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16th International Toki Conference on Advanced Imaging and Plasma Diagnostics

Temperature Diagnostics for Field-Reversed Configuration Plasmas on the Pulsed High Density (PHD) Experiment

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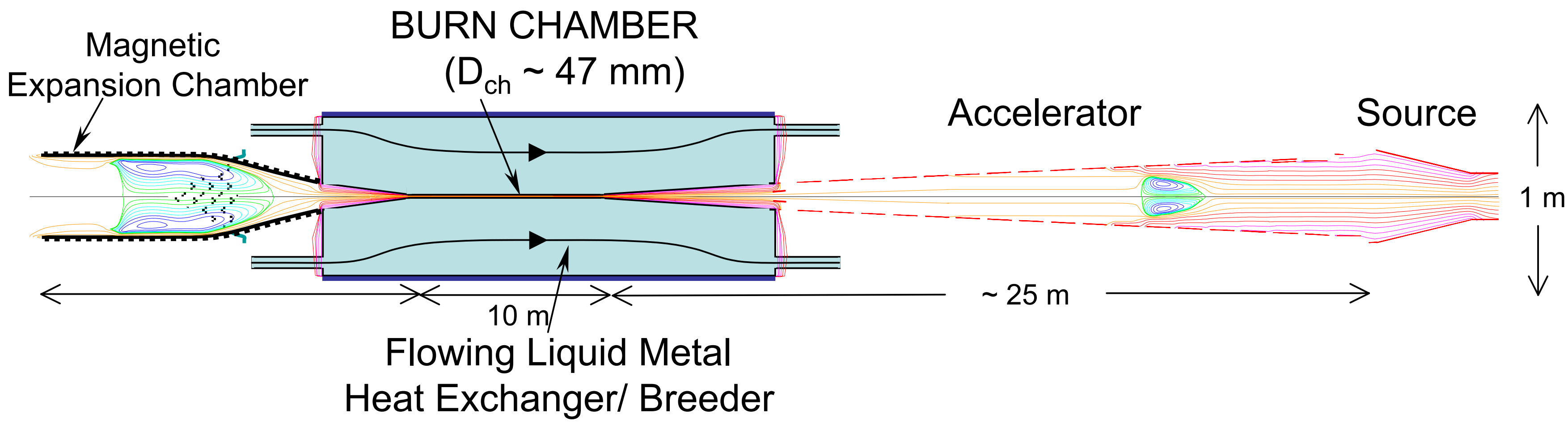
Pulsed High Density (PHD) Fusion Experiment

- PHD has been designed to determine and explore FRC stability boundary in both in situ and translating CTs
- PHD design point will provide the flux necessary for fusion gain in the reactor regime
- FRC acceleration has been demonstrated previously with (a > 10^{10} m/s^2), and PHD will extend these results in compression
- Initial PHD studies are aimed at achieving keV plasmas with significantly increased confinement parameters
- Device is first step in eventual fusion breakeven experiment

Outline of PHD Fusion Concept



1 - FRC formed at low energy (~30 kJ) and relatively low density (~10^{21} m^{-3})

2 - FRC accelerated by low energy propagating magnetic field (~ 0.5 T) to

3 - FRC is wall compressed and heated as it decelerates into burn chamber

4 - FRC travels several meters during burn time minimizing wall loading

5 - FRC expands and cools converting thermal and magnetic energy back into stored electrical energy

Field-Reversed Configuration (FRC) Geometry

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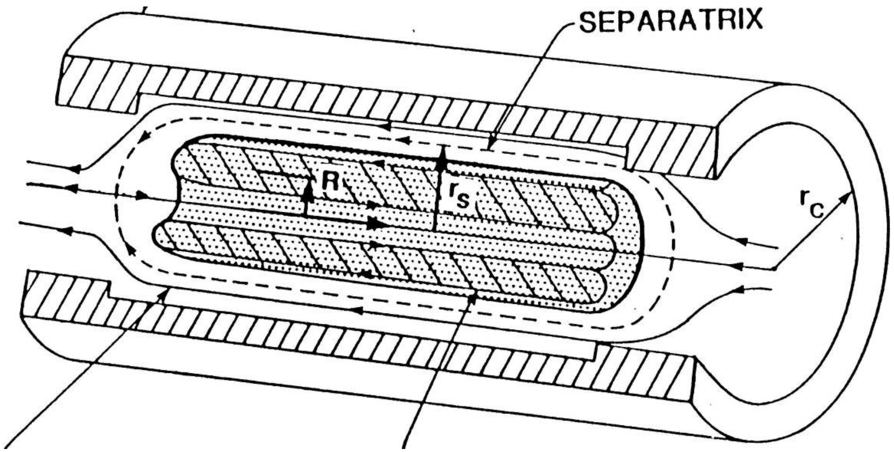

R – null radius

r_s – separatrix radius

r_c – coil radius

x_s – r_s/r_c

Equilibrium Relations

Radial Pressure Balance: $$P_0 = n_0 kT = \frac{B_{ext}^2}{2\mu_0}$$

Axial Pressure Balance: $$\langle \beta \rangle = \int_0^{r_s} \frac{2\mu_0 P}{B^2} dr = 1 - \frac{1}{2} x_s^2$$

Flux Conservation: $$B_{ext} = \frac{B_{vac}}{\left(1 - x_s^2\right)}$$

Total Temperature: $$T = \frac{B_{ext}^2}{2\mu_0 n_e e}\left(1 - \frac{1}{2} x_s^2\right)$$

Experimental Layout for the Initial Phase of PHD

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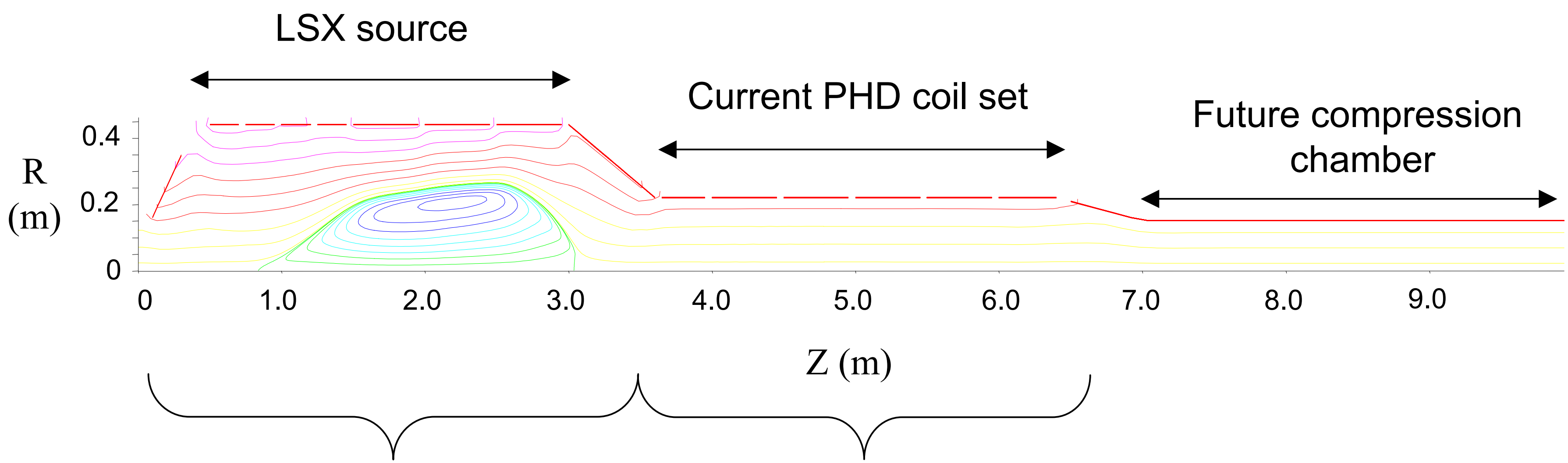
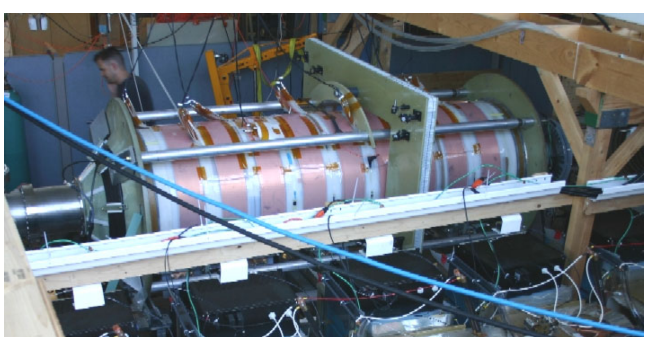
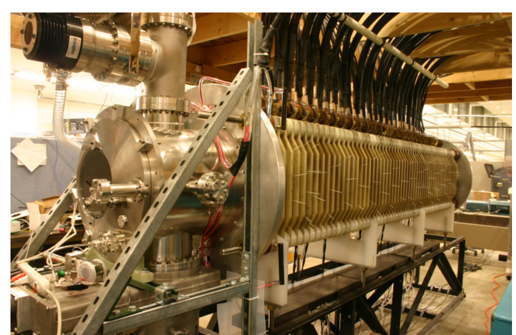


