Fast-ion D alpha diagnostic with enhanced FIDASIM in the Large Helical Device

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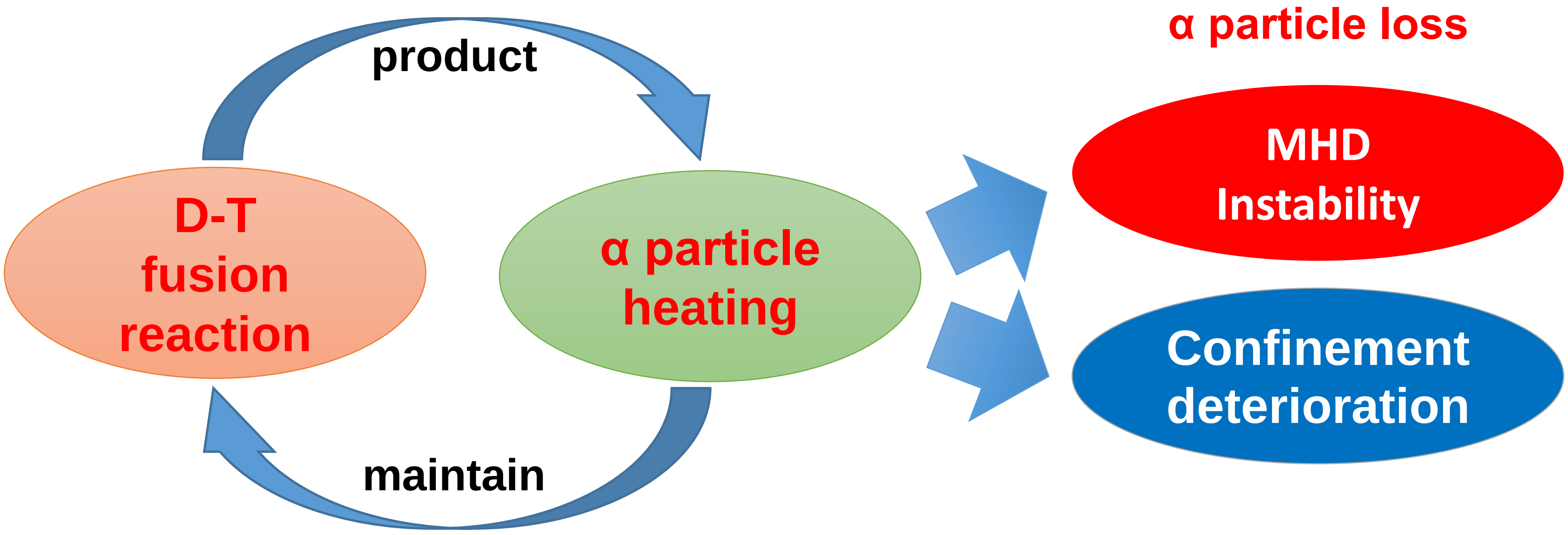
Background ~ the need for fast ion confinement studies ~

- In the fusion reactor, the high temperature plasma is maintained by heating of α particles (3.5 MeV) produced by the DT fusion reaction.
  - Efficient confinement of the high energy particles is necessary.

- However, as the pressure of the high-energy α particles increases, there is concern that the confinement becomes unstable due to the interaction between MHD wave and α particles such as Alfven eigenmodes.
  - It is necessary to study the wave-particle interaction.



Motivation of development of FIDA diagnostic

- In the large helical device(LHD), many kinds of diagnostics have been installed for the investigation of the confinement of fast ion.

- Especially, the most important topics in the fast-ion studies on LHD;
  1. **Confinement of NB-particle during its slowing-down processes.**
  2. **Particle-wave interactions between fast ions and MHD instabilities and/or ICRH induced waves.**
  3. **Confinement property of Fast Ions in the presence of electric fields.**

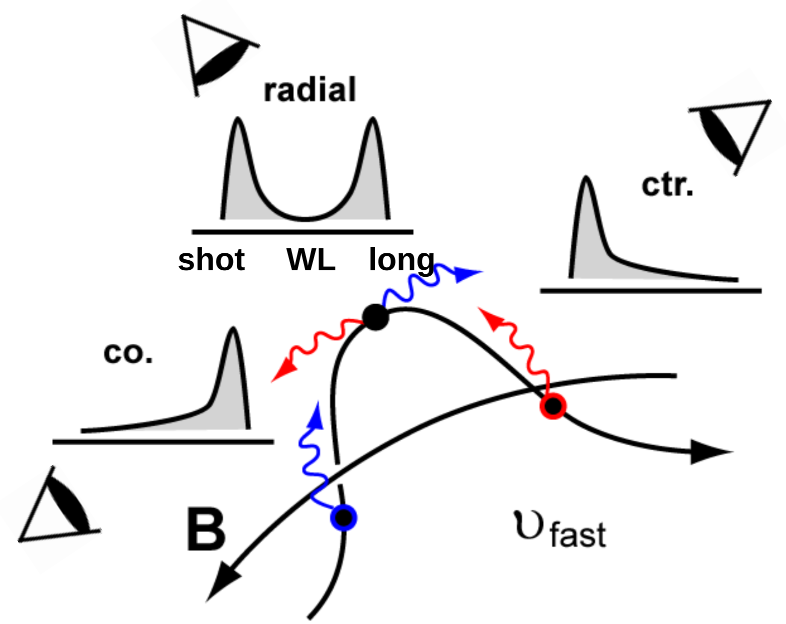
- For studying these issues, the internal properties of fast ions is required so that spatially-resolved fast-ion measurement is necessary.

Fast Ion D Alpha (FIDA) is a very useful tool for measuring spatial profile of fast ion pressure.

Fast Ion D Alpha (FIDA) diagnostic

fast ion probe NB γ

$$H^{+}_{fast} + H^{0}_{NB} \rightarrow H^{0}_{fast} + H^{+}_{NB}$$



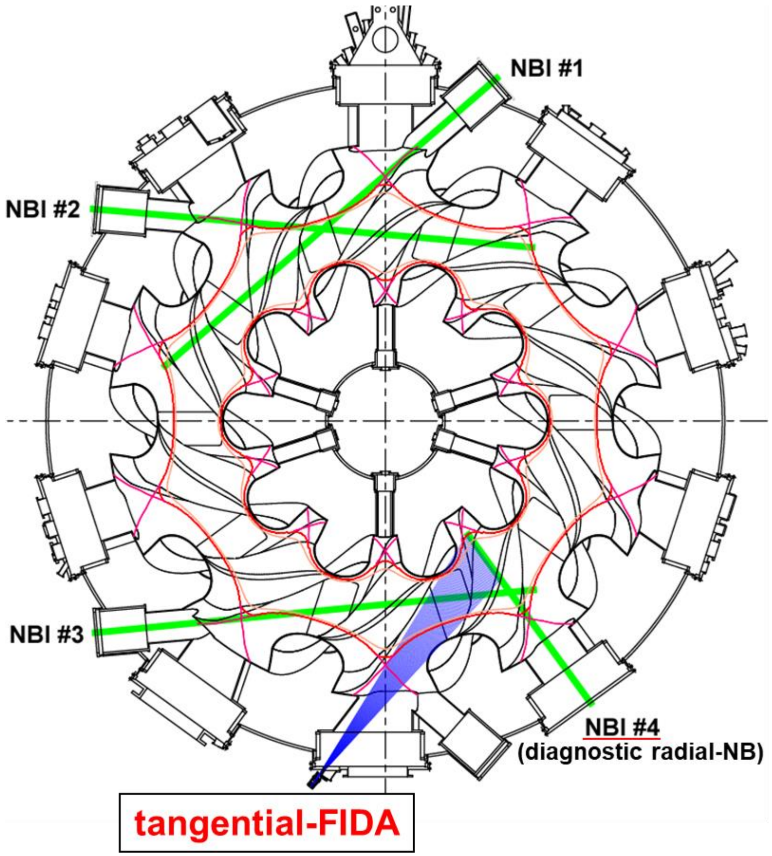
- FIDA diagnostic is a kind of beam probe diagnostics and is consists of measurement of **Doppler-shifted H_a lights from reneutralized fast ions** and evaluation of measured spectrum.

