Development of Ultrafast CXRS system in Heliotron J

Graduate School of Energy Science
Kyoto University
LU XIANGXUN
03/15/2016

Outline

- 1. Introduction
- 2. Charge eXchange Recombination Spectroscopy (CXRS)
- 3. Comparison between Ultrafast CXRS and conventional CXRS System
- 4. Design of Ultrafast CXRS System
- 5. Initial performance test
- 6. Summary

Introduction

- In magnetically confined fusion plasmas, fluctuation measurement of ion temperature and flow velocity can proivde indispensable information in anomalous transport study.

- Charge-eXchange Recombination Spectroscopy (CXRS) is a powerful method that measures the local ion temperature and flow velocity [1]. In Heliotron J, the parallel and poloidal direction Charge-eXchange Recombination spectroscopy (CXRS) system have been installed [2].

- The temporal resolution of conventional CXRS system is about 200Hz~1kHz. For fluctuation measurement, high temporal resolution up to several-hundred-kHz with high S/N ratio are required.

- In this study, the design of Ultrafast CXRS System will be introduced, and the initial test results will be shown.

[1] R. J. Fonck et al., Phys. Rev. A, **29**, 3288 (1984).
[2] H.Y. Lee et al., Plasma Fusion Res., **7**, (2012) 1402019.

Introduction

Heliotron J device

- Heliotron J is a medium-sized heliotron device in Instute of Advanced Energy (IAE) of Kyoto University.

Heliotron J Device parameter

Major radius: R=1.2m

Averaged minor radius: r=0.1-0.2m

Magnetic field strength (on axis): B<1.5T

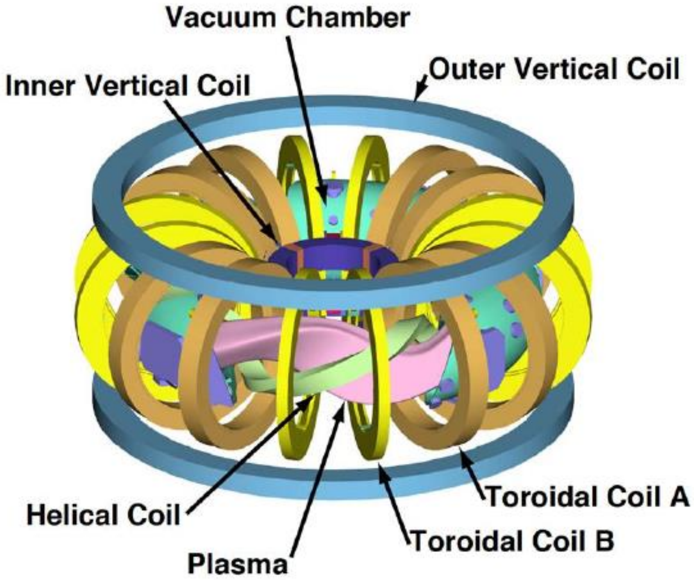
Plasma parameter:

Max Electron temperature: ~2.5keV

Max Ion temperature: ~400ev

Max plasma density: $\sim 10^{20} m^{-3}$

a. Side view



b. Top view

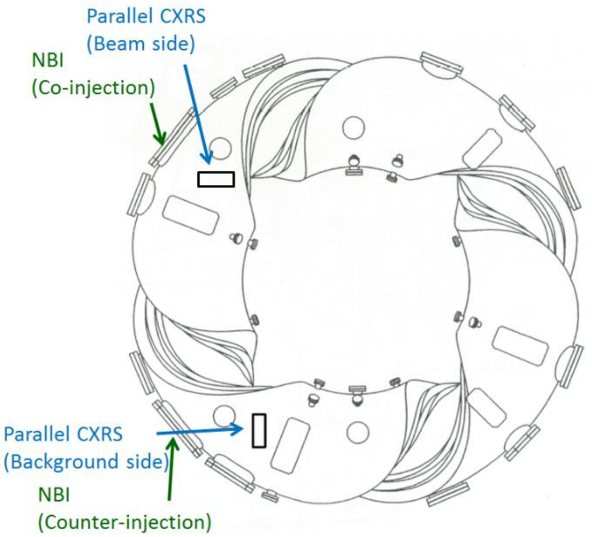


Fig.1. Schematic view of Heliotron J (a. side view , b. top view)

Introduction

Heliotron J device

- The magnetic confined fusion reactor can be generally divided into two groups: Tokamak and Stellarator device.
- Tokamak: The center coils are used to generate plasma current and twist the magnetic fields for plasma confinement.
- Stellarator: The magnetic fields are generated by twisted coil directly. Heliotron J is a special type of Stellarator device.