Dynamic formation of high flux, high β CT

Used for *In situ* high s FRC formation studies



High Flux Source



Accelerator section

Diagnostics on the HFS

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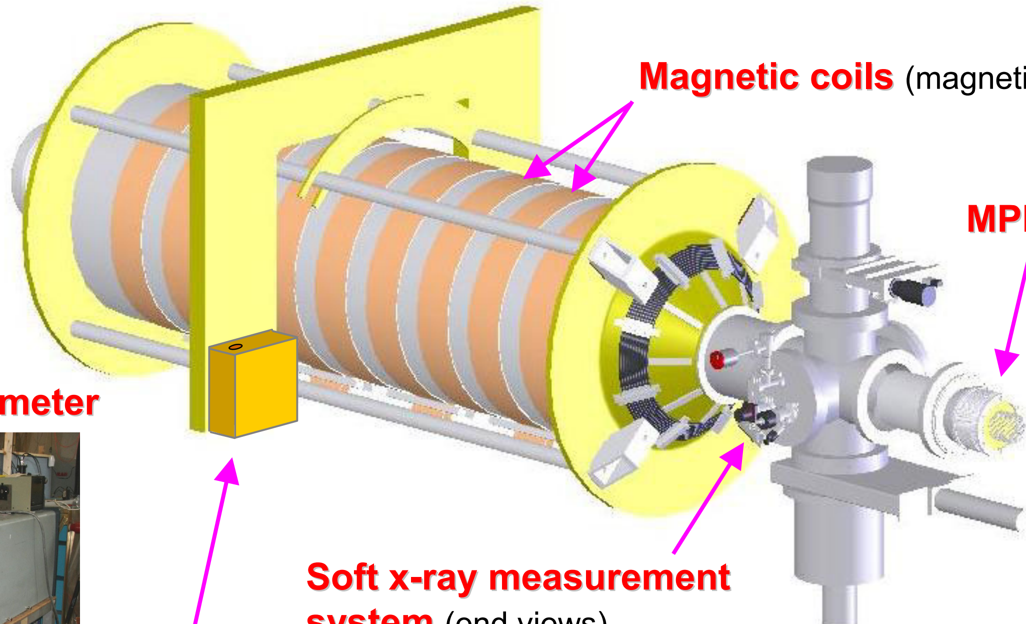
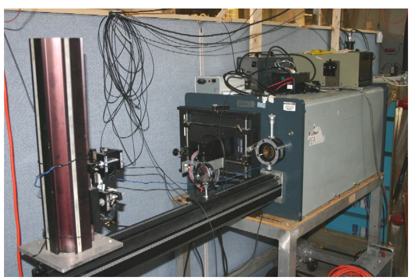


Magnetic coils (magnetic loops and flux loops)

end views

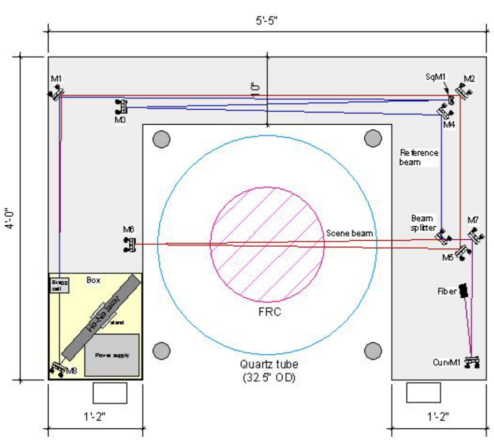
MPD (Magneto Plasma Dynamic)
For producing ionization plasma

16 channel spectrometer



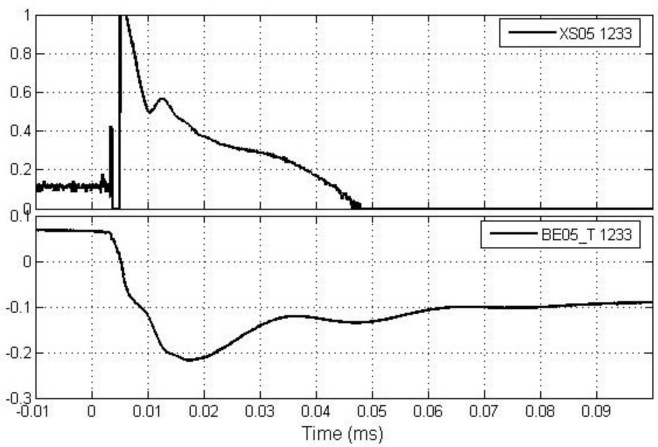
Soft x-ray measurement system (end views)

He-Ne laser Interferometer

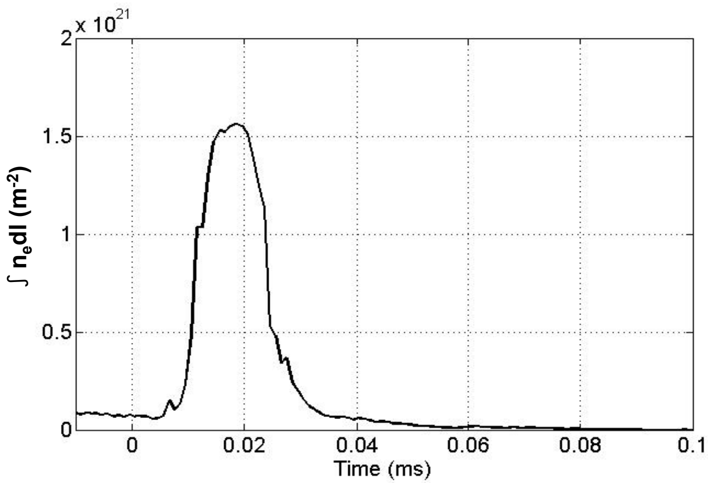


- **An axial array of 9 pairs of magnetic loops and flux loops**
  - ✓ external field, separatrix radius, volume, and energy
- **A 64 channel array of optical measurement system for tomography, and 14 channel array of visible light measurement**
  - ✓ visible bremsstrahlung tomography, plasma shape, and mode structure
- **A λ=632.8 nm He-Ne laser interferometer**
  - ✓ FRC line density, density, and total temperature
- **A single and 16 channel spectrometers, and a soft x-ray measurement system (including a bolometer)**
  - ✓ impurities, FRC velocity, ion and electron temperatures, and radiated power
- **An end-on fast framing camera, and CCD camera**
  - ✓ FRC density, shape and dynamics