- **FIDA is an active diagnostics** by using NBI so that the injection is required to be modulated for separating the FIDA component from the contribution of the neutral in the peripheral region or the other unnecessary component caused by injected NB.

- **Tangential viewing geometry is suitable for observing fast ions traveling parallel to magnetic field.**

FIDA diagnostic arrangement

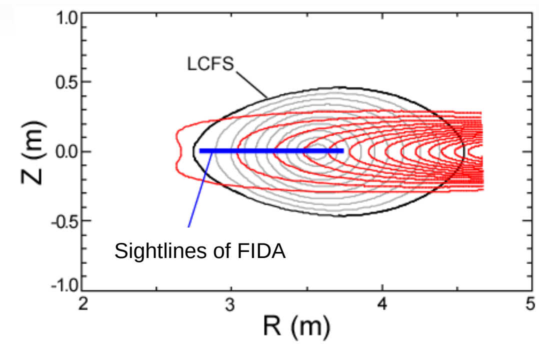
Top view of measurement system



- Tangential-FIDA use 50 fiber optics array(d=400 μm).We can chose 16 ch for measurement.

- Spectrometer is BUNKOKEIKI/FLP-200 with a CCD (ANDOR iXon Ultra 897).

Attenuation profile of NBI #4



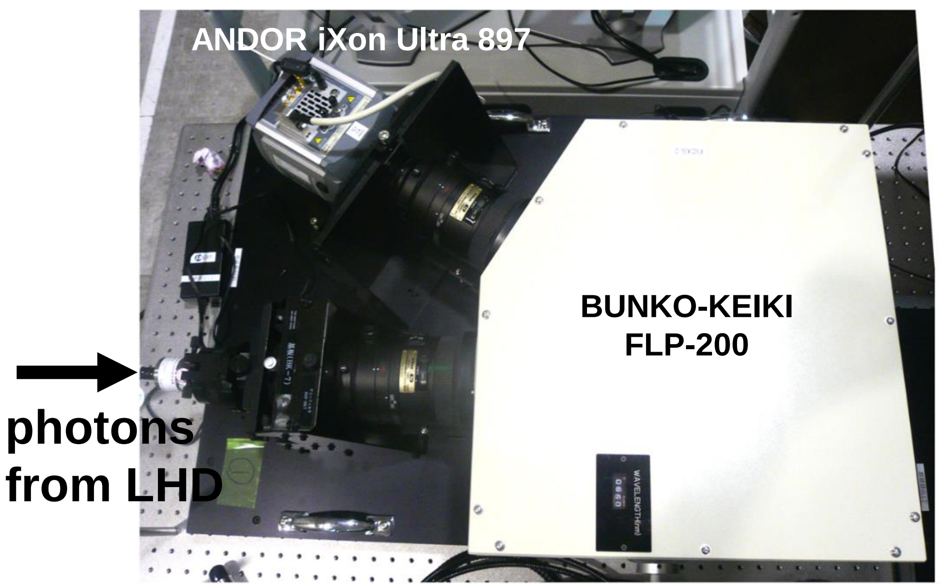
Probe beam: NBI #4 for searching parallel traveling fast ion

Line of sight for FIDA

Line of Sight	R [mm]
1	2958
2	3029
3	3099
4	3168
5	3237
6	3283
7	3329
8	3374
9	3419
10	3464
11	3509
12	3553
13	3597
14	3642
15	3685
16	3729

Characteristic of spectrometer for FIDA diagnostic

- The installed CCD camera makes higher capability for temporal background subtraction on FIDA measurement.
- High time-resolved FIDA signals can be obtained.
- Two spectrometers are utilized to separately observe signals from each red- and blue-shift side of Doppler-shifted Ha and Da spectra for a fine measurement on wide wavelength range.



■ **Spectrometer**

・focal length: 200mm
・f/2.8
・grating:2160/mm
・Chromatic aberration is intrinsically corrected by utilizing camera lens.
・fiber diameter: 400μm
・filter: notch filter (5nm at the center)

■ **CCD detector**

・sampling time: 7ms
・pixel pitch: 16μm(512x512)
・recording: 512x512 image

Experiment parameter and condition

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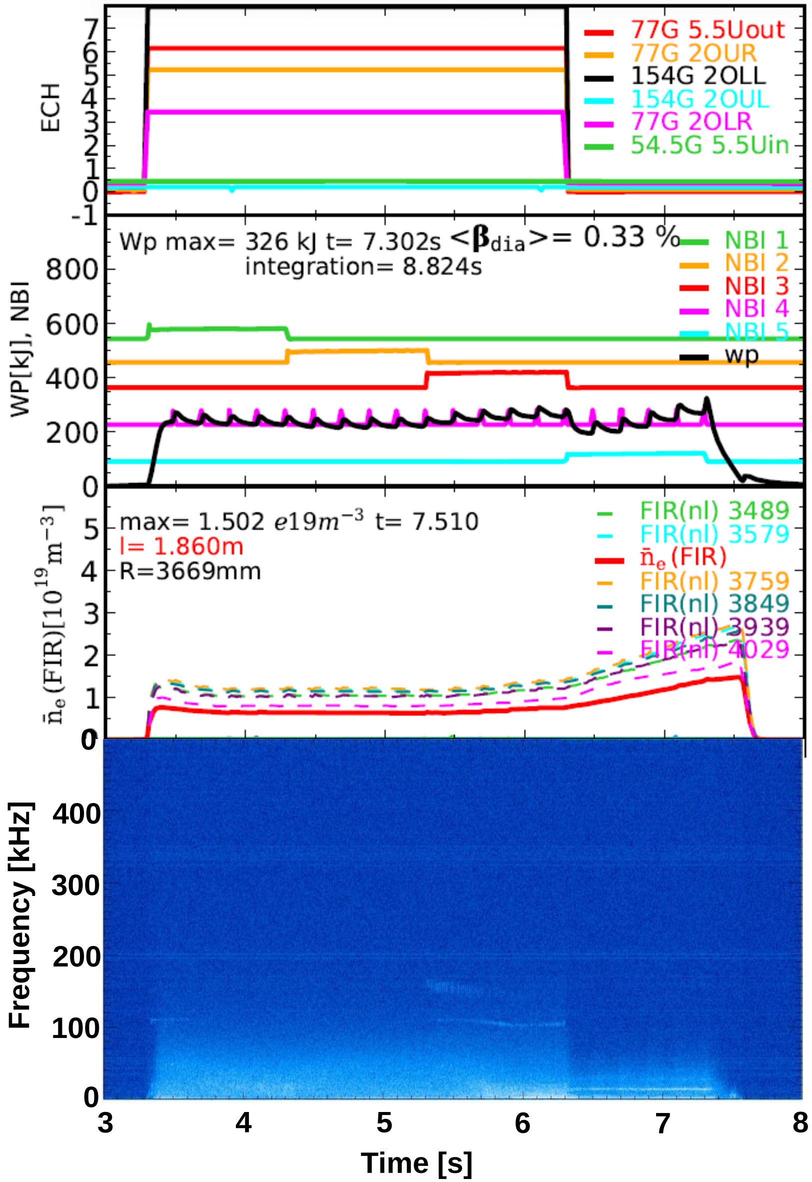
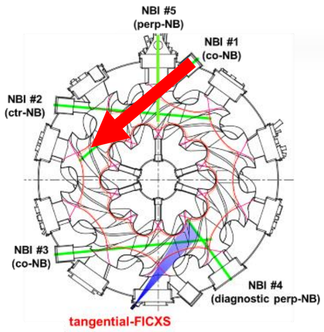