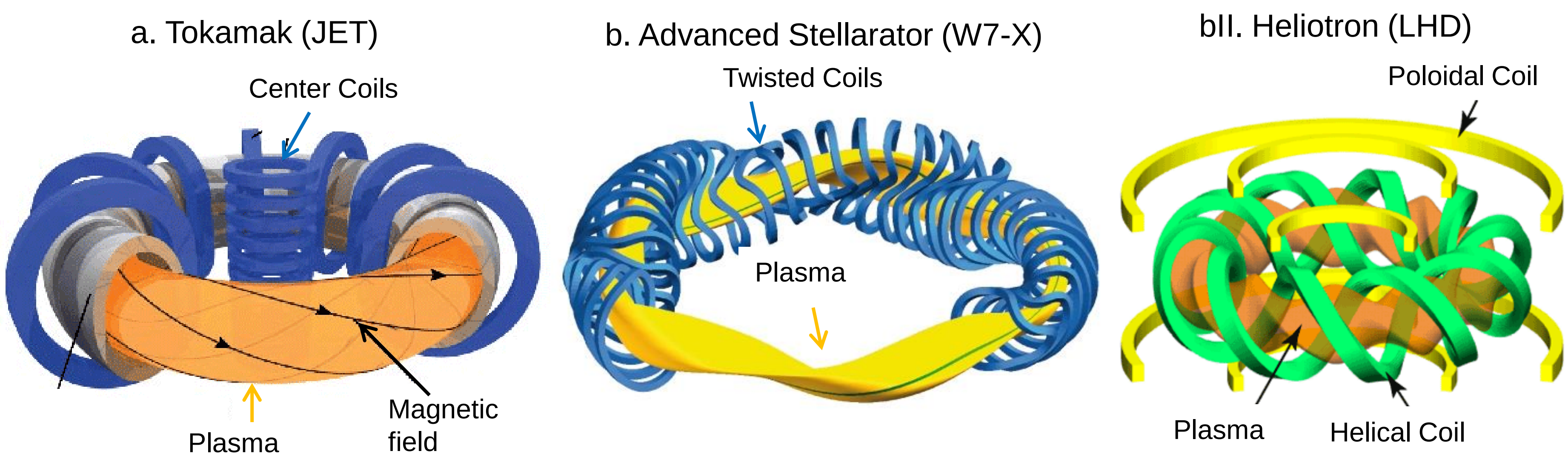


Fig. Schematic view of Tokamak device (a) and Stellarator device (b, c)

Charge eXchange Recombination Spectroscopy

- The Charge-eXchange Recombination Spectroscopy (CXRS) method measures the emission spectrum which emitted from Charge-eXchange Recombination (CXR) reaction .
- The CXR reaction occurrs with fast neutral beam particle and fully ionized impurity ion which described as follow equation.

$$H^0(Beam) + A^{z+} \rightarrow H^+ + A^{(z-1)+}\ (n = i + 1) \quad (1)$$

$$A^{(z-1)+}\ (n = i + 1) \rightarrow\ A^{(z-1)+}(n = i) + hv \quad (2)$$

- The temperature and flow velocity of impurity ion could estimated from the Doppler broadening and Doppler shift of emission spectrum.
- In Heliotron J, the CVI emission (n=8-7, 529.05nm) is being measured since carbon ions are intrinsic impurities.

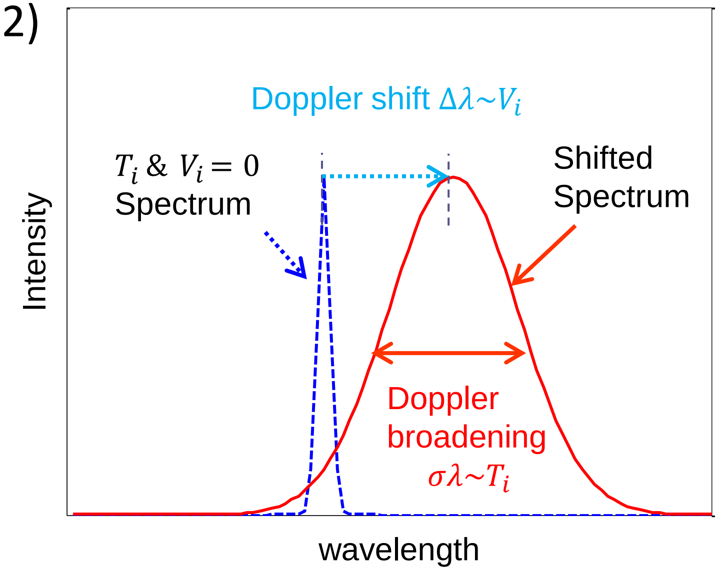


Fig.2. Schematic view of Doppler shift and Doppler broadening

Charge eXchange Recombination Spectroscopy

- However, the measured spectra also include the background emissions, which emitted from the charge-exchange reaction with thermal neutrals (3), electron impact excitation (4) and the electron recombination (5) [3].