Total Temperature (He-Ne laser interferometer)



x_s (=r_s/r_c) and external field



Line density

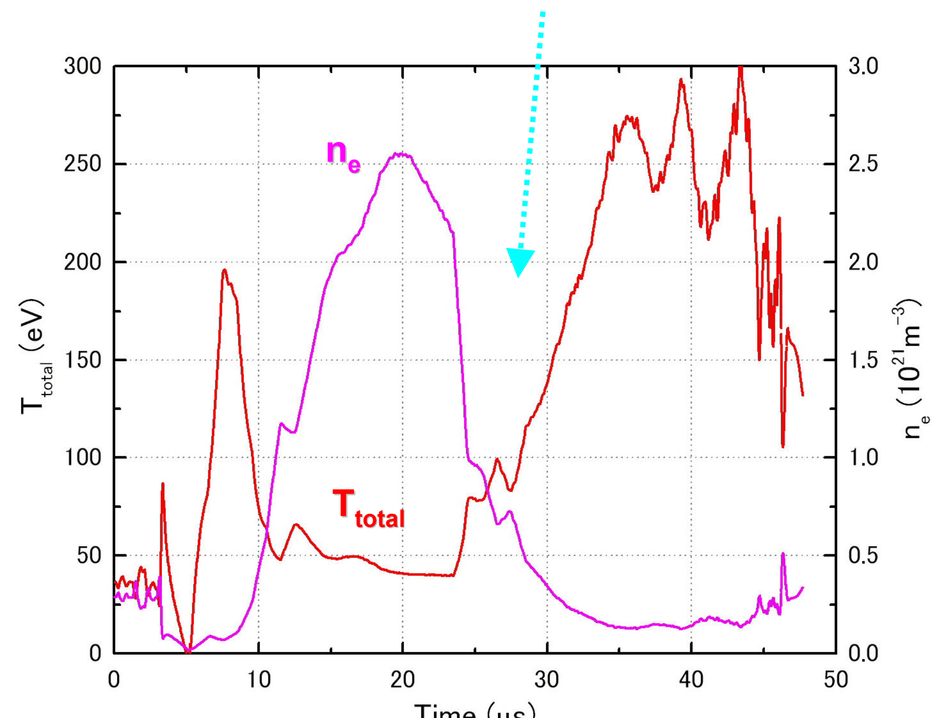
Electron density from the interferometer

Total temperature from the pressure balance

$$\langle n_e \rangle = \int n_e dl / 4 r_s$$

$$T_{total} = \frac{B_{ext}^2}{2\mu_0 n_e e}\left(1 - \frac{1}{2} x_s^2\right)$$

T_e increases caused by decreasing separatrix radius and electron density



Ion Temperature Diagnostics (16ch Spectrometer)

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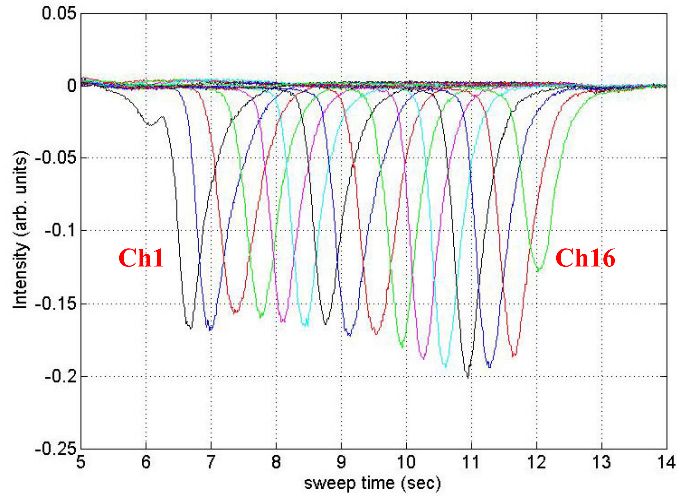
SPEX is installed viewing from the end, and plasma emission is focused through a ~2 μm entrance slit and detected by a 16ch PMT array.
For calibrating the intensity of 16ch PMT detector with –800 V supply voltage, a mercury pencil lamp is used and the detected wavelength compared with mercury lines from the *National Institute of Standards and Technology (NIST) Atomic Spectra Database*.

Calibration



The ion temperature of FRC plasma is measured in terms of the Doppler broadening. Under the assumption of a thermal Maxwellian velocity distribution, the Doppler broadened spectral line shape of the transition is expressed by a Gaussian profile

$$I(\lambda) \sim \exp\left[-(\Delta\lambda/\Delta\lambda_D)^2\right]$$

with the full width at half maximum

$$\Delta\lambda_{FWHM} = 2(\ln 2)^{1/2}\Delta\lambda_D = 7.71\times 10^{-5}\lambda(T_i/M)^{1/2}$$

where T_i is in eV, $\Delta\lambda_D$ centered at the wavelength of the observed spectra λ, and M is the ion mass in atomic units. This half-width and thus the corresponding apparent temperature must be corrected by taking into account the Zeeman and Stark effects. With these corrections taken into account, the measured Doppler broadening is used to solve for T_i.

Ion Temperature Diagnostics (16ch Spectrometer)

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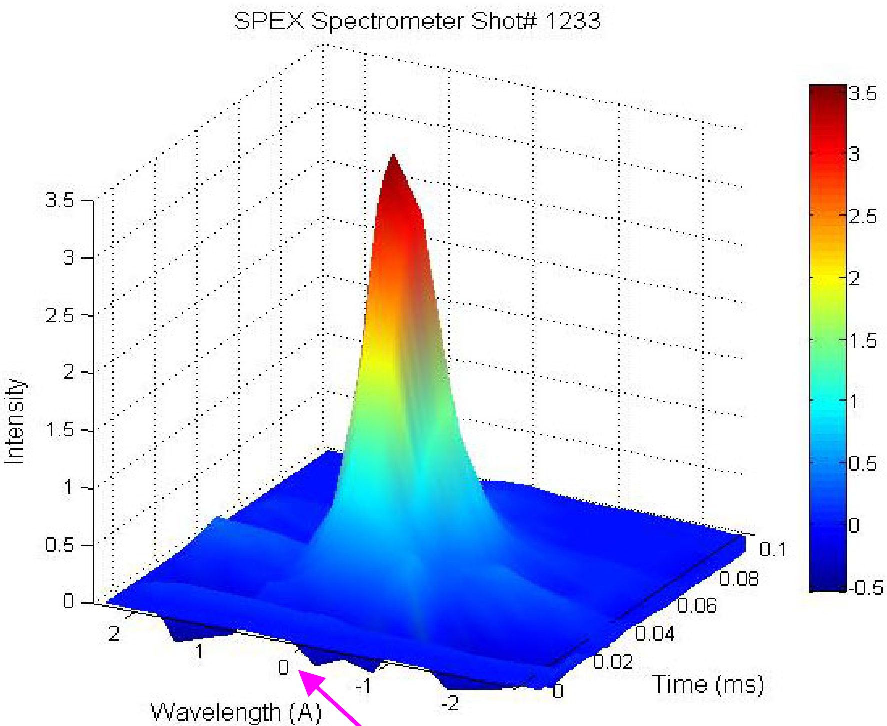
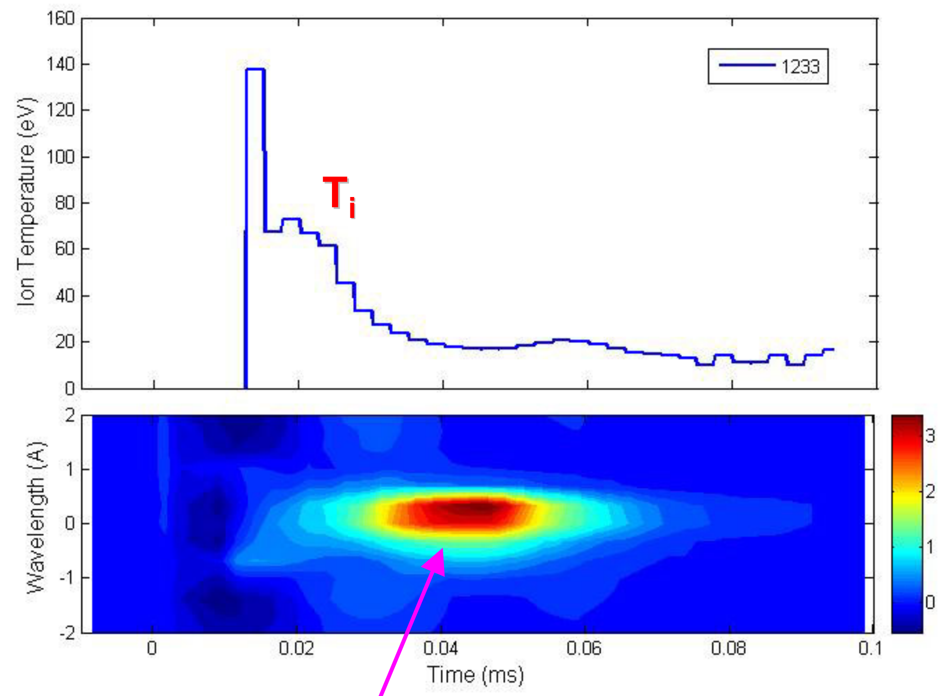
CIII line (λ=229.69 nm) are observed in this discharge.
Other possibility is CV line (λ= nm) or OVI line (λ= nm) for higher plasma temperature diagnostics.