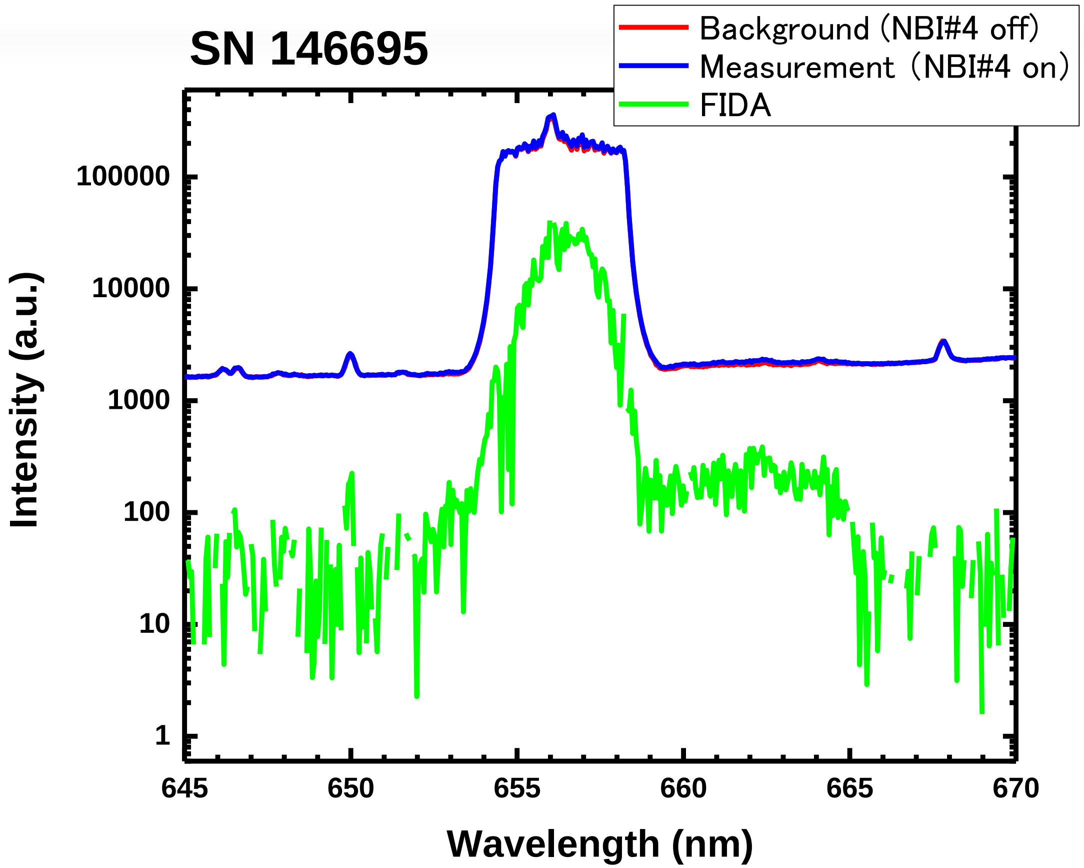
B=2.750 T (Counter),
Rax=3.600 m,
Gamma=1.354,
Bq=100
Gas: Deuterium

NB1: 174 keV 0.8 MW (ion source A)
NB2: 150 keV 1.1 MW (ion source A)
NB3: 175 keV 1.5 MW (ion source A)
NB4: 57 keV 5.9 MW

To observe fast ion radial profile in MHD-quescient deuterium plasmas, negative ion beams just use one ion source to limited each power.

Typical experiment data and How to get FIDA data





t= 4.26~4.28s

t= 4.28~4.30s

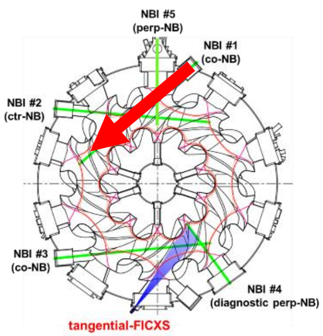
t= 4.28~4.30s

R=3.597 m

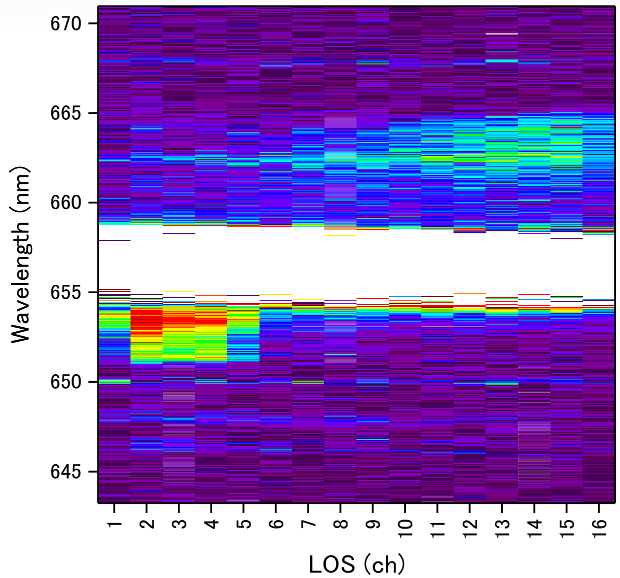
FIDA spectra are obtained by subtracting the background spectra from the foreground spectra. Fortunately, most of the impurity lines were removed by the background subtraction. The bremsstrahlung radiation was also removed because the electron density is almost stationary during the measurement.

Fast ion radial profile (NBI #1 and NBI #2 component)

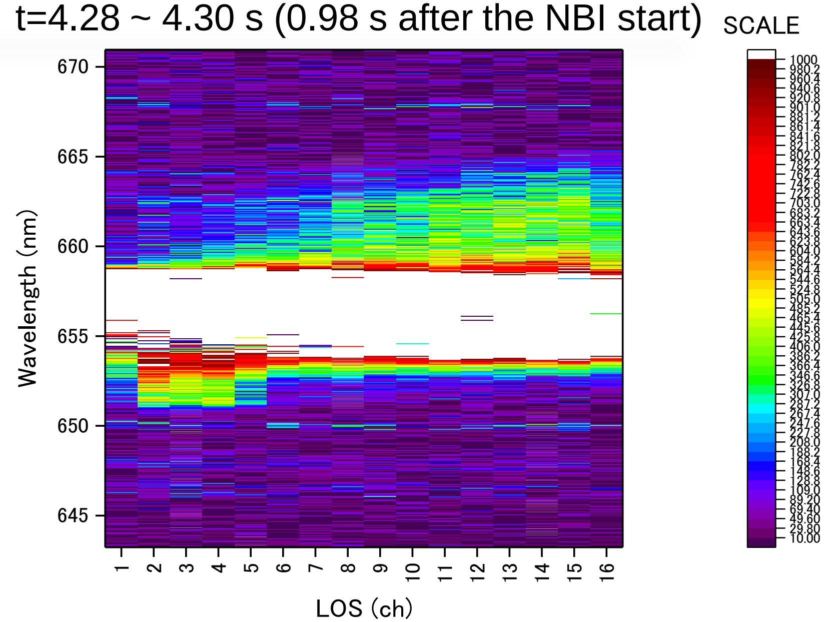
NBI #1



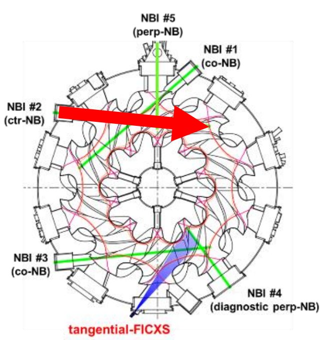
t=3.48 ~ 3.50 s (0.18 s after the NBI start)



