Two-dimensional HeII Doppler shift image measurement in QUEST

QUEST Advanced Fusion Research Center

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Introduction

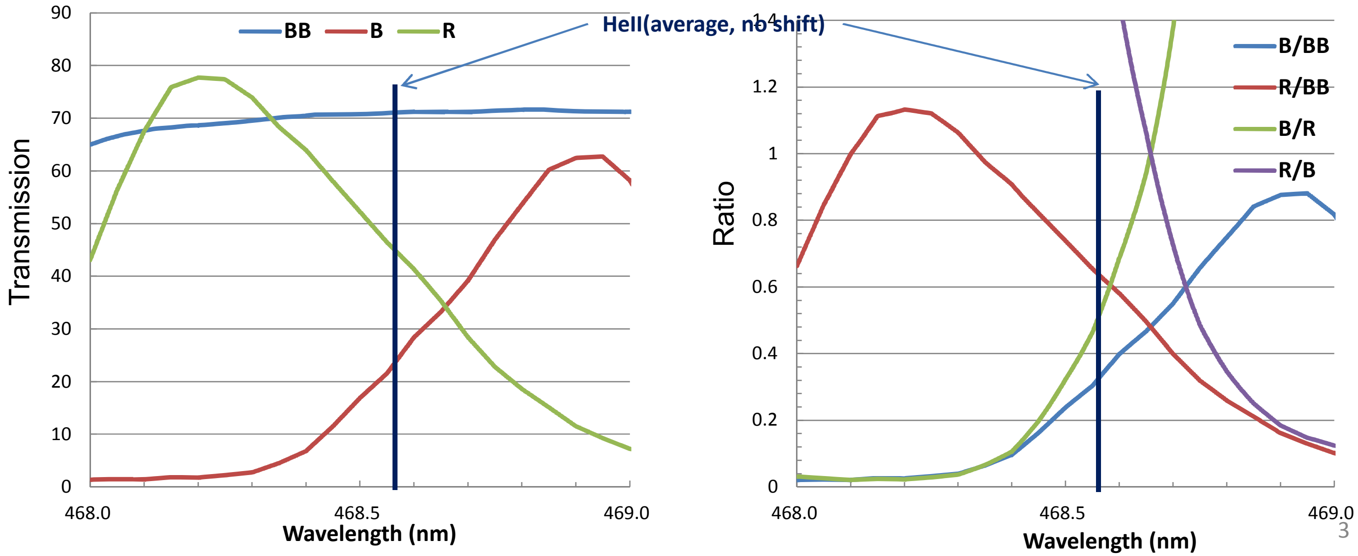
- Visible (or converted visible) light emission of two-dimensional profile is easily obtained by fast cameras, and the technology progress of the fast camera during recent decade is amazing.
- Fast cameras on many devices had shed much new light on the complex nature of plasma phenomena.
- And now, the qualitative analysis are needed to treat the image data.

- On the other hand,
- 2D Ion flow (or ion velocity) profile is also very useful information for understanding plasma physics.
- However, 2D ion flow profile measurement is not fully developed up to now.

- SWIFT (Shifted Wavelength/Interference Filter Technique) is easy to extend to 2D measurement for getting the ion flow profile.
- Therefore, this time we tried to measure HeII Doppler shift along the toroidal direction in QUEST plasma using a fast camera, several optical filters for HeII and an image intensifier.
- The original idea is SWIFT, and we modify this method.

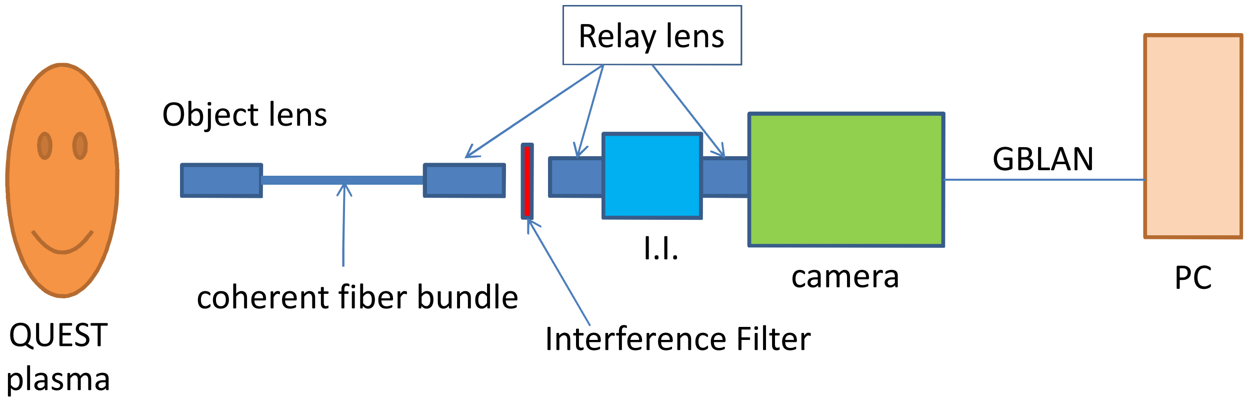
Principle of Doppler shift measurement

- Target line is HeII (this time).
- Various IF for target line are used (Blue edge, Red edge, Broad-Band at this time).
- The transmission of each filter depends on the wavelength.
- If the ratio of the transmission of each filter is a single-valued function of the wavelength, Doppler shift will be determined.