Center of wavelength (λ=2296.9 Å)



At this time (peaked impurity), FRC plasma already moved from the center and disappeared

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Development of Soft X-Ray Measurement System

For detailed density and temperature analyses, a soft x-ray measurement system is recently developed on the end flange of the HFS. This system consists of collimators and five AXUV100 photodiodes with directly deposited filters which have approximately 0.1-0.3 μm thick films (Al, Zr/C, Sn/Ge, Cr/Al, and Ti/Pd) on each diode.

Both parameters of electron temperature T_e and electron density n_e are approximately determined by comparing the response of the several filtered detectors to their computed response using the emissivity from an atomic model of the plasma with T_e convolved with the spectral responsivity of each detector. To estimate the sample spectrum on the PHDX, the spectral analysis code (PrismSPECT) is used. Once we have an emissivity for some nominal choice of impurities, we can use simple scaling with impurity density to assemble an emissivity spectrum for a combination of impurities.

Development of Soft X-Ray Measurement System

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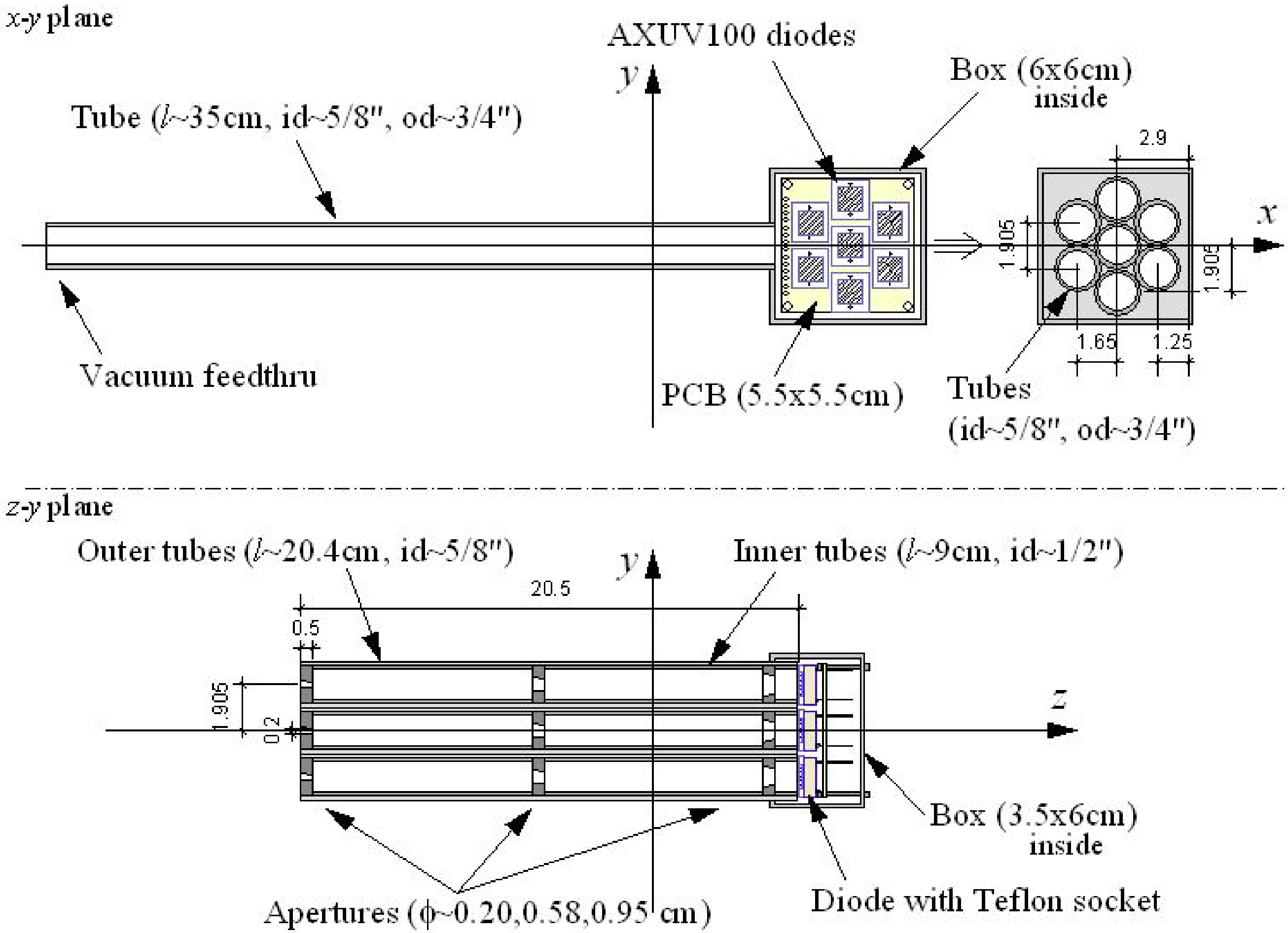
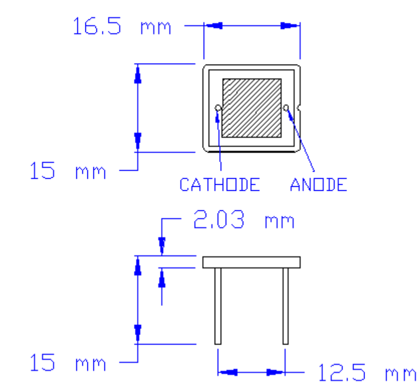
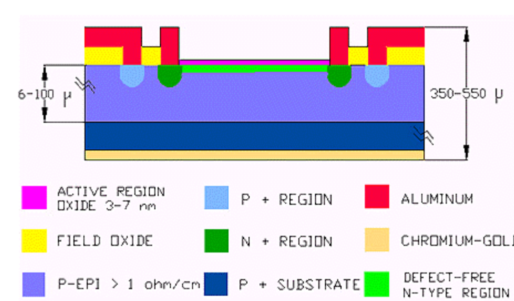


Schematics of SXR system

Photodiodes are manufactured by the International Radiation Detectors, Inc.