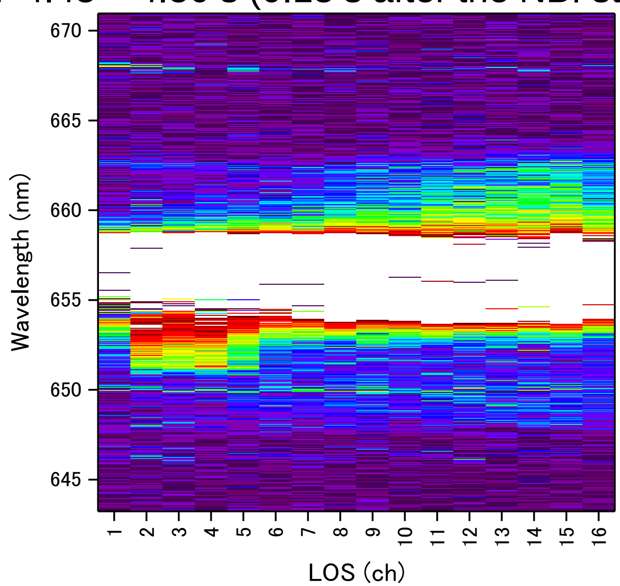
t=4.28 ~ 4.30 s (0.98 s after the NBI start)



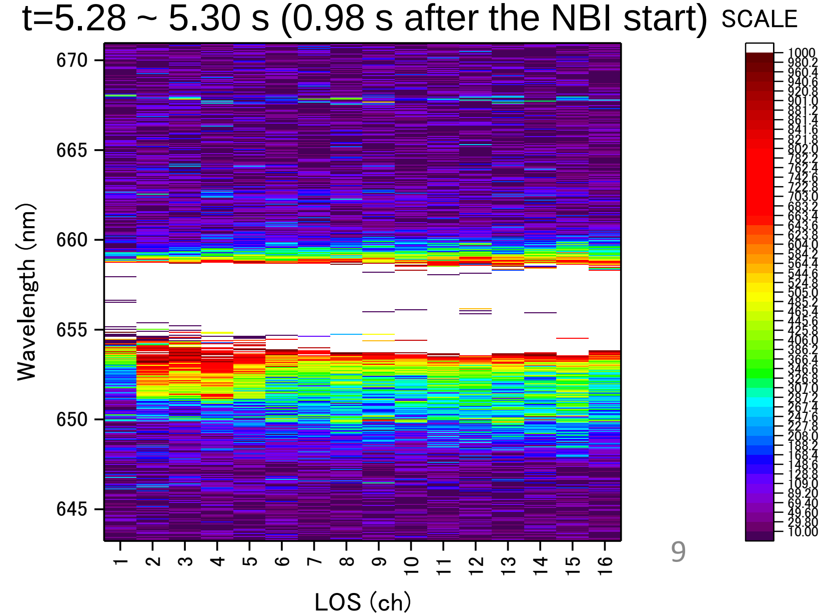
NBI #2



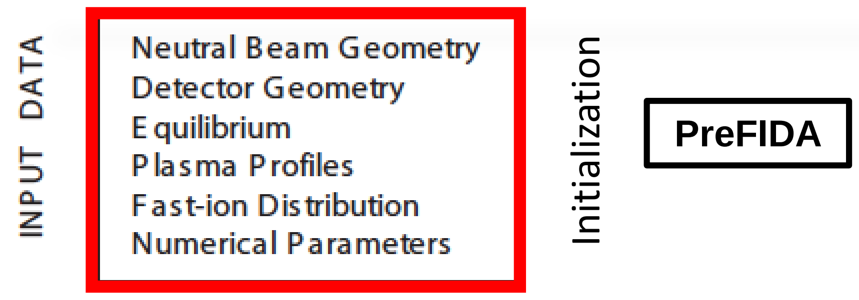
t=4.48 ~ 4.50 s (0.18 s after the NBI start)



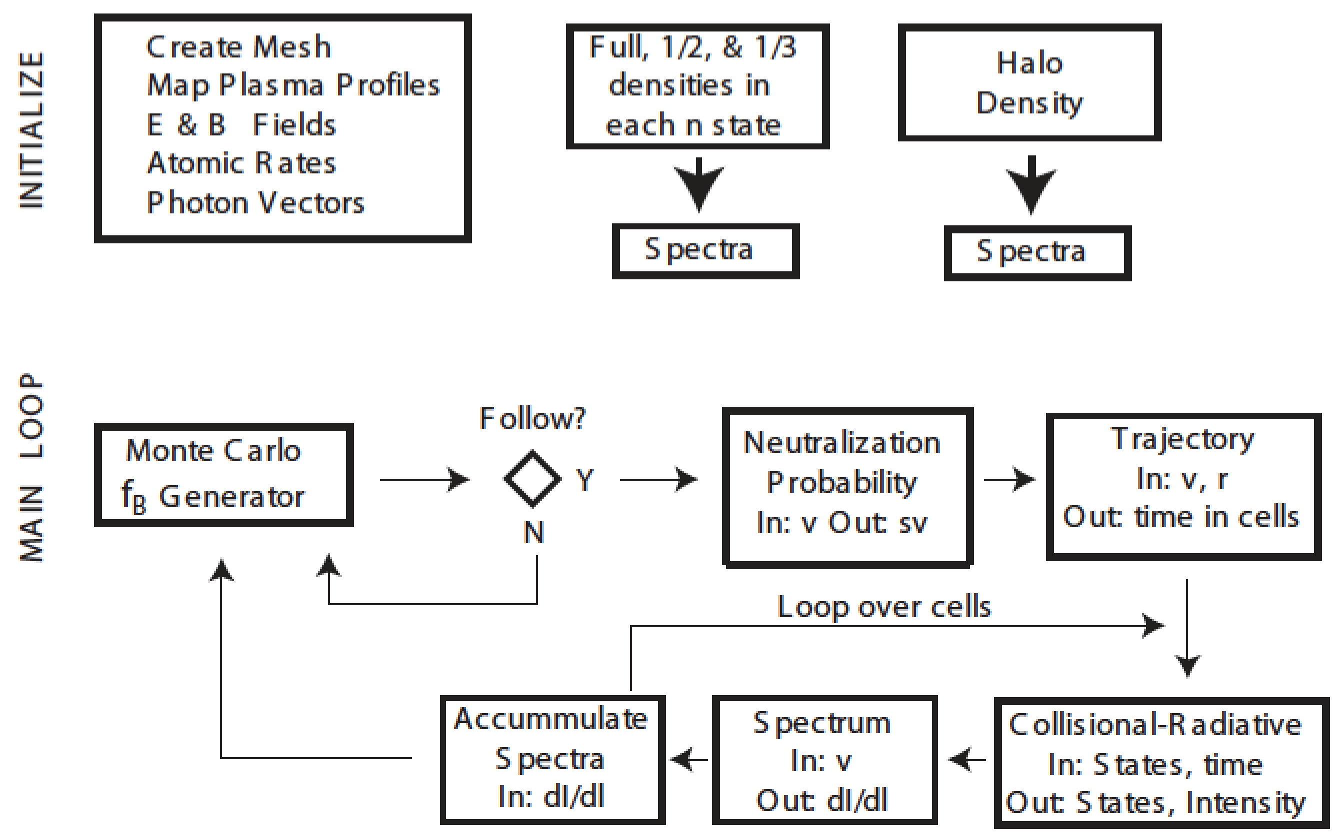
t=5.28 ~ 5.30 s (0.98 s after the NBI start)