$$H^0(Thermal) + C^{6+} \rightarrow H^+ + C^{5+}\ (n = 8) \rightarrow C^{5+}\ (n = 7) + hv \quad (3)$$

$$e^- + C^{5+} \rightarrow e^- + C^{5+}\ (n = 8) \rightarrow C^{5+}\ (n = 7) + hv \quad (4)$$

$$e^- + C^{6+} \rightarrow C^{5+}\ (n = 8) \rightarrow C^{5+}\ (n = 7) + hv \quad (5)$$

- To subtract the background emissions, we installed two optical sets in beam side (sightline crossed with NBI) and background side (sightline not crossed with NBI) individually.

[3] M. TUNKLEV et al., Plasma Phys. Control. Fusion, 41, 985 (1999).

Design of Ultrafast CXRS System

Comparison between conventional CXRS System

- Conpared between conventional CXRS, the Ultrafast CXRS System is focus on the high temporal resolution, therefor the number of channels would be the disadvantage.

- Conventional CXRS in Heliotron J:
  Temporal resolution: 400Hz
  32 channels (200um of core diameter for each channel)
  Detector: EMCCD with 512×512 pixels, $16 \times 16 um/pixel$

- Ultrafast CXRS in Heliotron J:
  Temporal resolution: 200-500kHz
  8 channels (800um of core diameter for each channel)
  Detector: APD camera with 4×8 elements APD array, $1600 \times 1600 um/element$

Design of Ultrafast CXRS System

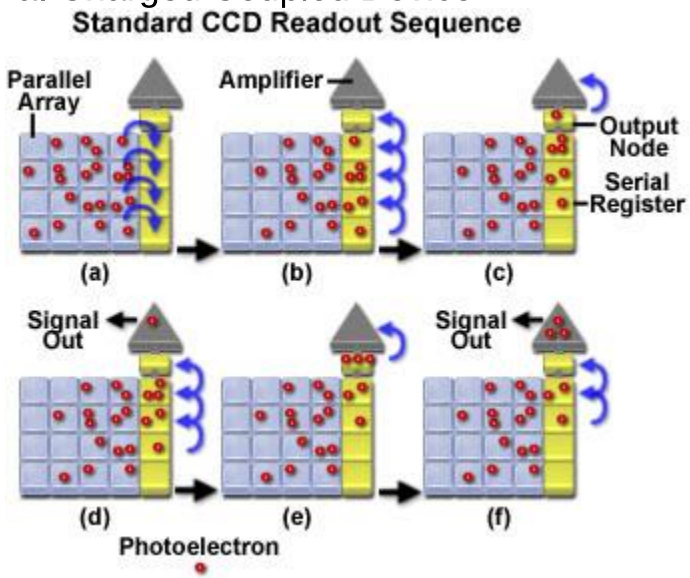
About the detector

- The EMCCD (Electron Multiplying CCD) is being used as the detector of conventional CXRS system.

  Merit: High Scalability & High QE & Low noise Demerit: Long readout time
- The APD (Avalanche Photodiode) array is being used in Ultrafast CXRS system.

  Merit: Extermely high sensitivity Demerit: Low Scalability & High noise

a. Charged Coupled Device



b. Avalanche Photodiode

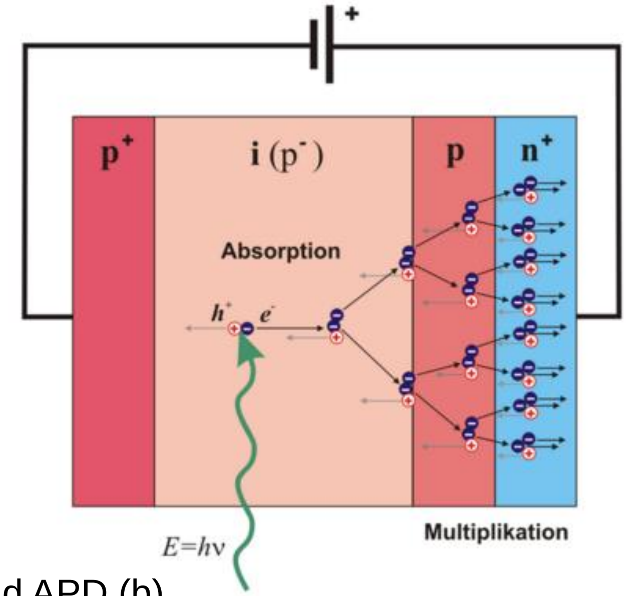


Fig.3. Schematic view of CCD (a) and APD (b)

Design of Ultrafast CXRS System

System view

- The frequency of turbulent are typically a few 100 kHz for typical fusion plasmas, therefore high temporal resolution up to 1 us is required for turbulent measurement [4].