AXUV100 Photodiode



Soft X-Ray Detectors

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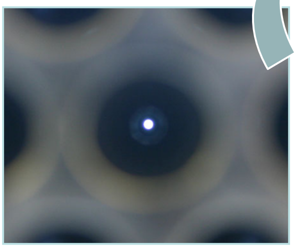
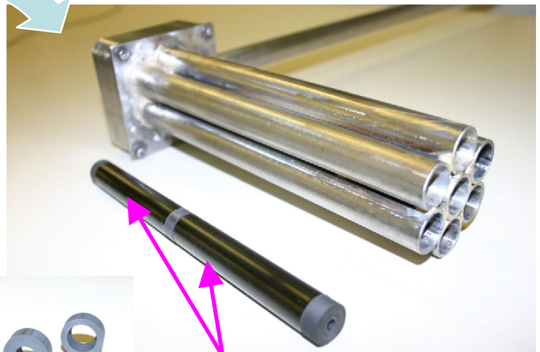
Collimating system

End view

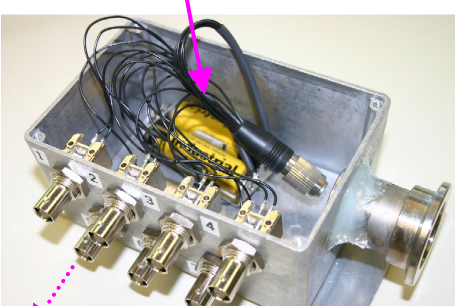




Apertures (Graphite)

Carbon fibers

2xAA battery (-3V supply)



to digitizer

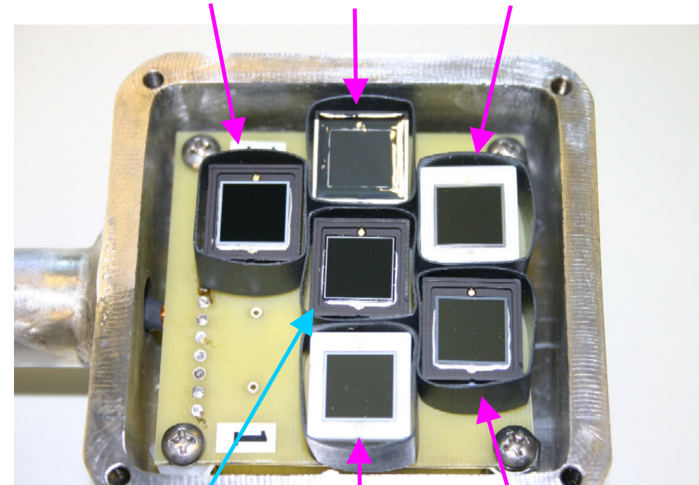
16 pins connector

AXUV100 diode with directly deposited filters

Zr/C

Sn/Ge

Ti/Pd



Cr/Al

Al

unfiltered (use as bolometer)

Characteristics of Filter

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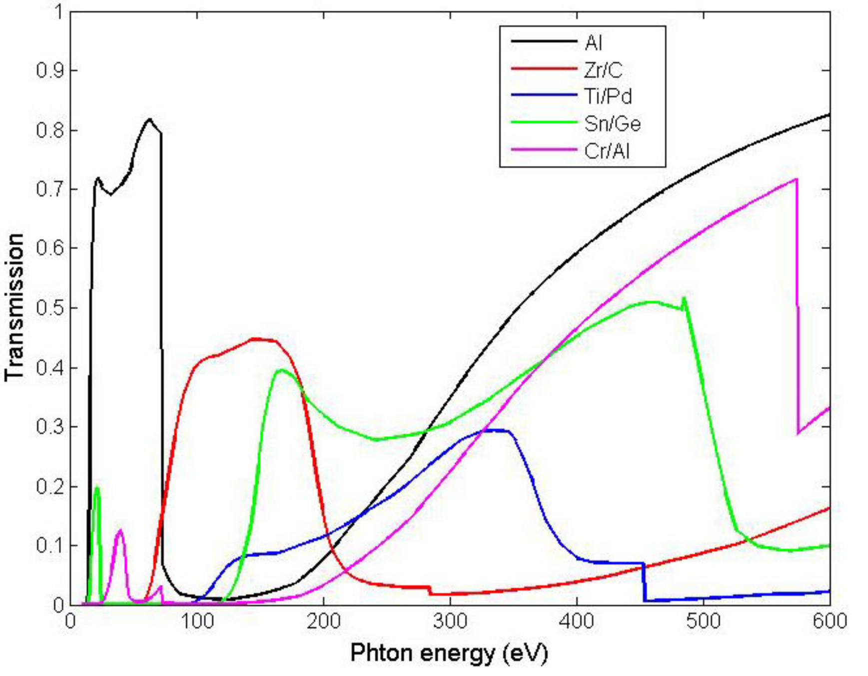
Filter transmission is obtained from the x-ray database at the *Center for X-Ray Optics of Lawrence Berkely Laboratory*. URL (http://www-cxro.lbl.gov)



Filter materials	Thickness (nm)	Transmission region (eV)
Aluminum	150	15–73 eV, @peak (63 eV, 0.817) 150 eV~ (relatively linear grad)
Zirconium/Carbon	200/50	62–230 eV (FWHM: 79–194 eV), @peak (147 eV, 0.447)
Titanium/Palladium	200/100	100–453 eV (FWHM: 227–375 eV), @peak (337 eV, 0.293)
Tin/Germanium	200/10	15–25 eV, @peak (21 eV, 0.197) 125 eV~, @peaks (167 eV, 0.394) & (462 eV, 0.51)
Chromium/Aluminum	60/150	26–53 eV, @peak (40 eV, 0.125) 175 eV~ (relatively linear grad), @peak (574 eV, 0.717)

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Installation of SXR system

Soft x-ray measurement system is mounted at the end flange viewing on z-axis.