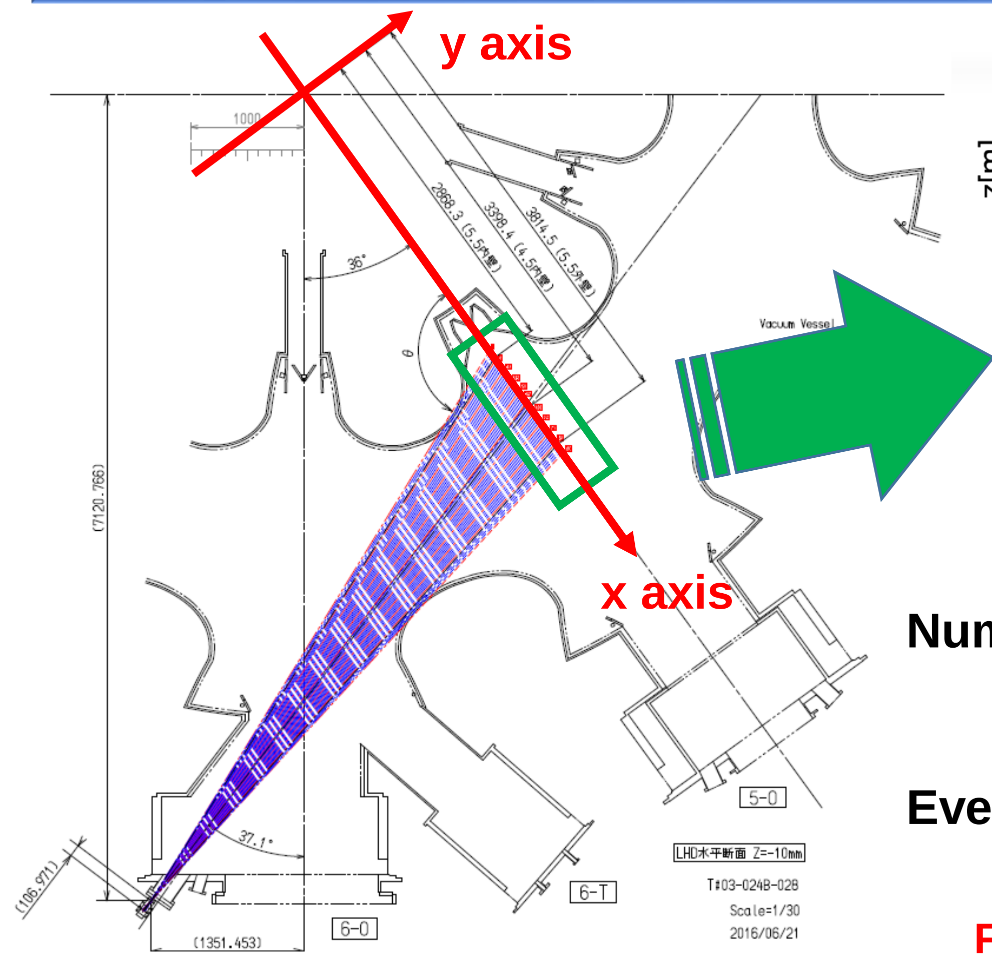
Enhanced FIDASIM for 3D magnetic configuration

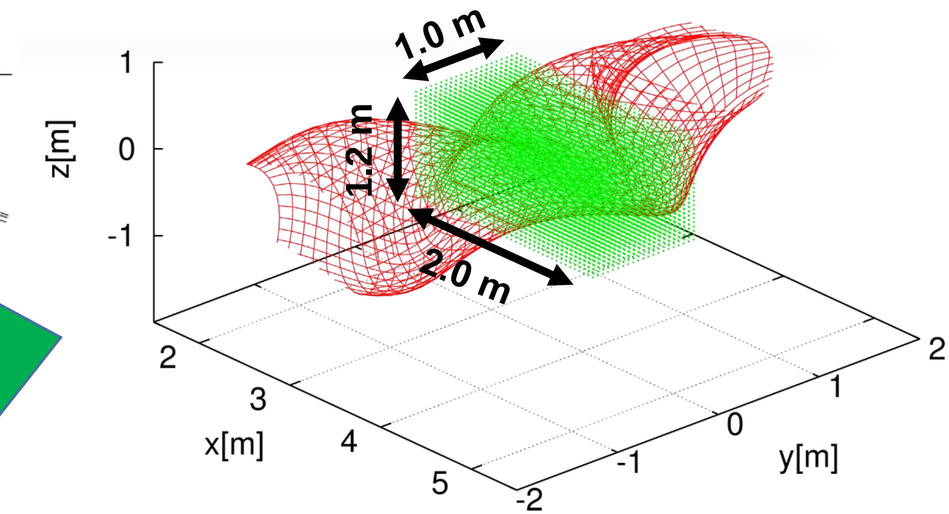


- **FIDASIM is a famous tool of analyzing FIDA.**
- **However, it was developed for a 2D magnetic configuration.**
- **Collaborating research with Heidbrink's group.**



Calculation of distribution function by GNET





Y. Fujiwara, et al., Plasma Fus. Res. 14 (2019) 3402129.

Line of sight for FIDA

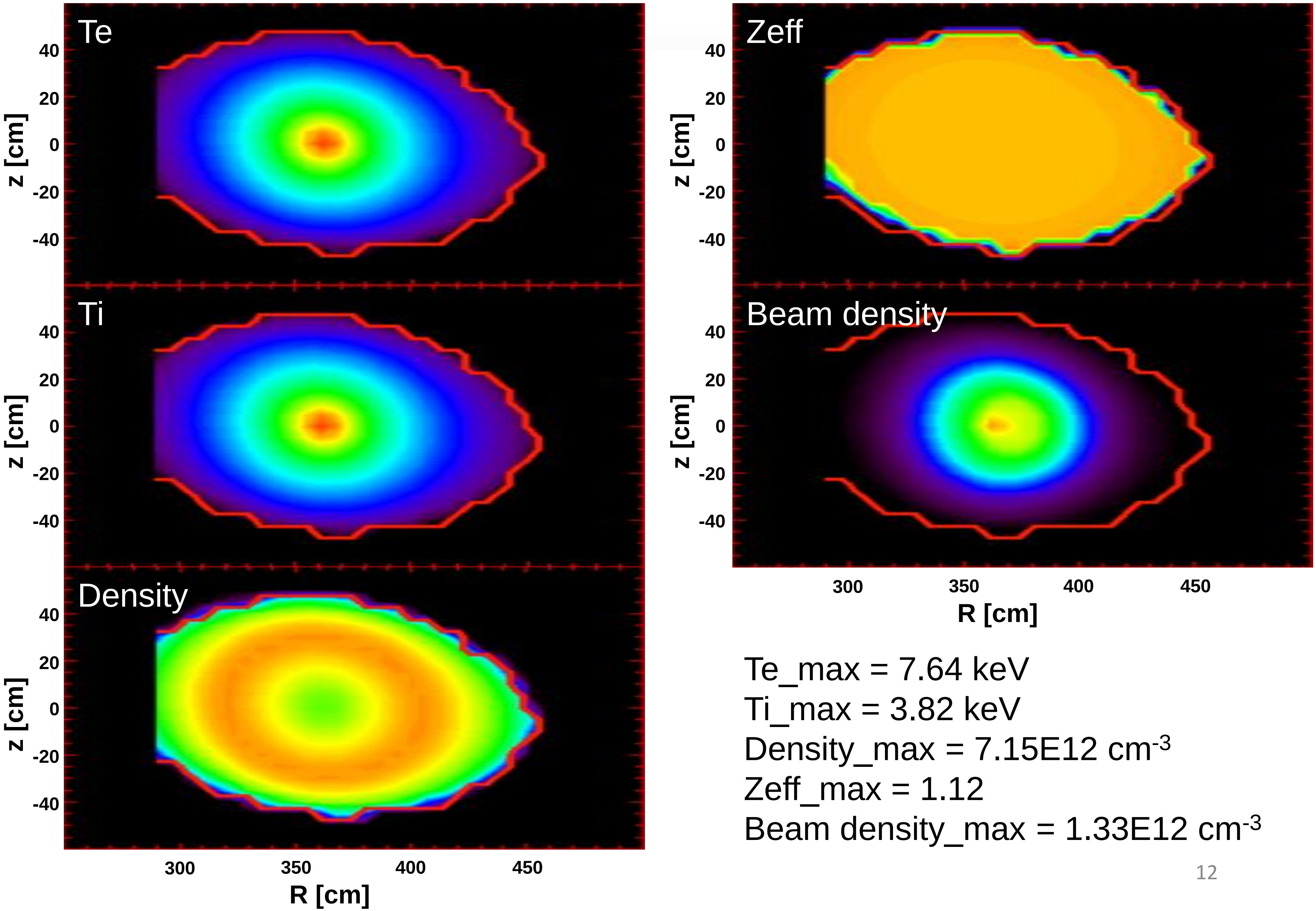
The x axis was set in the opposite direction of neutral beam.
The y axis was set rectangular to the x axis.
The z axis was set in the height direction.