- To achieve high temporal resolution with acceptable signal to noise ratio, a high throughput optical system with high sensitive, high speed photon detector are required.

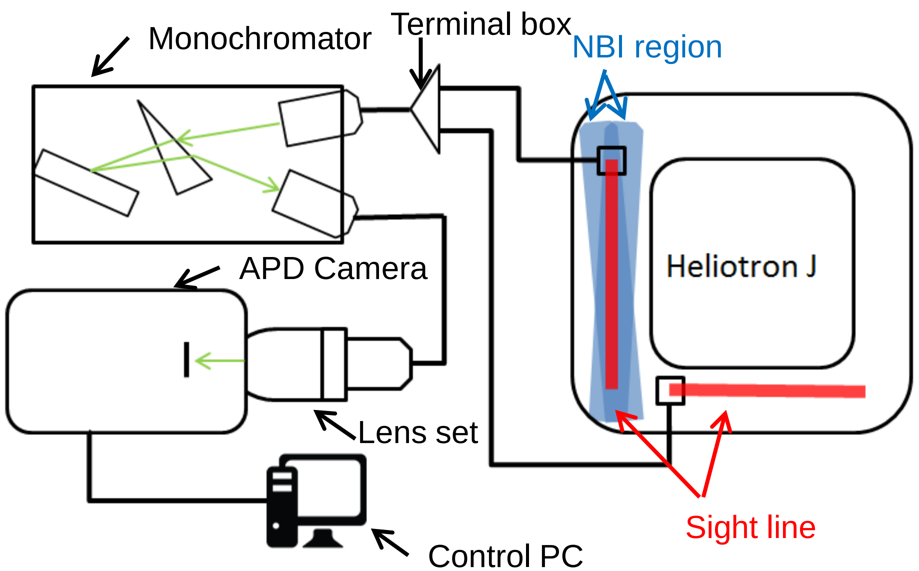


Fig.4. Schematic view of Ultrafast CXRS System

- The Ultrafast CXRS System consists of optical system, monochromator and detector.

[4] McKee, G. R., et al., Rev. Sci. Instrum. 79 (2008): 10F528.

Design of Ultrafast CXRS System

Optical system

- The observation ports are mounted in NBI beam region and background region, and the sight lines are parallel to the magnetic axis.
- The light signal is transmitted by optical fiber with large core diameter (0.8mm).
- A image fiber is used to connect the monochromator and lens set.