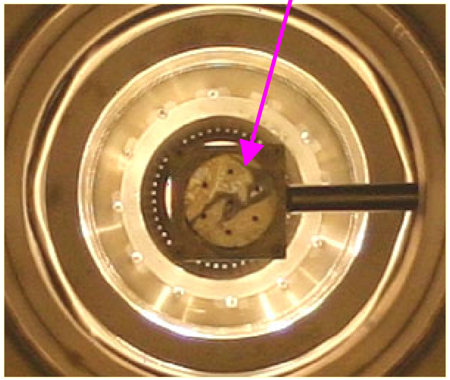
End flange

High Flux Source

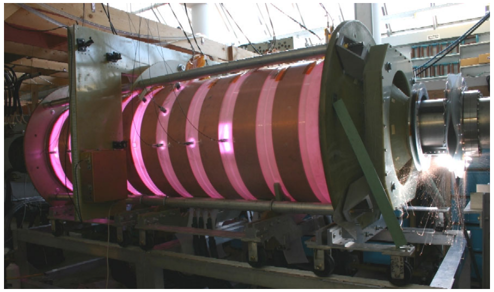
MPD

Initial plasma

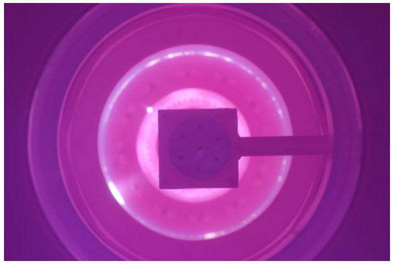
Thin Tungsten film



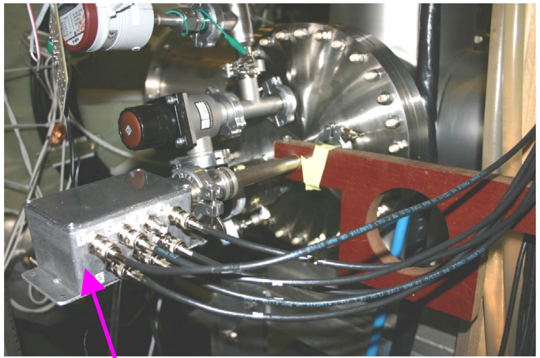
End view from downstream



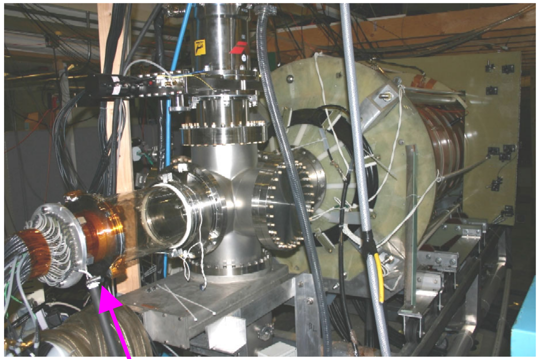
Plasma shots



Plasma shots



Aluminum box (batteries inside)



MPD

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Estimation of Detector Signal

The emissivity of SXRs can be determined either from a bremsstrahlung formula or using a spectral analysis code.

The continuum radiation is approximated by a bremsstrahlung formula

$$\frac{\Delta W}{\Delta E} \propto n_e^2 T_e^{-1/2} \exp\left(-E/T_e\right)$$

where, ΔW is the power radiated in the photon energy interval ΔE. To calculate the detector signal, we can numerically integrate above Eq. over photon energy and along the detector line of sight *l* , taking into account the filter transmission (quantum efficiency):

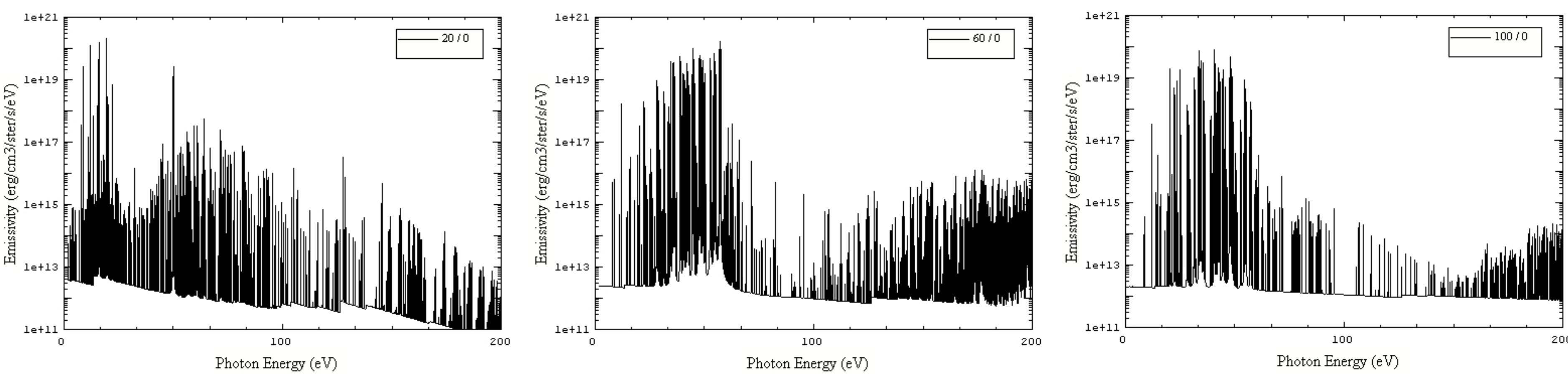
$$I_{\det} \propto \int_l \int_E n_e^2(l) T_e^{-1/2}(l) \exp(-E/T_e(l)) S(E) I(E,l) dE dl$$

where, *S* and *I* represent the filter transmission and the relative intensity of impurity lines to the continuum, respectively.

Sample Spectrum on PHDX

To estimate the sample spectrum on the PHDX, PrismSPECT (spectral analysis code from Prism Computational Sciences, Inc.) is used. The assumptions for these calculations are: time-independent, non-LTE (collisional radiative equilibrium) ionization and level population calculation, with optically thin radiation transport. Predominantly **Deuterium plasma**, but with the following impurities, % atomic: **Carbon-0.25%, Oxygen-0.5%, and Silicon-0.1%**. Based on the atomic model (ATBASE v5.1), we used H-61 levels, C-641 levels, O-1304 levels, and Si-3833 levels.

Simulation conditions: n~3×10^{21}m^{-3} and T_e~20,60,100eV



Sample Spectrum on PHDX

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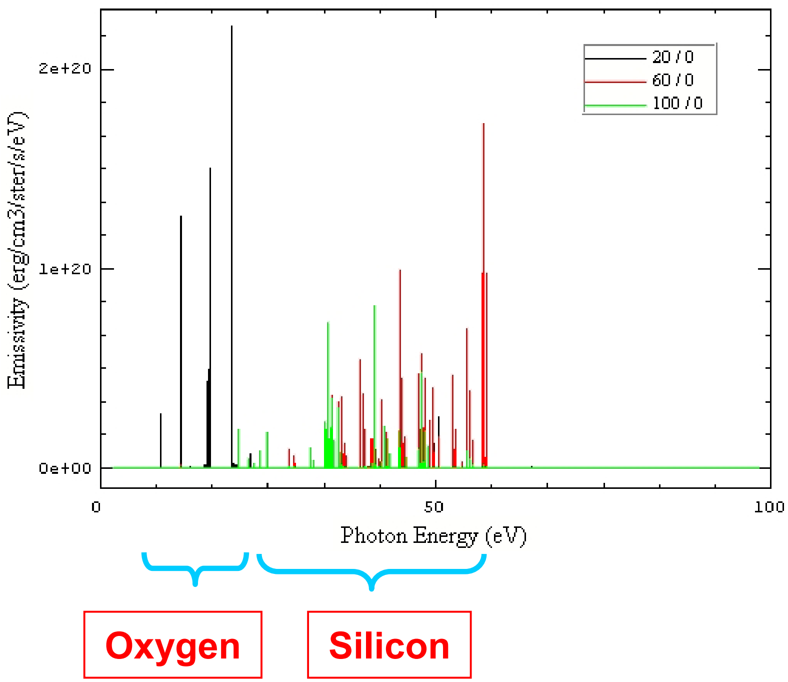
linear scale