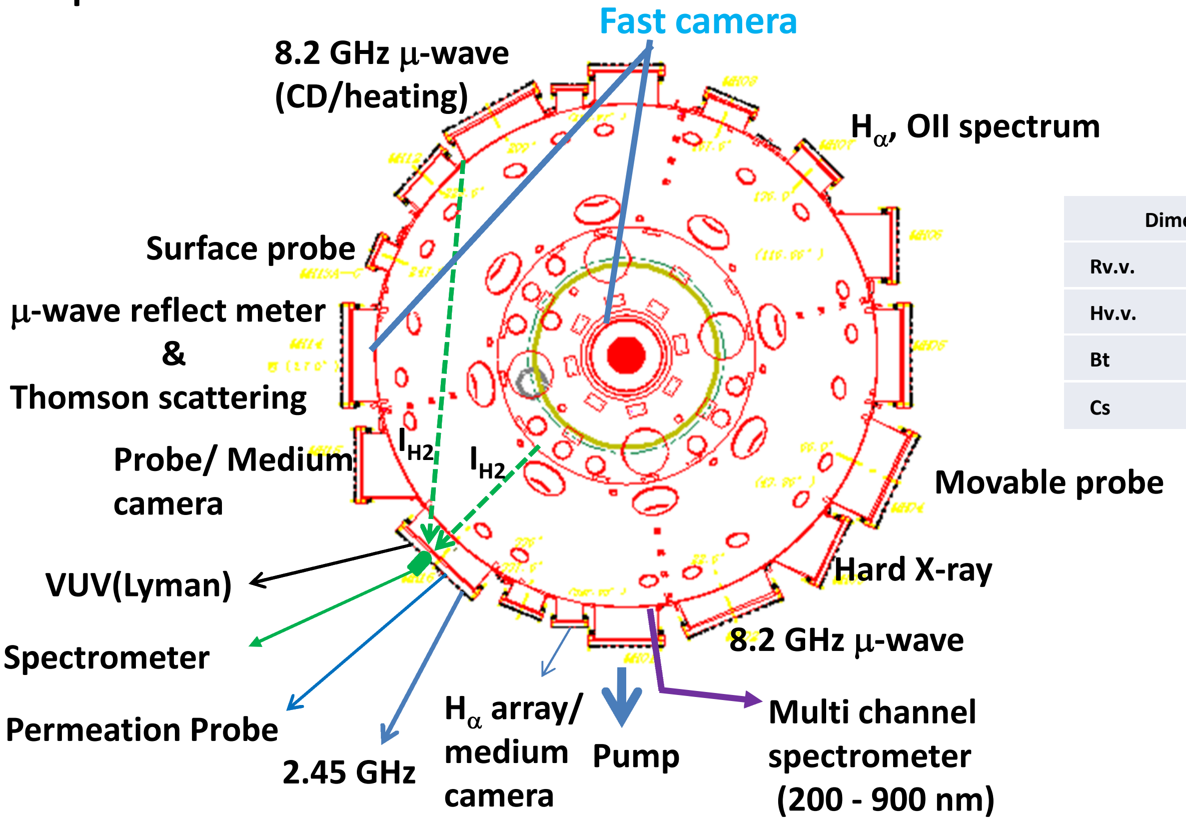
Fast camera with the Image Intensifier

- A coherent fiber bundle was used for wide application.
- The image intensifier was used due to lack of photons.



QUEST

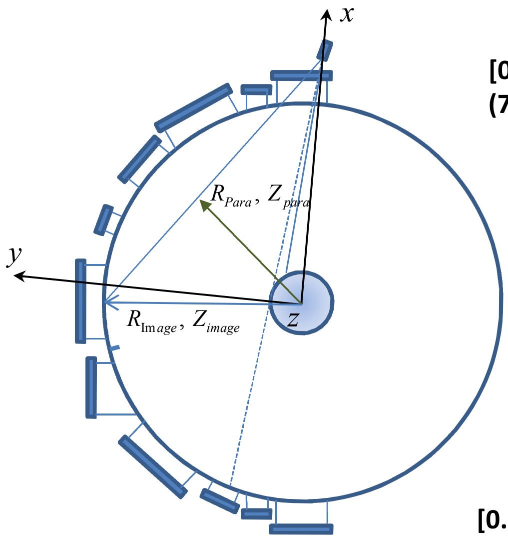
- **Top view and camera location**

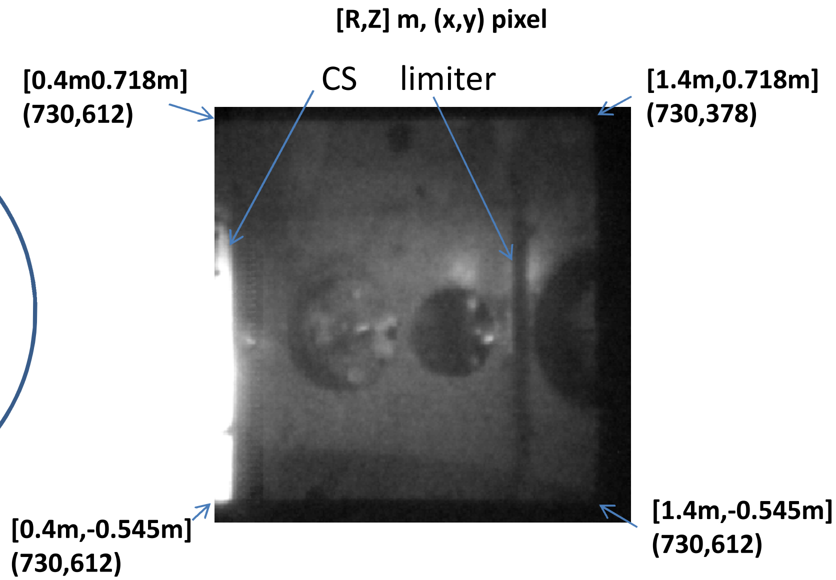


Dimensions	
Rv.v.	1.4m
Hv.v.	2.8m
Bt	0.25T
Cs	ϕ0.4m

Description of the coordinates for analysis

- The location of the fast camera is set to x-axis, and the center of the center stack is the origin.
- Z-axis is height, and right-hand side coordinate is used.