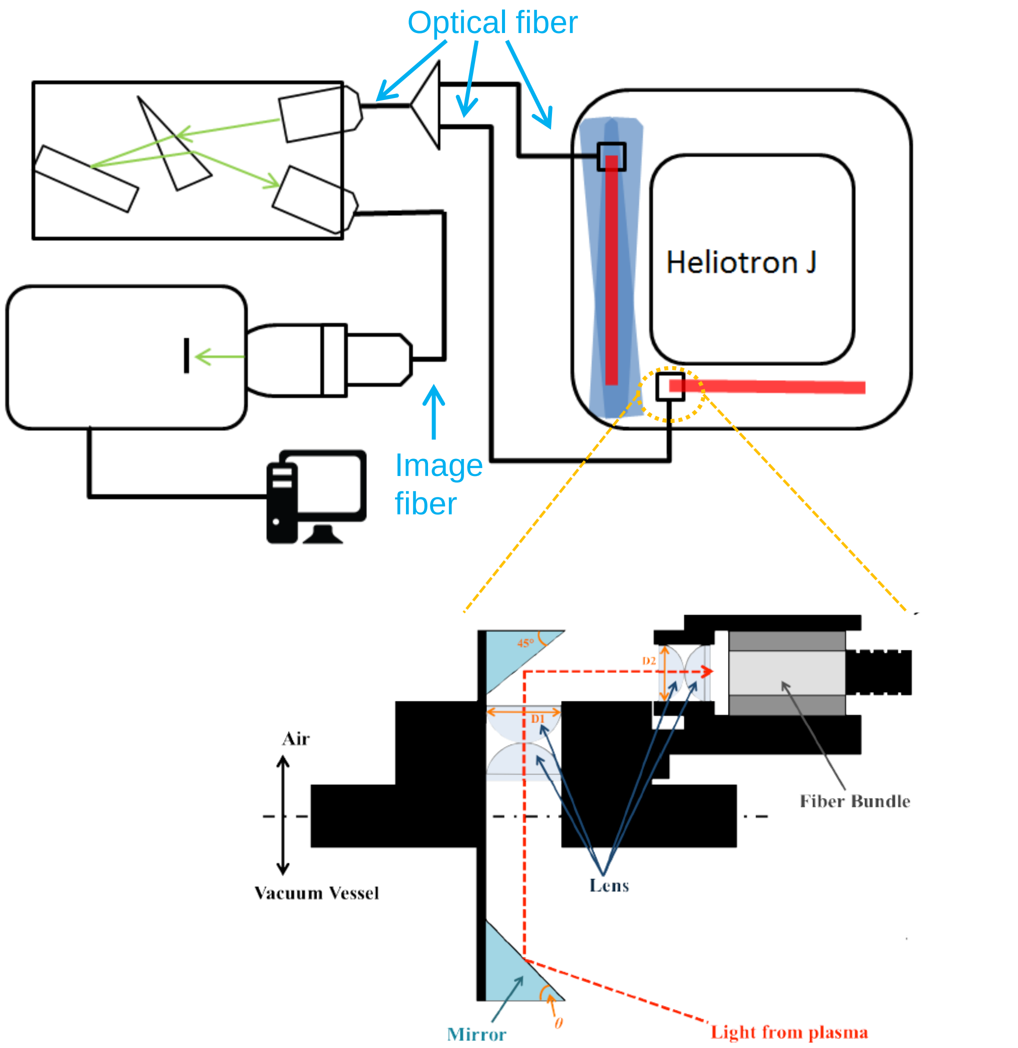
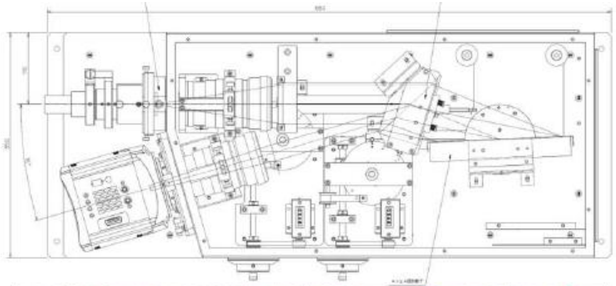
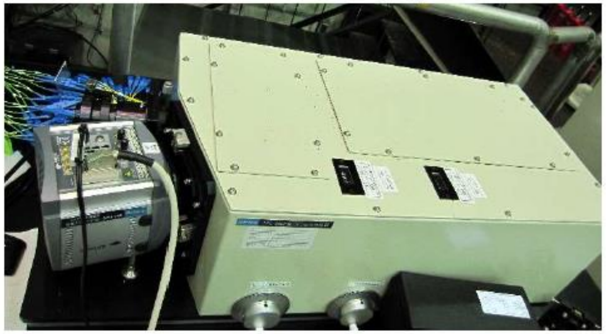