T_e~20,60,and 100eV



Ionization balance – mean charge states

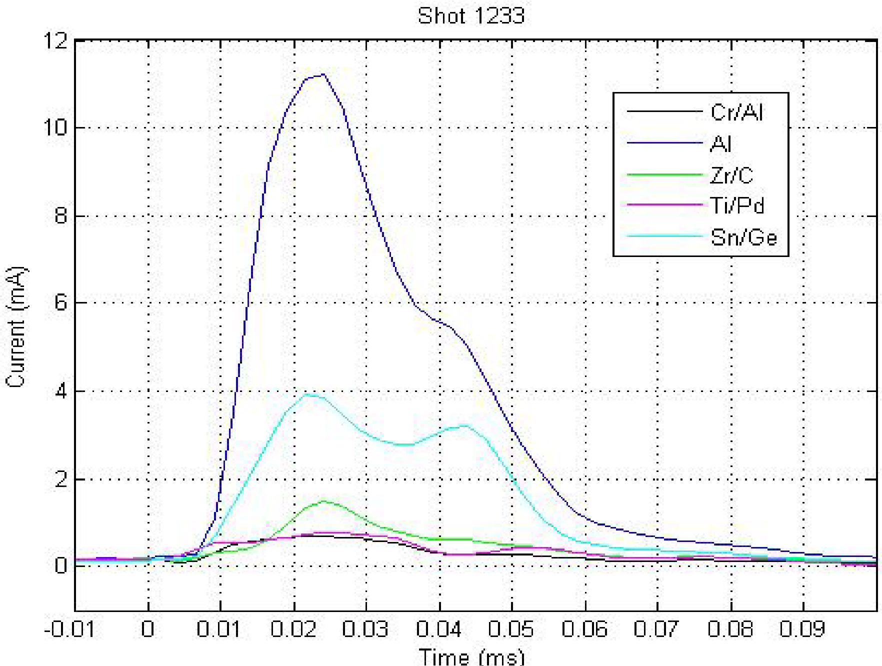
	20 eV	60 eV	100 eV
Z_H	1 (3.16×10^{-6} H^o)	1 (6.36×10^{-7} H^o)	1 (3.11×10^{-7} H^o)
Z_C	3.997 (99.7% C^{+4}, 0.3% C^{+3})	4.558 (54% C^{+5}, 45% C^{+4})	5.255 (68% C^{+5}, 29% C^{+6} , 3% C^{+4})
Z_O	4.799 (40% O^{+4}, 37% O^{+5}, 21% O^{+6})	5.992 (99.2% O^{+6}, 0.7% O^{+5})	6.048 (95% O^{+6}, 5% O^{+7})
Z_{Si}	4.111 (89% Si^{+4}, 11% Si^{+5})	7.359 (38% Si^{+7}, 35% Si^{+8}, 14% Si^{+6})	9.914 (52% Si^{+10}, 22% Si^{+9}, 18% Si^{+11})

In a given spectrum a small number of strong lines dominate, and a single element can completely dominate the emission; dominate impurity lines, for instance, are all from Oxygen at 10 eV and Silicon at 50 eV.
Impurity lines dominate over continuum, and note that the continuum is dominated by recombination, rather than free-free emission

Result from Soft X-Ray Detectors

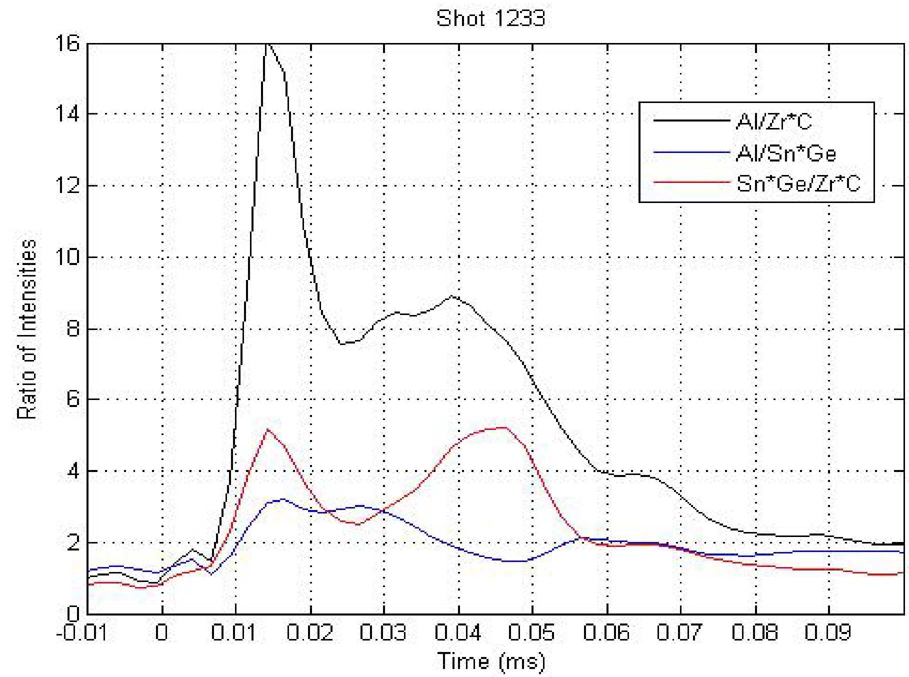
We assume that each detector measures the same plasma conditions (density and temperature profiles) and line of sight.

SXR signals of all five filtered-diodes are subtracted by that of a vacuum reference, respectively.
Since the Al filter has wideband and high transmission at low photon energy region, peak current of the diode is approximately 11 mA (*t*~22 μs).



Signals from SXR detectors

Here we can obtain the ratios of several choices of signal combination and time point



Ratios of intensities

Calculated Responses using Spectral Analysis Code

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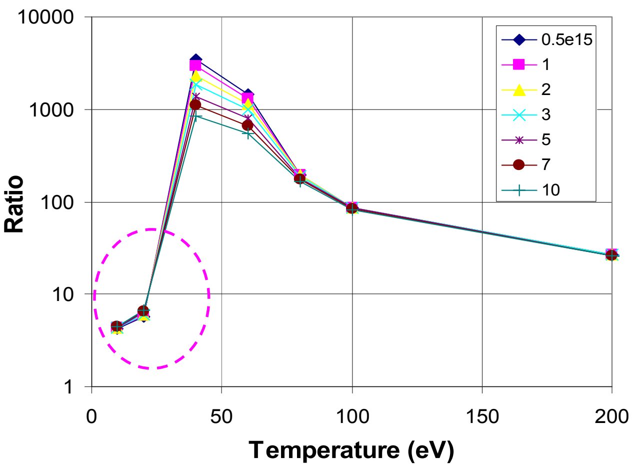
Electron temperature T_e and electron density n_e are approximately determined by comparing the response of the several filtered detectors (experiment) to their computed response using the emissivity from the PrismSPECT (simulation).

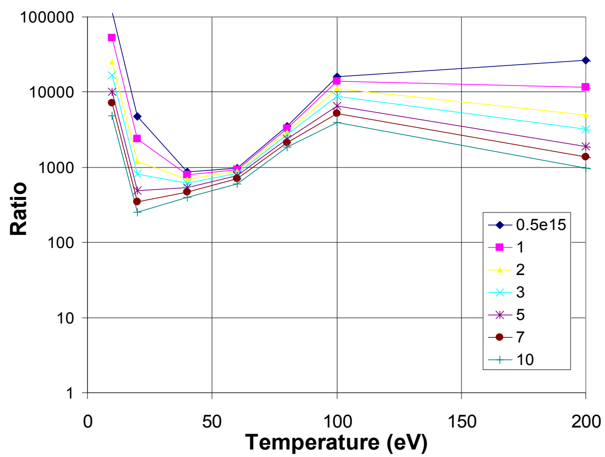
We calculated several plasma conditions: n~0.5-10x10^{-21}m^{-3}, T~10-300eV.

After integrated the emissivity over photon energy with filter transmission, the ratio of responses as a function of electron temperature is obtained.