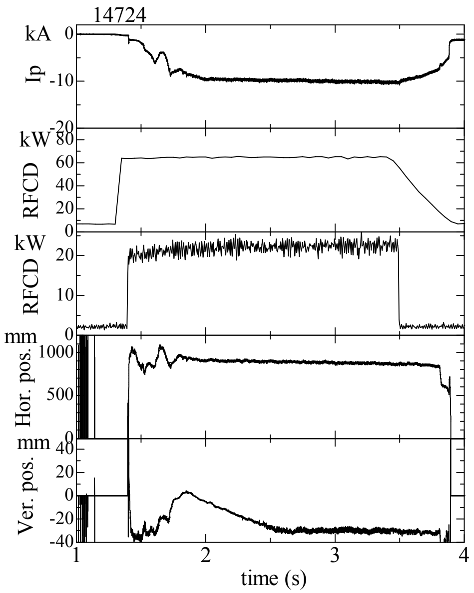


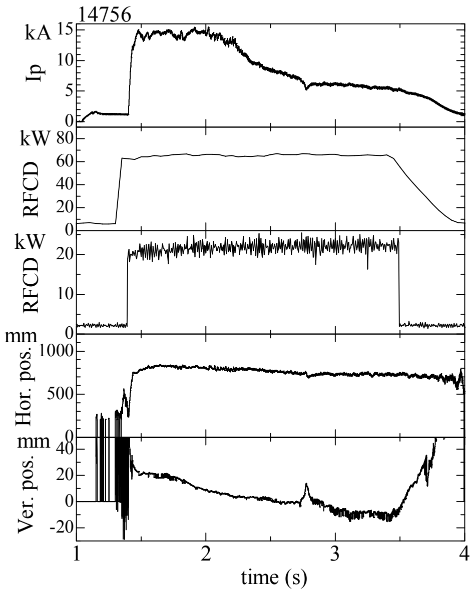


Reference image of the fast camera

QUEST PLASMAS

- Waveforms of RF current drive plasmas, two samples are shown.
- Normal Ip<0.

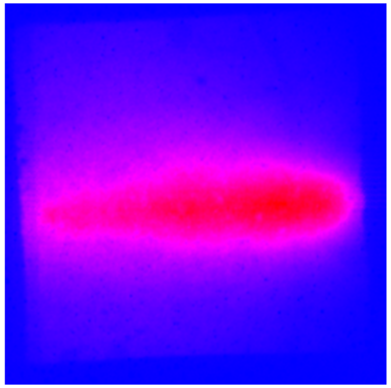




Images with optical filters – Normal Ip –

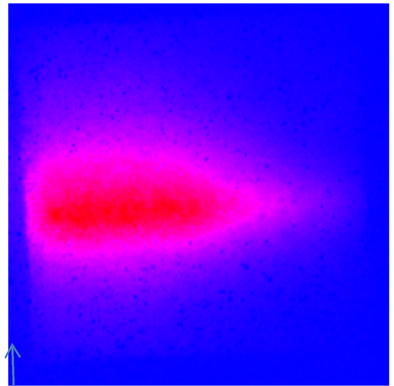
- Measurement was done with shot by shot due to single camera.
- #14724-#14726, Ip=-10kA, raw image (average of 0.1s images), 1000FPS

#14724, 2.0-2.1s average



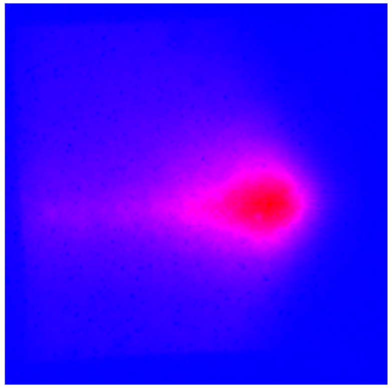
BB filter

#14725, 2.0-2.1s average

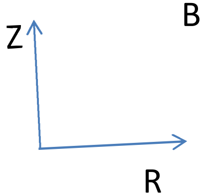


R filter

#14726, 2.0-2.1s average



B filter



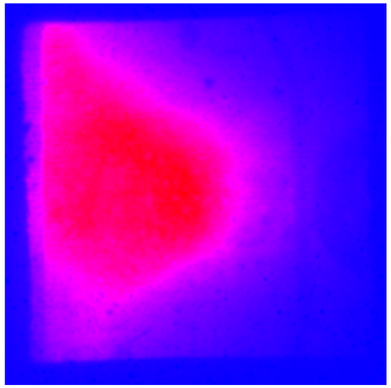
CS

The average of 100 images is taken to remove noise. Intensity is auto scale.
Plasma image is tilted a little, but the size is the same as that of the reference.

Images with optical filters – Reversed Ip –

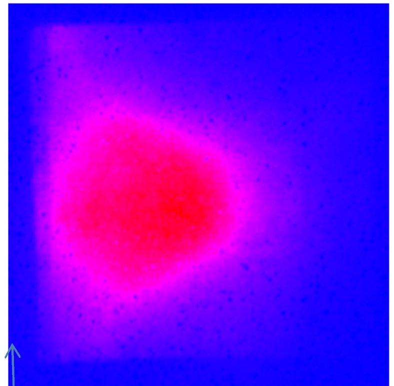
- #14756-#14758, Ip=15kA , raw image (average of 0.1s images), 1000FPS