Fig.5. Schematic view of observation port

Design of Ultrafast CXRS System

Monochromator





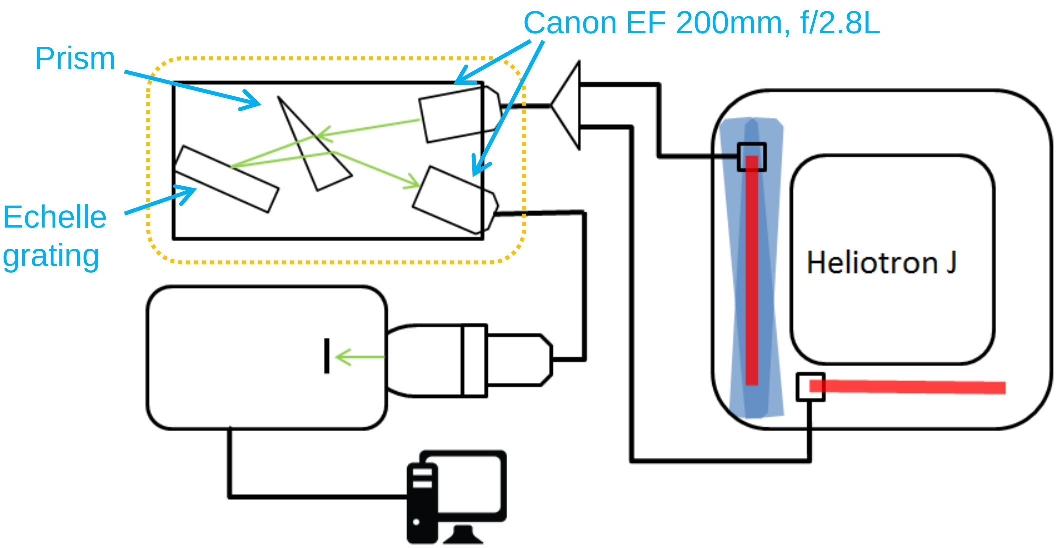


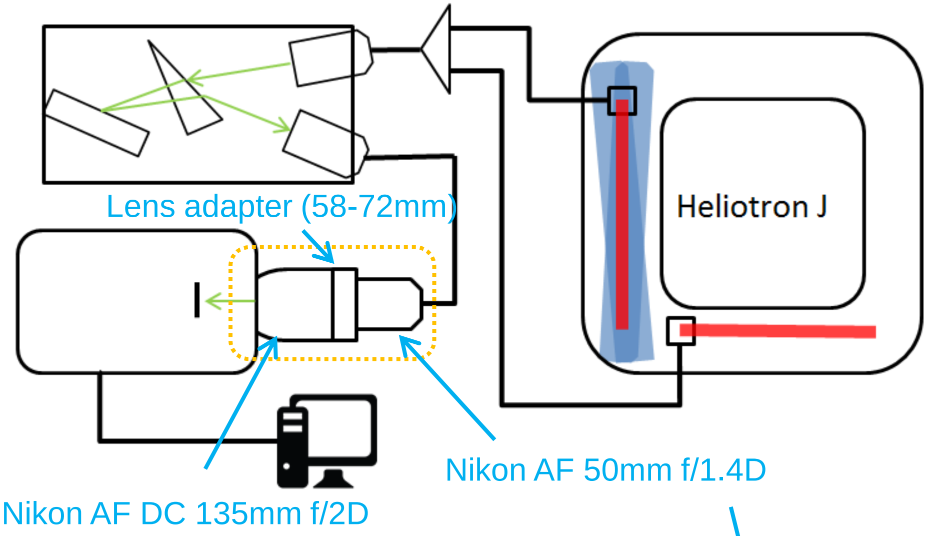
Fig.6. The Echelle-grating monochromator

- A high throughput Echelle-grating monochromator (Bunkoukeiki, SPL-200P) is being used .
- The focal length is 200mm and the f number is 2.9.
- The dispersion of monochromator is 0.185nm/mm at 529.05nm.

Design of Ultrafast CXRS System

Lens set

- The typical spectrum width at the output port of monochromator is about 2.72mm in the case of $T_i = 250eV$.
- A lens set (Nikon AF 50mm f/1.4D and AF DC 135mm f/2D) is used to zoom in the spectrum with a magnification of 2.7 times.



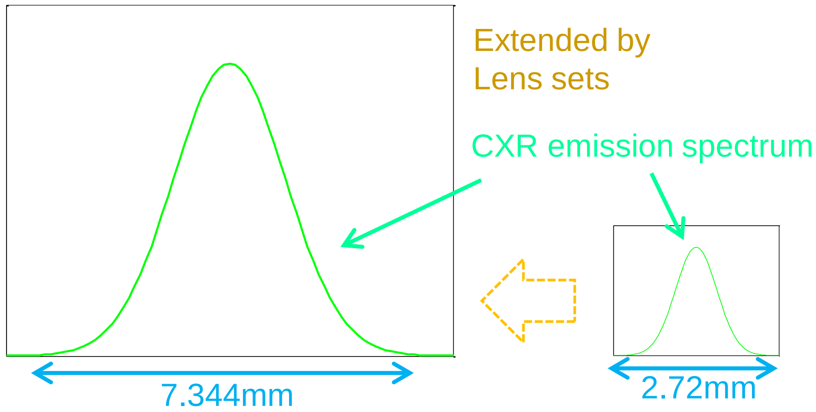


Fig.7. The lens set and extended CXR emission spectrum

Design of Ultrafast CXRS System

Detector

- The APD camera (Fusion Instruments Kft. APDCAM) with a Nikon F mount is coupled with the lens set.
- A 4 × 8 element APD array is being used as the detector.
- The typical gain factor is about 50 with 320V reverse voltage and the quantum efficiency is about 82% at 529.05nm

