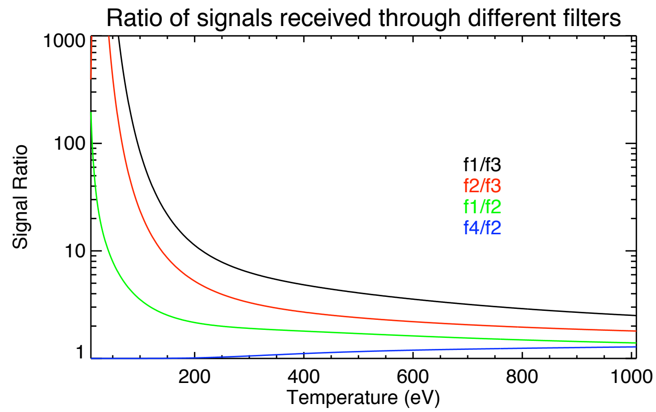




Signal is calculated by using the Bremsstrahlung and recombination equations, applying the ZrC filter, integrating over conic volume with view angle of ~8^{o} and applying the AXUV diodes responsivity of 0.26 A/W.

Signals on LDX should be strong enough to detect with transimpedance amplifiers.

Filtered Signal Ratios



Relations between the filter ratios and the electron temperature were calculated numerically using the frequency dependent equations for bremsstrahlung and recombination radiation and the filter transmission coefficients. Density was 5e16 m^{-3}. Filter selection is optimal for 100-250 eV.

Potential Pitfalls

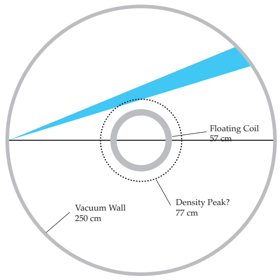
There are three critical problems we may encounter:

1. Insufficient signal strength. LDX has relatively lower densities compared to other plasma devices but simulations suggest the signal strength will be strong enough.

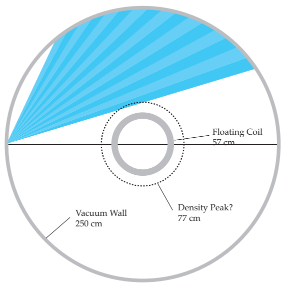
2. Impurity line radiation. Line radiation from impurities could distort the ratios between detectors give incorrect temperature measurements.

3. Contamination of the warm electron emission spectrum by the hot electron emission.

SXR Array

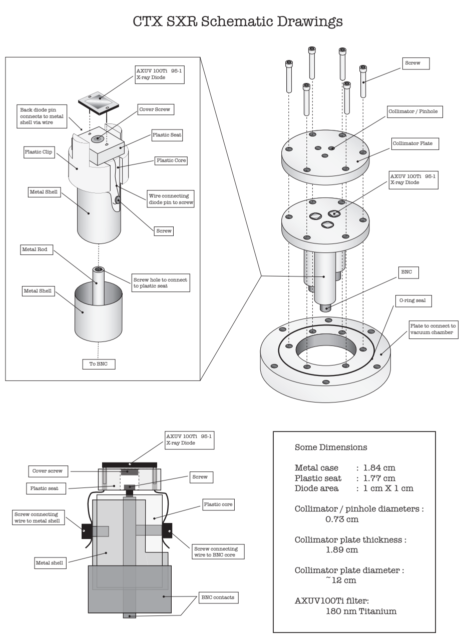


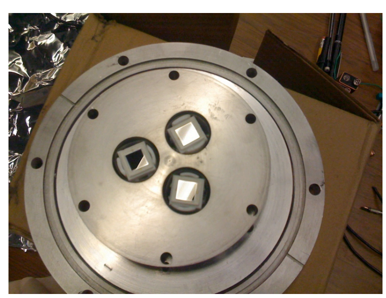
Initial diagnostic has only one plasma view and is intended test whether the signal strength is sufficient.

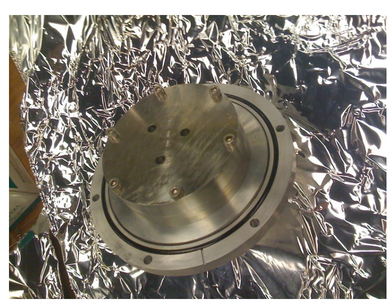


A more complete diagnostic will have views at multiple radii allowing for an Abel inversion of the emissivity.

CTX SXR Diagnostic

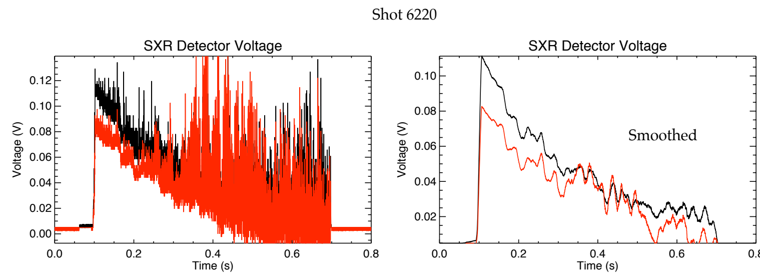


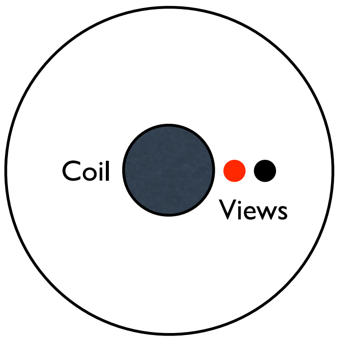




CTX SXR Measurements

CTX SXR data with
peak parameters:
$N \sim 10^{10}\ cm^{-3}$
$T_e \sim 50$ eV

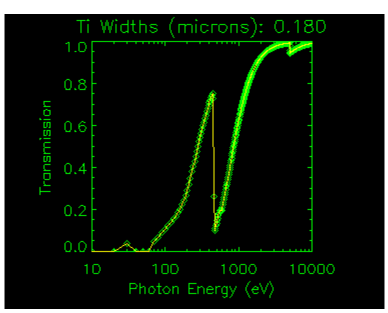




The CTX SXR has views through plasma that are roughly orthogonal to the dipole equatorial plane and have a view angle of 42°. The peak temperature and density is reached between 0.1-0.15 seconds.

Comparison to CTX SXR

CTX SXR filter transmission



As check of the computer codes written to design the LDX SXR we input the CTX parameters and compared the results they produced with the actual CTX data.

The codes used the Bremsstrahlung and recombination radiation equations to simulate the radiation in CTX and integrated over a homogeneously emitting transparent view. They then filtered the radiation using the transmission coefficients of the 180 nm titanium filter. Correcting for geometry and other electronics we obtained a signal of ~0.1 V.

This value is consistent with the measured value; however, the simulated value does not take into consideration the temperature and density gradients that should decrease the signal. Nonetheless, the simulated value is qualitatively consistent with the measured value.

Future Work

Build it!

Build the single view multi-filter and install it on LDX. This will allow us to determine if the signal strength is sufficient and whether the line emission and hot electron emission is sufficiently small to allow for an accurate measure of the warm electron temperature.