#14758, 1.6-1.7s average



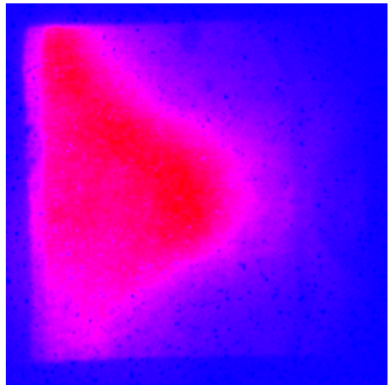
BB filter

#14756, 1.6-1.7s average



R filter

#14757, 1.6-1.7s average



B filter

Z

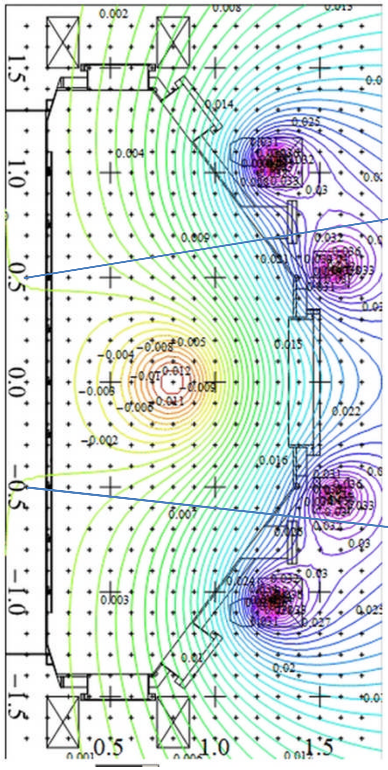
R

CS

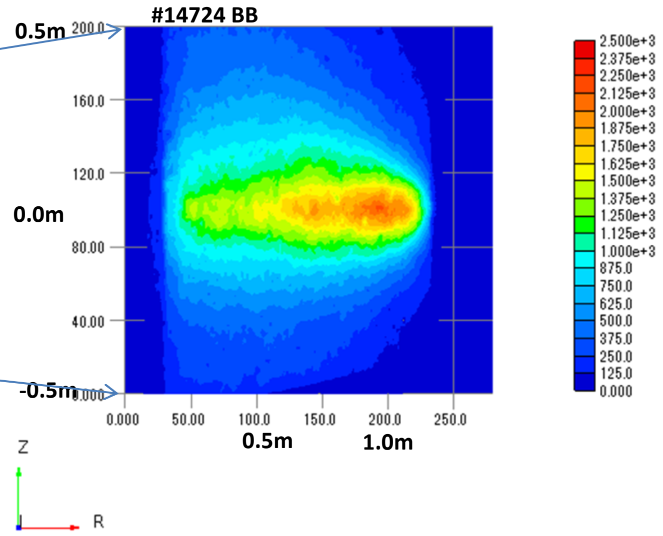
The average of 100 images is taken to remove noise. Intensity is auto scale.
Plasma image is tilted a little, but the size is the same as that of the reference.

HeII emission profile and magnetic flux cal.

- #14724 Limiter configuration (normal Ip)

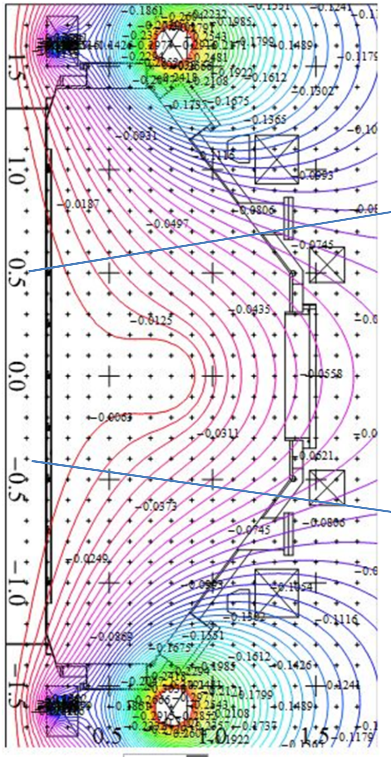


- Simple coordinate conversion
- Fan beam to Parallel beam conversion at every horizontal line

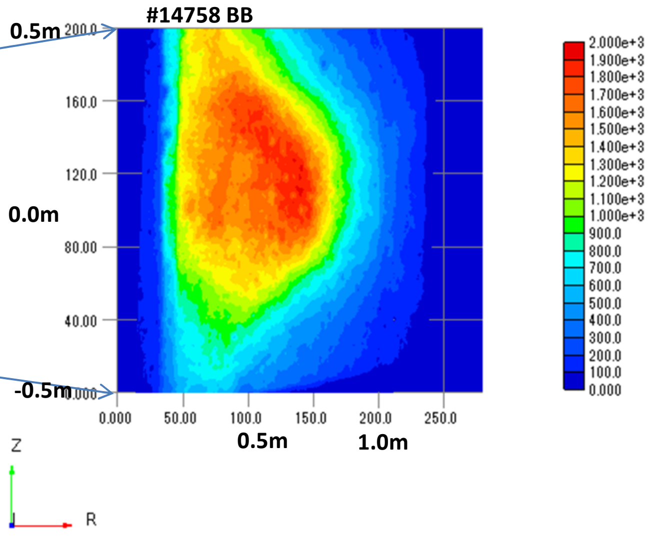


HeII emission profile and magnetic flux cal.

- #14756 Inner null configuration (reversed Ip)



- Simple coordinate conversion
- Fan beam to Parallel beam conversion at every horizontal line



Ratio image with R, B, BB

- Using the average <u>raw</u> image (R/BB and B/BB image)
- Limiter configuration (normal Ip)

Image R/BB #14725/24

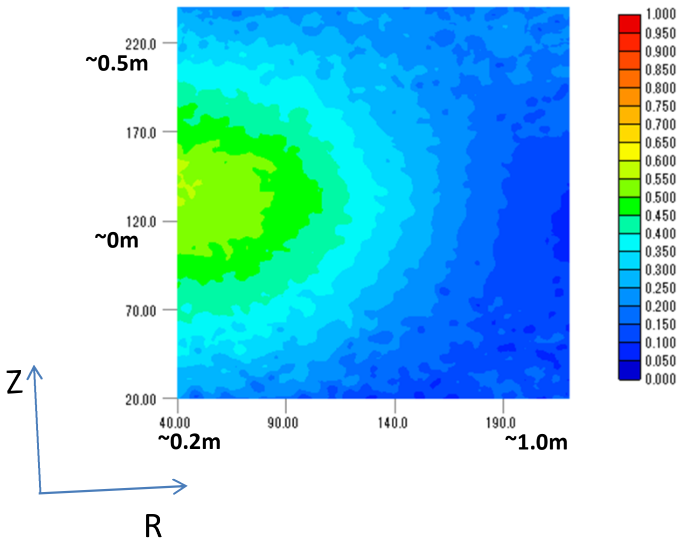
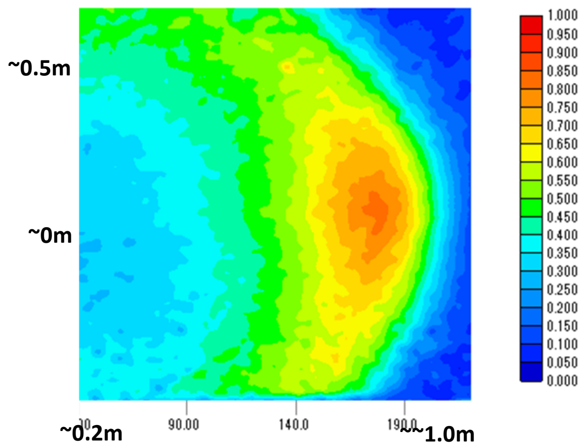