Number of grids:
nx=40, ny=21, nz=25
nE=50, np=33
Every grids in 5 cm steps.

x: 2.7 ~ 4.7m
y: -0.5 ~ 0.5m
z: -0.6 ~ 0.6m

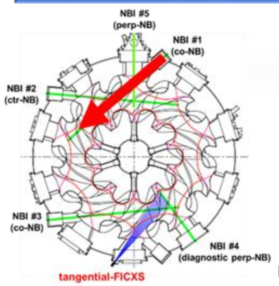
FIDASIM requires plasma profiles, magnetic fields, and distribution function in (R, z, phi) coordinates.
PreFIDA interpolate inputs data from Cartesian coordinates to (R, z, phi) coordinates.

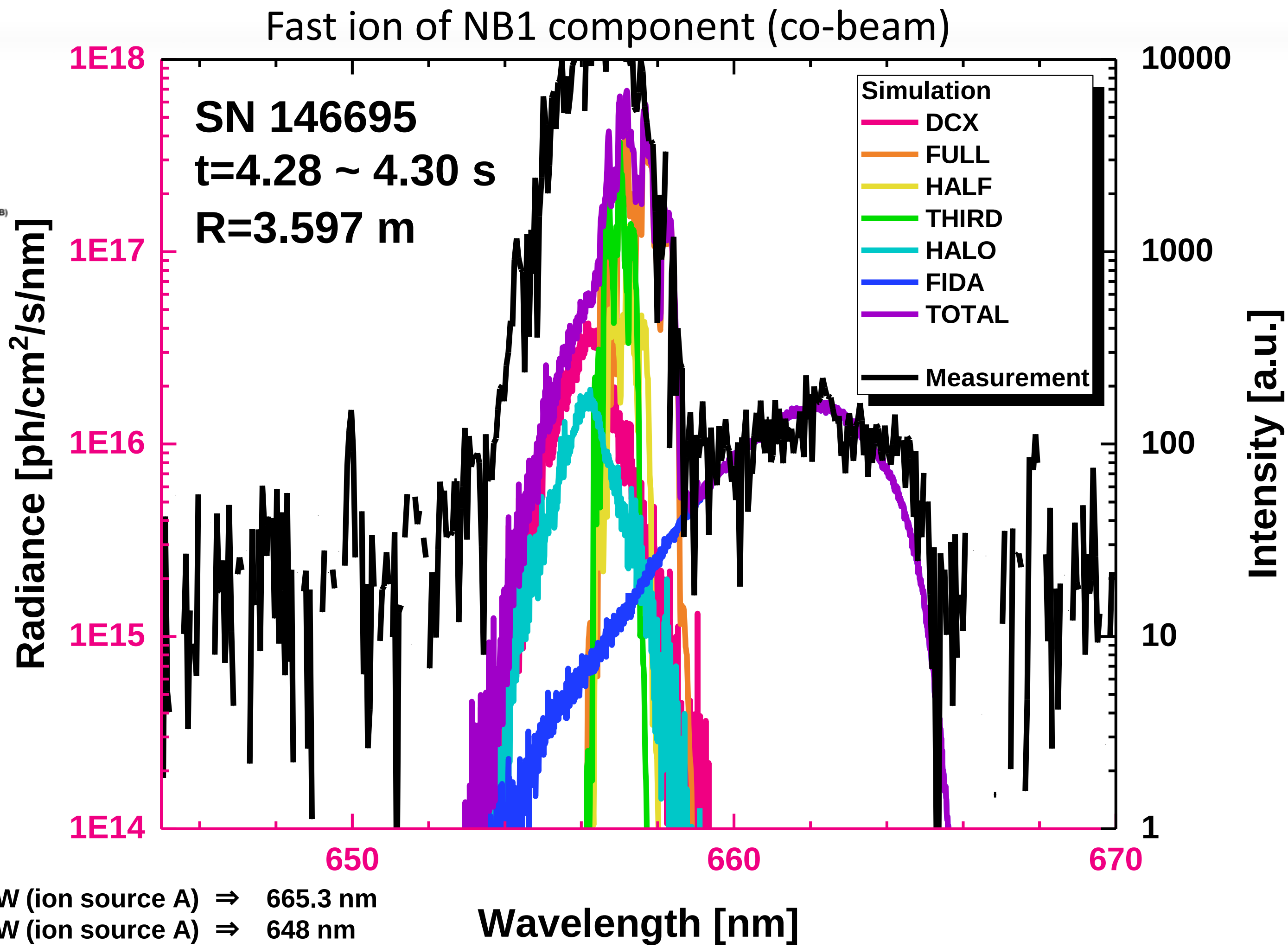
Visualize inputs data of FIDASIM (using Ti = Te/2)



Te_max = 7.64 keV
Ti_max = 3.82 keV
Density_max = 7.15E12 cm^{-3}
Zeff_max = 1.12
Beam density_max = 1.33E12 cm^{-3}

Comparison of FIDA with FIDASIM result (NB1 component)