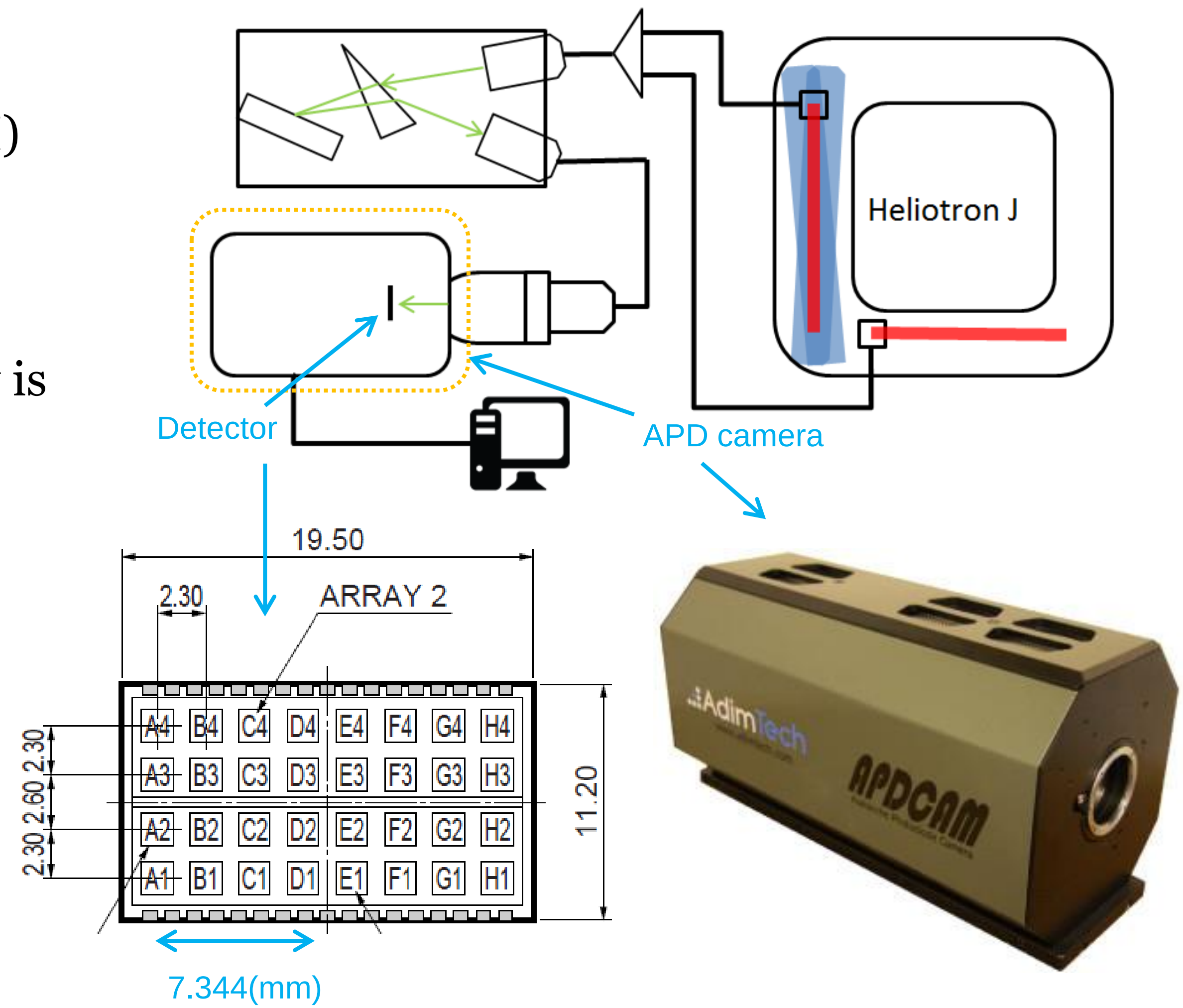


Fig.8. The APD camera and 4 × 8 element APD array

Initial performance test

- The APD camera was tested by a LED lamp and function generator.
- A sine wave was generated by the function generator and the intensity variation of LED lamp was measured by APD camera to measure the frequency characteristic, and the cutoff frequency of APD camera is about 220kHz.