Image B/BB #14726/24



Ratio image with R, B, BB

- Using the average raw image (R/BB and B/BB image)
- Inner null configuration (Reverse Ip)

Image R/BB #14756/58

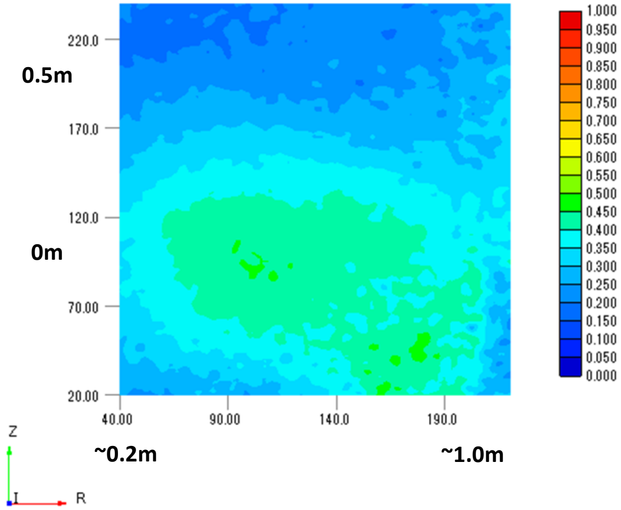
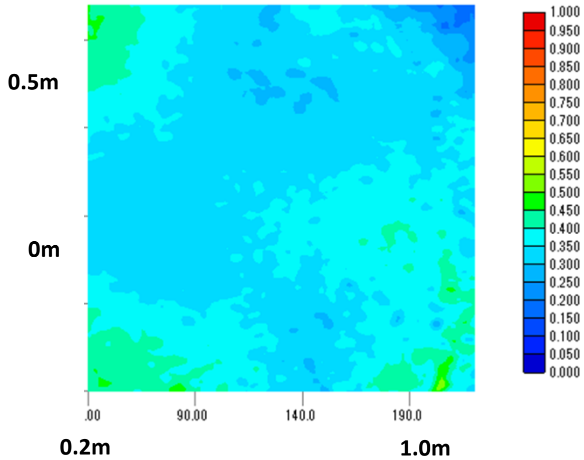


Image B/BB #14757/58



How to convert the image taken by this system to ion flow map

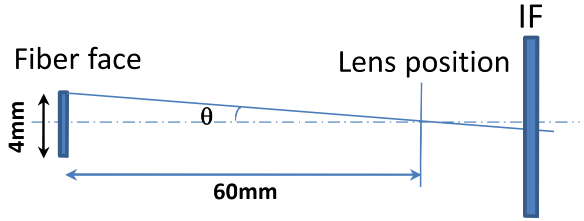
- Even though target plasma was thin (~$10^{18}m^{-3}$), using Image Intensifier and fast camera with 1000 FPS HeII emission profile was observed.
- It seems that the ratio of HeII emission using various filters and time average of 0.1s were useful.
  - Conversion of fan beam to parallel beam may be useful.
  - HeII emission patterns were different in two types of discharges.

- To estimate the Ion velocity from these images, the calibration procedure is needed to get zero ion flow (offset).

- An idea is that plasma of no current may give us the offset information on HeII flow.
- Before this procedure the incident angle dependence should be included.

Transmission dependence of the Incident angle

- Transmission of IF depends on the incident angle.
- Focal length of the lens at the fiber exit is ~60mm, and the fiber face size is 4x4mm, and the size of each fiber is 10μmx10μm.



- There is well known formula on the wavelength shift due to the incident angle.

$$\lambda = \lambda_{\max}\sqrt{1-\left(\frac{n_0}{n_e}\sin\theta\right)^2}$$

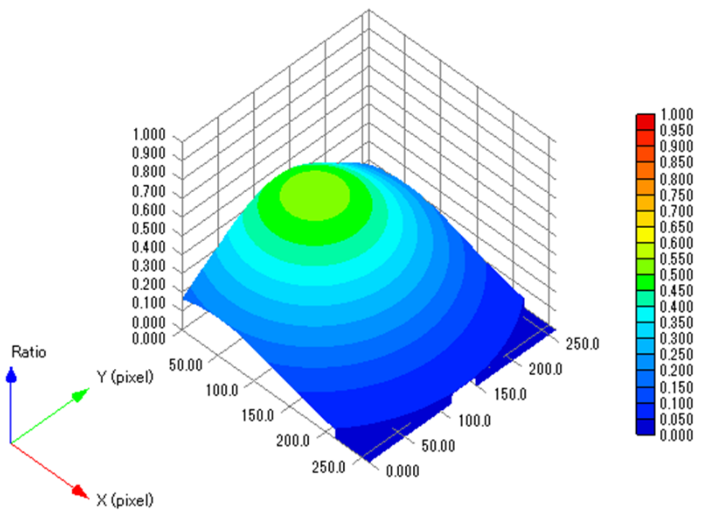
- Therefore, transmission of the same wavelength should be the concentric circle in the image.

$$\Delta\lambda = \lambda_{\max}\left[1-\sqrt{1-\left(\frac{n_0}{n_e}\right)^2\left(1-\frac{1}{\tan^2\theta}\right)}\right], \qquad \tan\theta = \frac{0.01X(fiber)}{60}$$

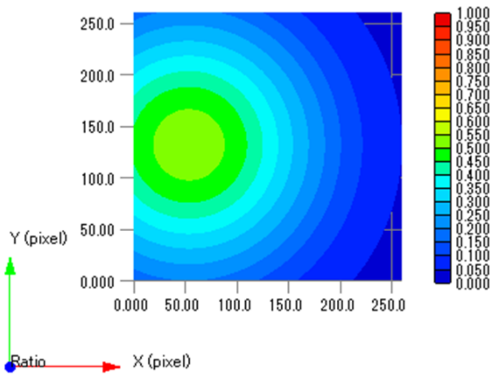
$$if\ \theta \ll 1,\ \ \Delta\lambda \approx \frac{1}{2}\left(\frac{n_0}{n_e}\frac{0.01}{60}\right)^2 \lambda_{\max} X^2, \qquad \sin\theta \approx \tan\theta$$

Calibration curve (surface)

- According to the previous formula, the transmission calibration curve was made. Typical calculation result is shown .
- The incident angle to the pixel depends on the length between the pixel and the optical center of IF.
- As a results, on the top view the concentric circle was given under the assumption of that BB filter has no effect on the incident angle.