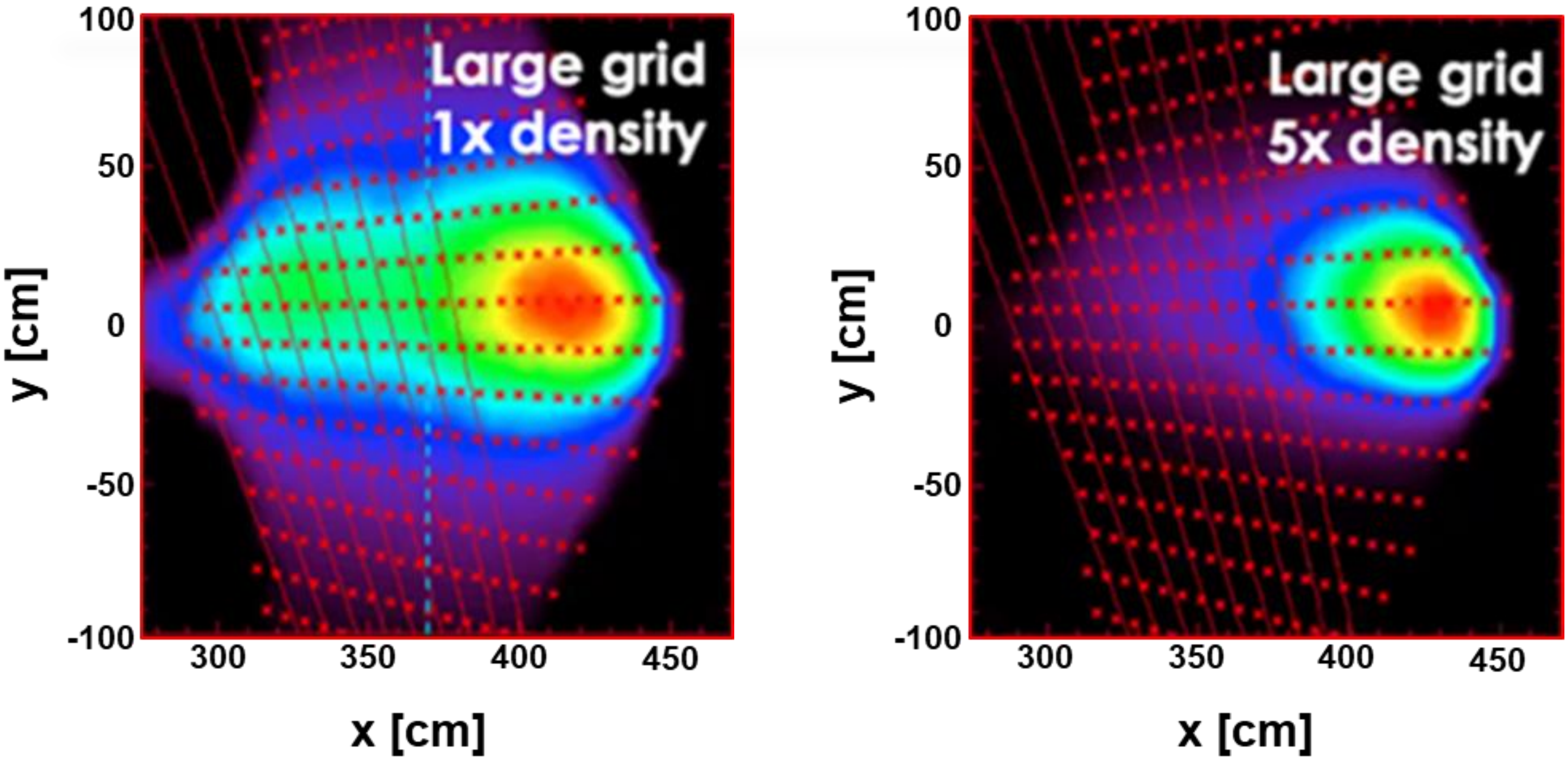




NB1: 174 keV 0.8 MW (ion source A) ⇒ 665.3 nm
NB2: 150 keV 1.1 MW (ion source A) ⇒ 648 nm
NB3: 175 keV 1.5 MW (ion source A) ⇒ 665.3 nm

- FIDA component result of FIDASIM is good agreement with FIDA measurement.
- DCX and HALO components is smaller than measurement.

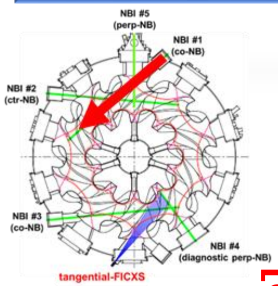
Changed number of grids for GNET calculation

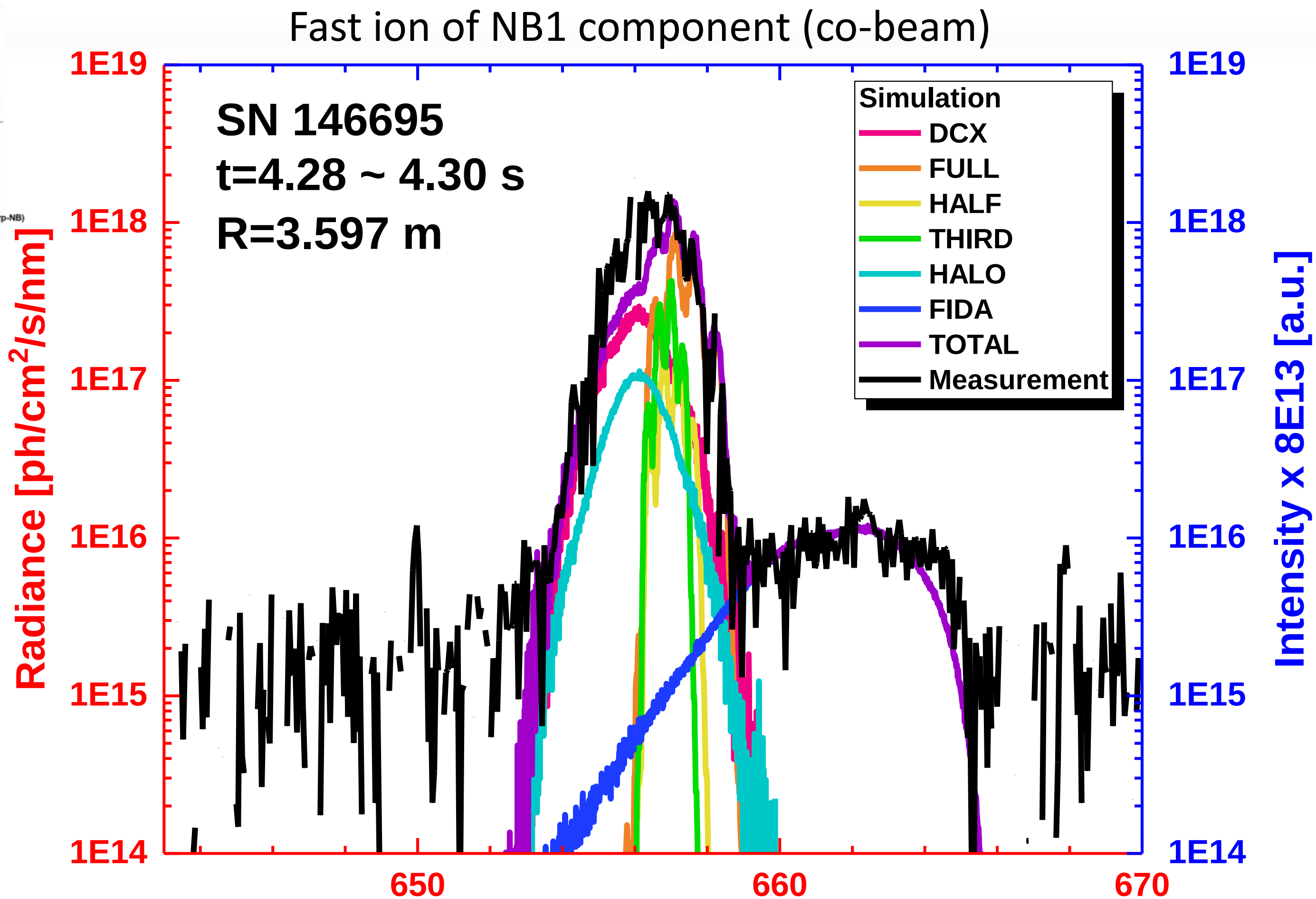


- Density is ~0.7×10^{19} m^{-3}, so mean free path is about 100 cm.
- Halo expanded at low electron density situation.

We recognized FIDASIM need more large grid in the low electron density situation.
We changed twice large number of grid for y axis.