a. Schematic view of test experiment

b. The frequency response of APD camera

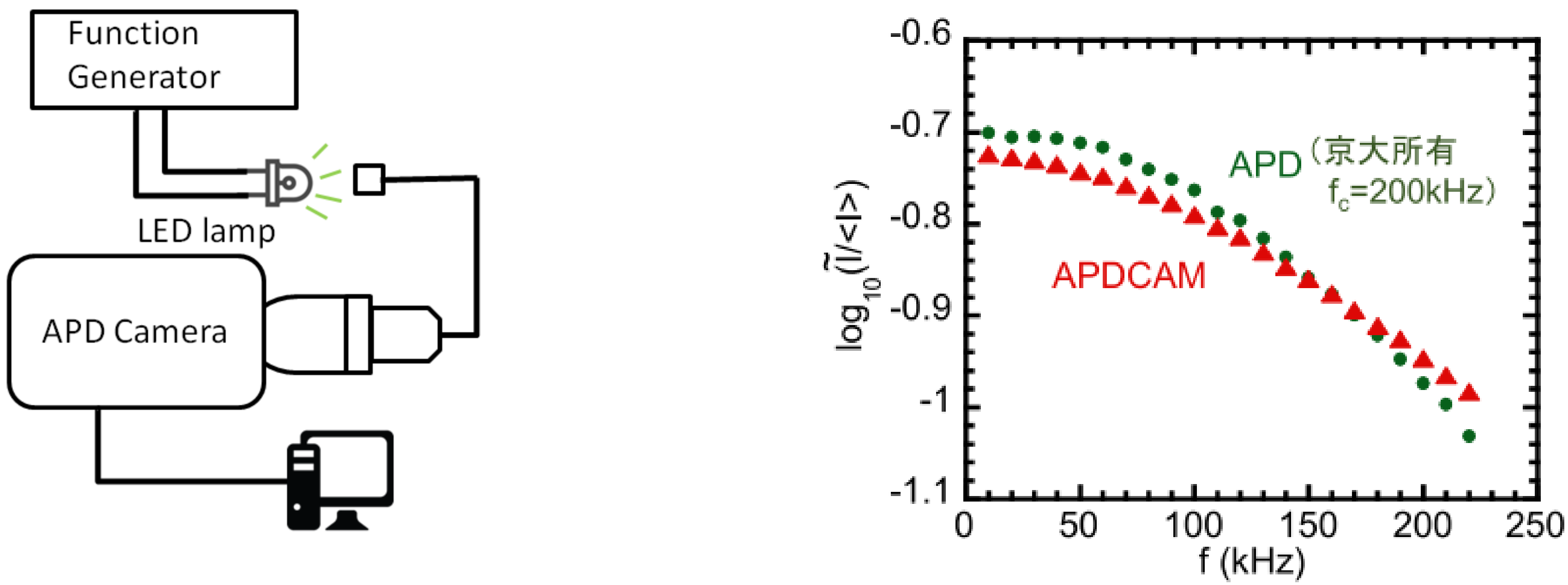


Fig.9. The test experiment (a) and frequency response of APD camera (b)

Initial performance test

- The intensity sensitivity of APD camera was also measured by change the amplitude of wave(10%, 1%, 0.1%).
- The data was processed using an ensemble averaging technique and the sensitivity is up to 0.1%.
- The maximum stable sampling frequency is 0.9MHz within 2 seconds acquisition time, depending on the data transfer rate to the control PC.

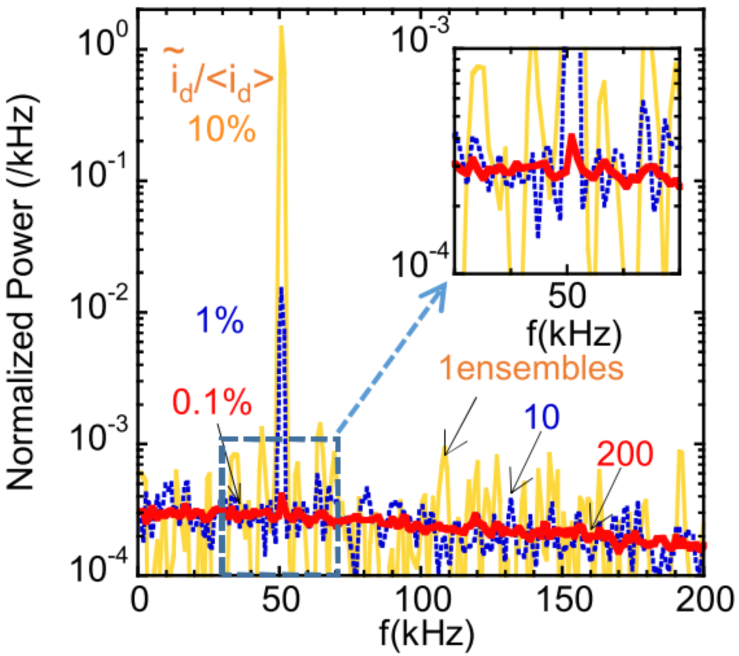


Fig.10. The sensitivity of intensity fluctuation

Summary

- In magnetically confined fusion plasmas, fluctuation measurement can proivde indispensable information in anomalous transport study.
- For ion temperature and flow velocity fluctuation measurement, a Ultrafast CXRS System aim to achieve 1us temporal resolution and acceptable signal to noise ratio is under development.
- The large core diameter optical fiber and high throughput Echell-grating monochromator is being used.
- The maximum stable sampling frequency is 0.9MHz and the sensitivity of intensity fluctuation is up to 0.1% in initial testing

Future works

- Calibrate the absolute sensitivity between each APD element.
- Complete the program for APD Camera control and data processing.
- Measure the CVI spectrum during plasma discharge and evaluate the ion temperature fluctuation.

Thank you for your attention!