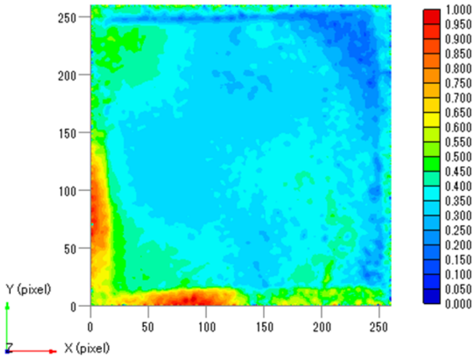
For #14757/58



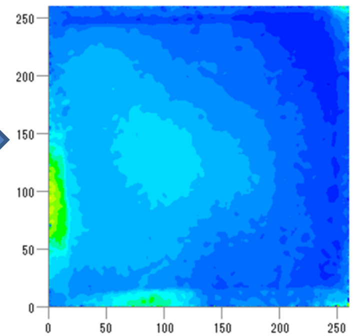
Convert to wavelength, velocity information
- Inner null configuration -

- Use calibration curve and convert the ratio image to wavelength image.

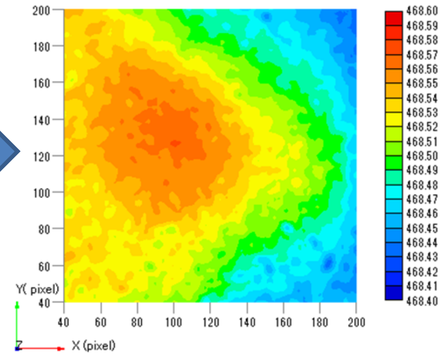
Image B/BB #14757/58



Ratio image (no cal.)

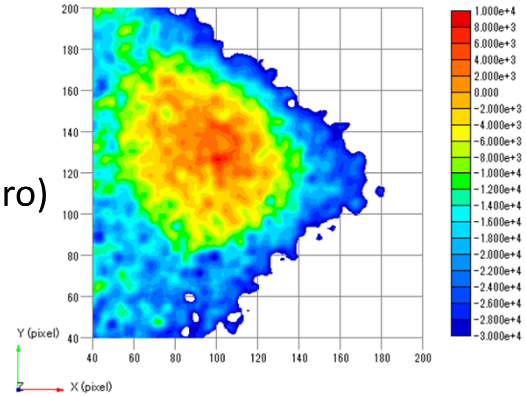


Calibrated ratio image



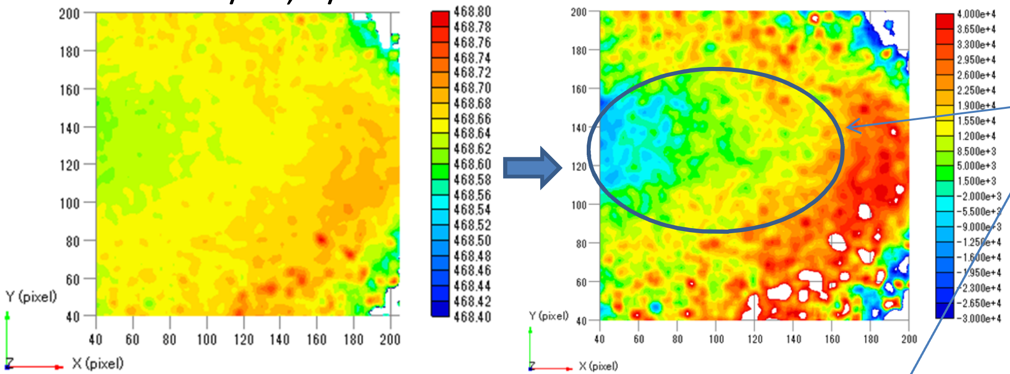
Wavelength

Relative velocity
(Optical center is zero)