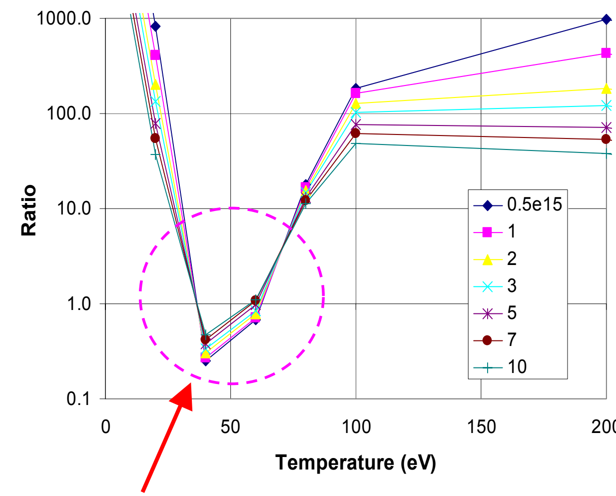
Al / Sn*Ge



Al / Zr*C



Sn*Ge / Zr*C



Reasonable order

Electron Temperature Diagnostics (Soft X-Ray Measurement)

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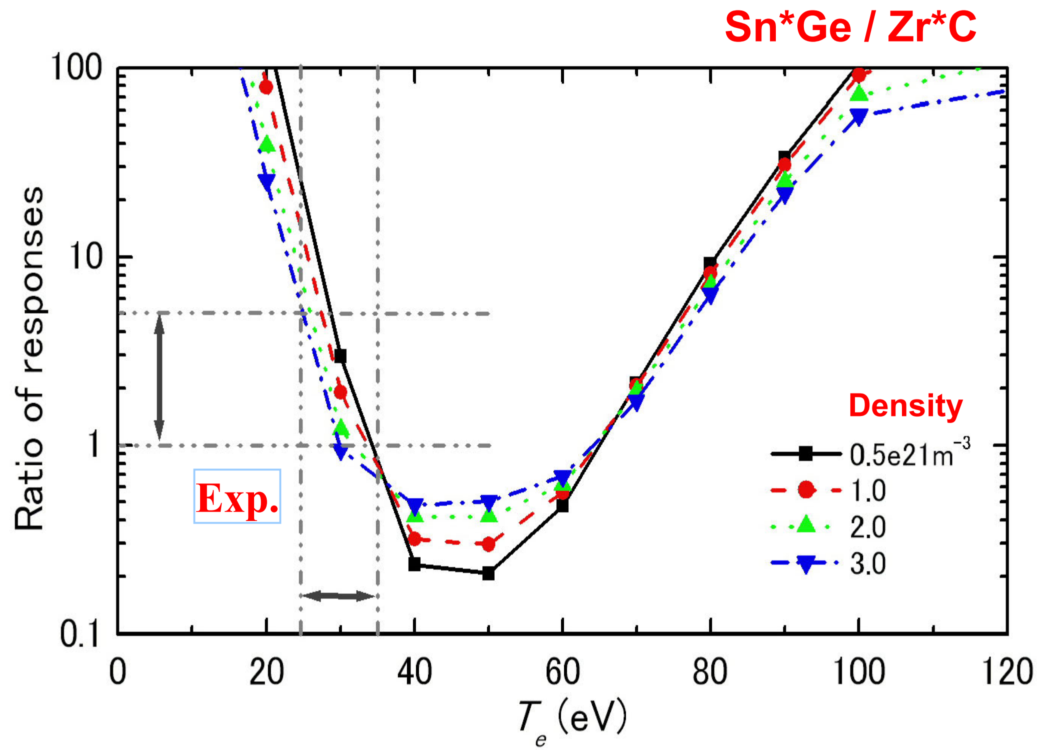
To compare the results of response between experiment and simulation, we chose the ratio of Sn/Ge- to Zr/C-filtered responses.

In this analysis it is hard to determine the plasma density in detail, so that information must be approximated from the result of interferometer.



According to a comparison of responses from both experiment (e.g. ratio of Sn/Ge to Zr/C signals is 2.7 at 22 μs) and simulation, T_e~30±2 eV can be estimated. It is a reasonable electron temperature, but comparison of other response ratios between experiment and simulation do not show adequate results. We presume some assumptions made in the simulation are inaccurate, for instance, an assumed the steady-state equilibrium and fixed impurity fractions of HFS.

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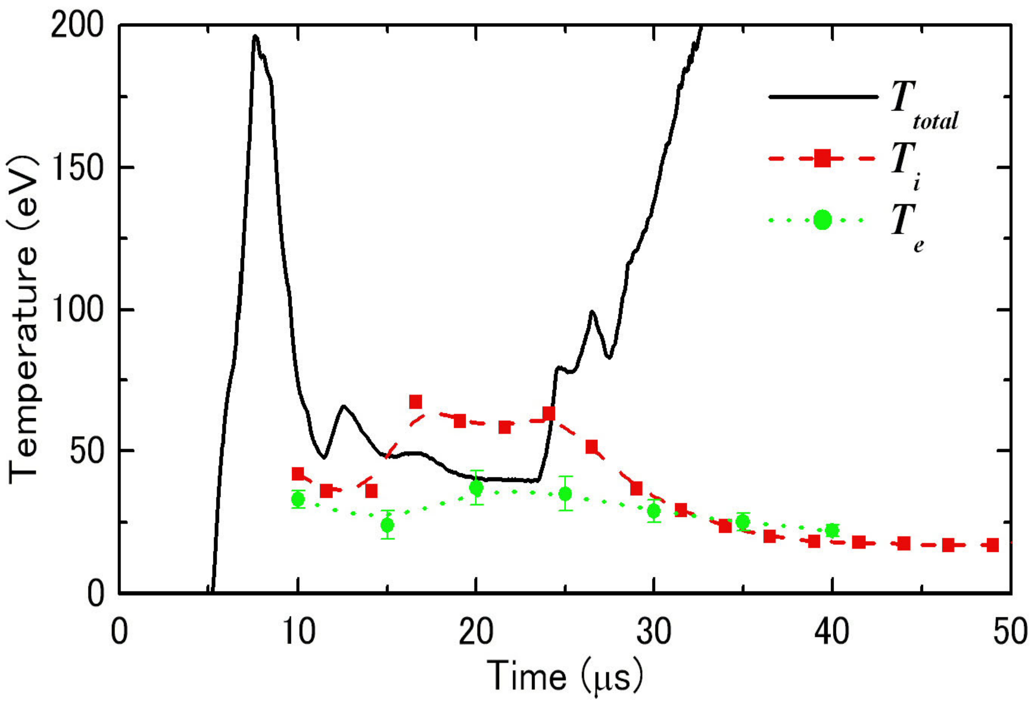
Comparison of Results from All Temperature Diagnostics

We finally got results from all three temperature diagnostics for FRC plasmas. Now comparison of all results (T_{total}, T_i, and T_e) is shown.

In case of the equilibrium of FRCs, we can be simply presumed the relation of $T_{total}=T_i+T_e$.



Result indicates the relatively good agreement of $T_{total} \approx T_i+T_e$ at t=10–15μs, but during 15–25μs it is to be $T_{total}<T_i+T_e$, especially high T_i.

- **Experimental problems**
  - **Setup of the devices (position)**
  - **Plasma condition (equilibrium?)**
- **Simulation problems**
  - **Any assumptions (steady-state?, impurity)**
  - **Analysis method (comparison of responses)**

Summary

In order to obtain the electron density n_e and total temperature T_{total} of the FRC plasma, a λ=632.8 nm He-Ne laser interferometer system is set up near the midplane of the HFS. To estimate ion temperature T_i of FRCs a 16 channel spectrometer (SPEX) is installed for end-on viewing. For more detailed density and temperature analyses, we recently developed soft x-ray measurement system on the end flange of HFS. This system consists of collimators and five AXUV100 photodiodes with directly deposited filters: approximately 0.1-0.3 μm thick films (Al, Zr/C, Sn/Ge, Cr/Al, and Ti/Pd) on each diode. To estimate the sample spectrum on HFS, the spectral analysis code (PrismSPECT) is used.

Results from these diagnostics, we obtained time sequence of FRC plasma temperature. The preliminary experimental results are T_{total}~50 eV, T_i~50 eV, and T_e~25 eV at a relatively quiescent phase (t=15 μs). They are not an exact match; $T_{total} \neq T_i + T_e$ during discharge. For future iterations we will change the location and observation impurity line of spectrometer, fractions of impurity on HFS, and our assumptions of the plasma condition.