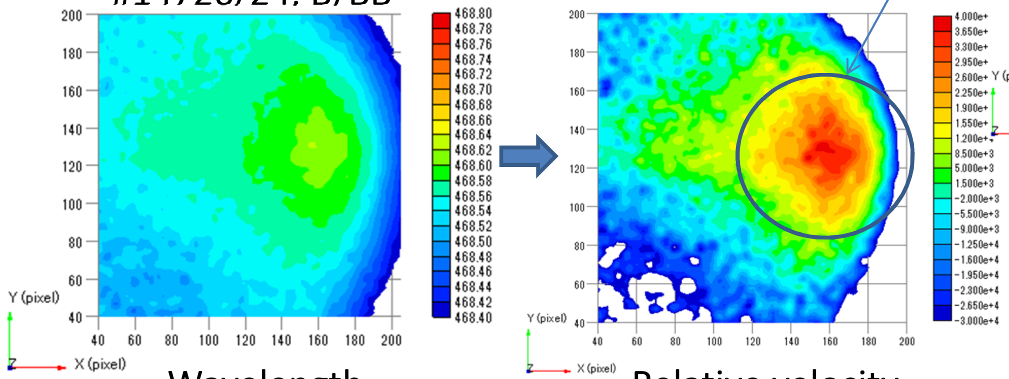


Wavelength, velocity information
- Limiter configuration -

- #14725/24, R/BB



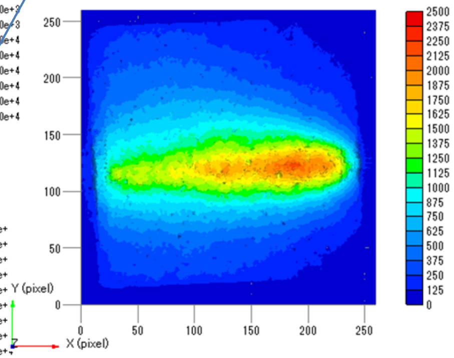
- #14726/24, B/BB



Wavelength

Relative velocity

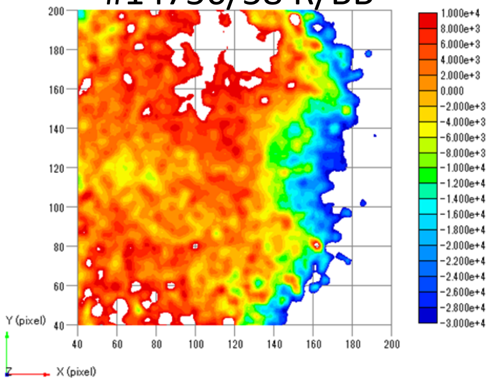
Bright region



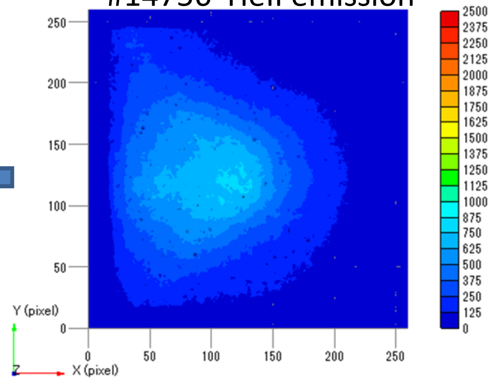
HeII emission

Velocity information
- Inner null configuration -

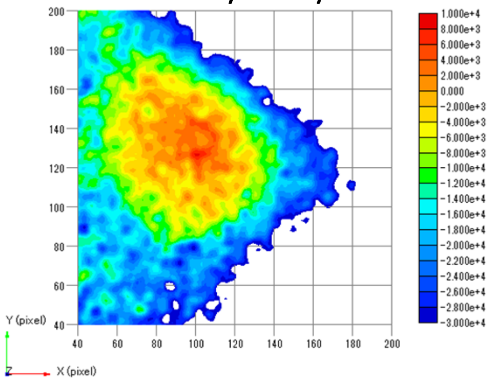
- #14756/58 R/BB



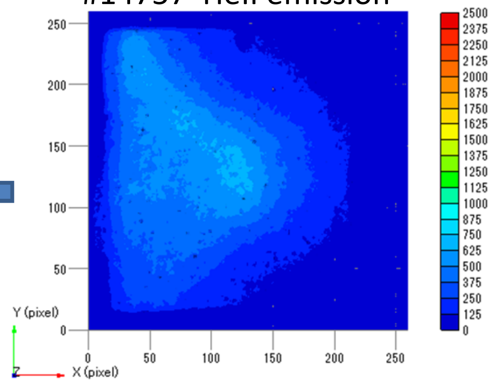
- #14756 HeII emission



- #14757/58 B/BB



- #14757 HeII emission



Relative velocity

Discussion

- Wavelength (velocity) profile obtained by this measurement is somewhat larger than that expected, because RF CD plasma was used here.
- This may be caused by
  - Adjustment← IF was changed by manual
  - Lack of photons
  - Accuracy of the transmission curve of IF?

- Steps to improvement
  - Use more precise optical equipment
  - Take Longer average time at steady state plasma
  - or get high density plasma
  - Check the transmission curve
  - or Use other IF?

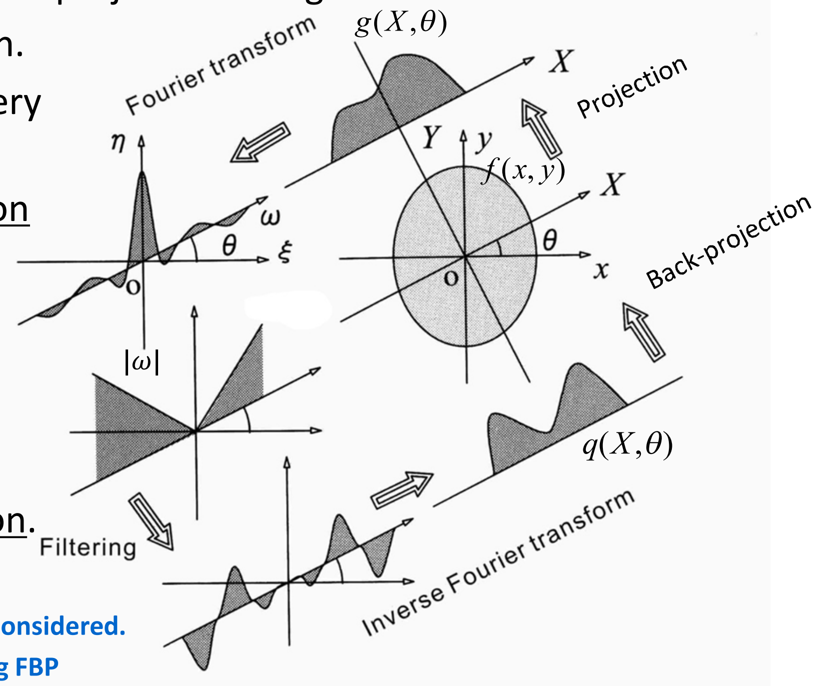
Conclusion

- Two dimensional ion flow measurement system using HeII optical filters was demonstrated in QUEST.
- Under several plasma conditions with He gas puff the various ion flow profiles were observed (two cases were shown).
  - The obtained ion flow profile seemed to change with the magnetic configuration.
  - However, calculated ion velocity has somewhat ambiguity, and the reference light source (zero ion flow) is needed.

- In the near future we will improve this system with taking precise adjustment and performing the elaborate calculation.
  - To get ion flow profile from the images FBP method will be used with the assumption of toroidal symmetry.

FBP (Filtered Back-Projection) Method

- FBP is well known method and it is widely used as the reconstruction method of CT in the medical field to resolve the original object.
- f(x,y) is the object, and g(X,θ) is its projection along Y-axis.
- $|\omega|$ is used as the filter function.
- It is very simple, and also it is very fast using FFT.
- Use FBP to get the <u>initial solution</u> for 2D line emission profile.
- Central horizontal line of the image reconstructed by FBP should be the exact solution.
- At other lines in the image give us an <u>approximated solution</u>.



- **The effect of the elevation angle should be considered.**
- **Need fan-para beam conversion before using FBP**

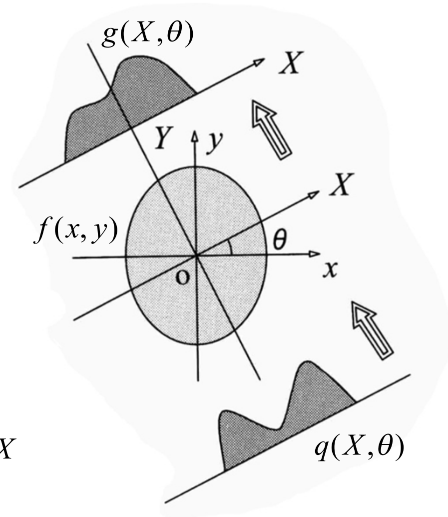
Ref: H.Hashimoto, et. al., SPECT: the basis of the image reconstruction, IryoKagakusha (in Japanese)

Description of FBP method

- Projection g(X,θ) is the line integral of f(x,y)

$$g(X,\theta)=\int_{-\infty}^{\infty} f(x,y)dY$$

- Double Fourier Transform of f(x,y) is



$$F(\xi,\eta)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)e^{-i(\xi x+\eta y)}dxdy \qquad \begin{cases}\xi=\omega\cos\theta\\ \eta=\omega\sin\theta\end{cases}$$

$$=F(\omega\cos\theta,\omega\sin\theta)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)e^{-i\omega(x\cos\theta+y\sin\theta)}dxdy$$

$$X=x\cos\theta+y\sin\theta,\ \ \mathrm{d}x\mathrm{d}y=\mathrm{d}X\mathrm{d}Y$$

$$=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)e^{-i\omega X}dXdY=\int_{-\infty}^{\infty}\left[\int_{-\infty}^{\infty} f(x,y)dY\right]e^{-i\omega X}dX=\int_{-\infty}^{\infty} g(X,\theta)e^{-i\omega X}dX$$

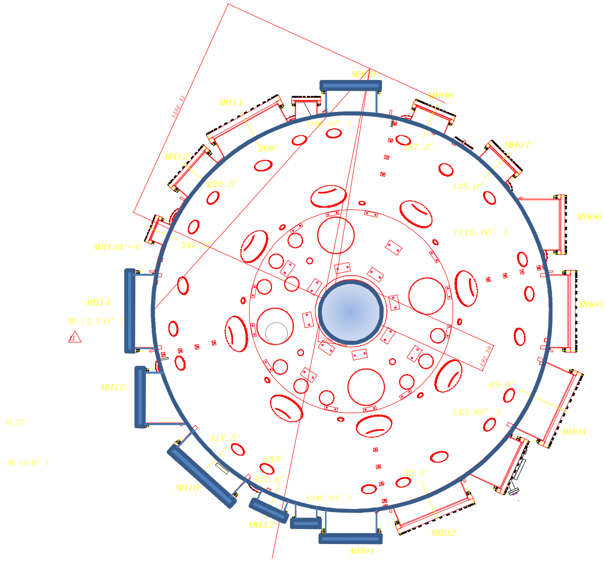
$$f(x,y)=\frac{1}{(2\pi)^2}\int_0^{2\pi}\int_0^{\infty}F(\omega\cos\theta,\omega\sin\theta)e^{i\omega(x\cos\theta+y\sin\theta)}\omega d\omega d\theta=\frac{1}{2(2\pi)^2}\int_0^{2\pi}\int_{-\infty}^{\infty}F(\omega\cos\theta,\omega\sin\theta)e^{i\omega X}|\omega|d\omega d\theta$$

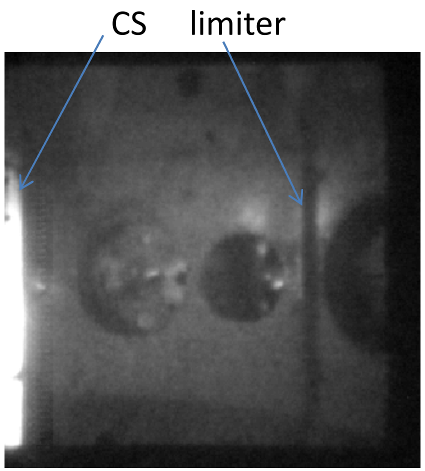
$$q(X,\theta)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\left[\int_{-\infty}^{\infty} g(X,\theta)e^{-i\omega X}dX\right]|\omega|e^{i\omega X}d\omega$$ ← filtering

$$f(x,y)=\frac{1}{4\pi}\int_0^{2\pi} q(X,\theta)d\theta$$ ⇐ Back-projection

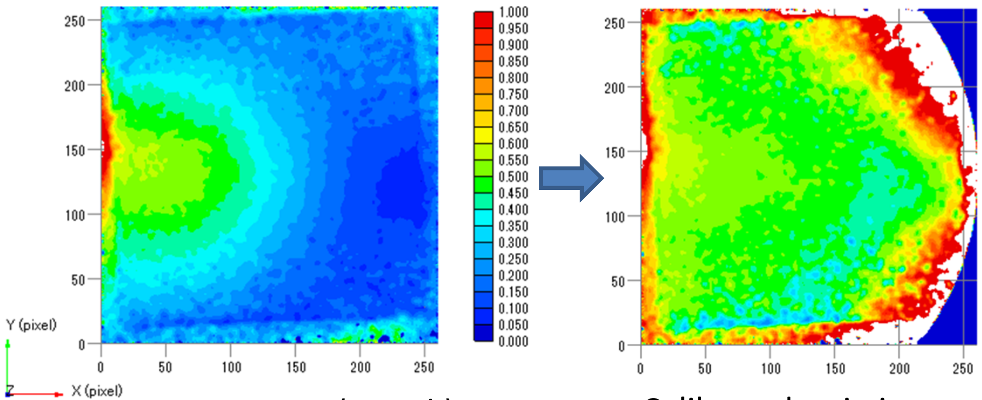
Description of the coordinates for analysis

- The location of the fast camera is set to x-axis, and the center of the center stack is the origin.
- z-axis is height, and right-hand side coordinate is used.





Reference image of the fast camera



Ratio image (no cal.)

Calibrated ratio image