Comparison of FIDA with FIDASIM (large grid) result

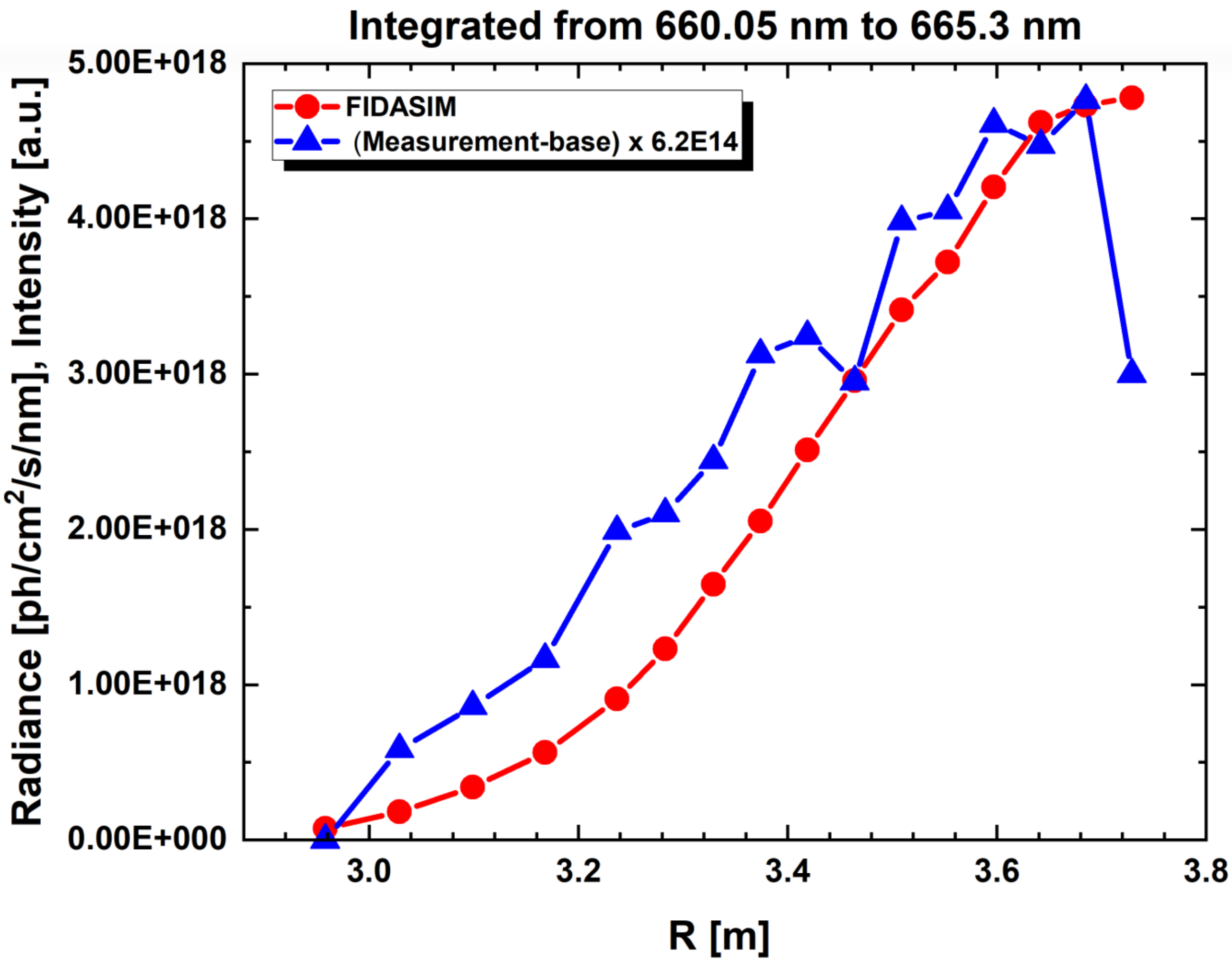




NB1: 174 keV 0.8 MW (ion source A) ⇒ 665.3 nm
NB2: 150 keV 1.1 MW (ion source A) ⇒ 648 nm
NB3: 175 keV 1.5 MW (ion source A) ⇒ 665.3 nm

- FIDASIM is good agreement with FIDA measurement.
- The figure shows enhanced FIDASIM is possible to simulate the FIDA measurement in the 3D magnetic fields devise such as LHD.

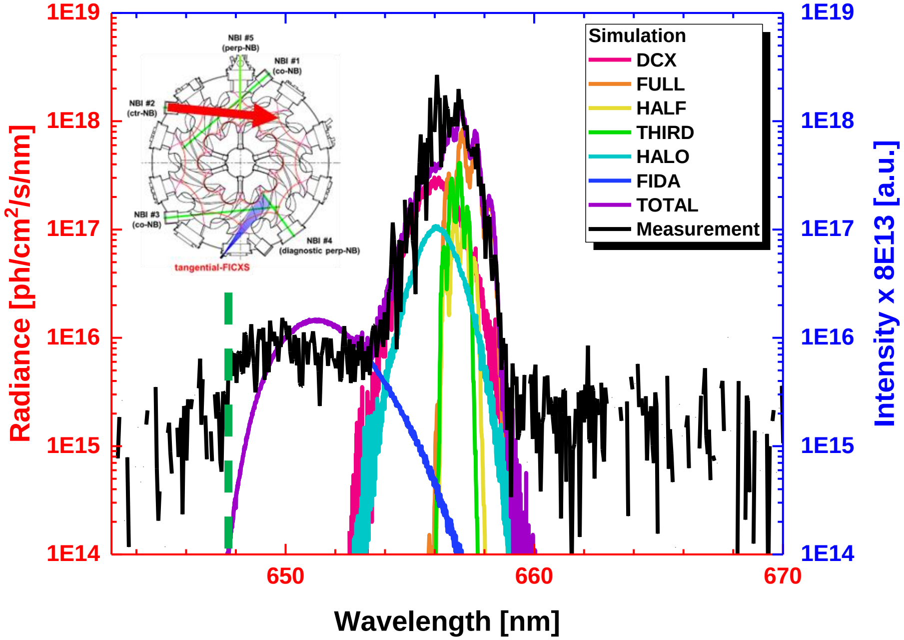
Comparison of Integrated FIDA signal with FIDA and FIDASIM



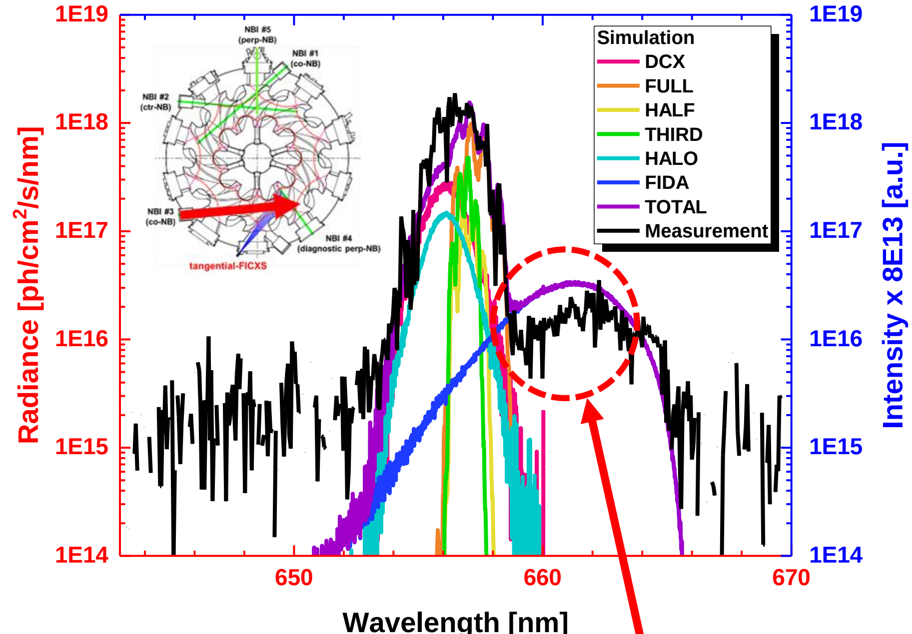
- Measurement and simulation results are good agreement in MHD-quescient plasmas .
- We obtained the strong tool to understanding fast-ion behavior with the MHD instabilities.

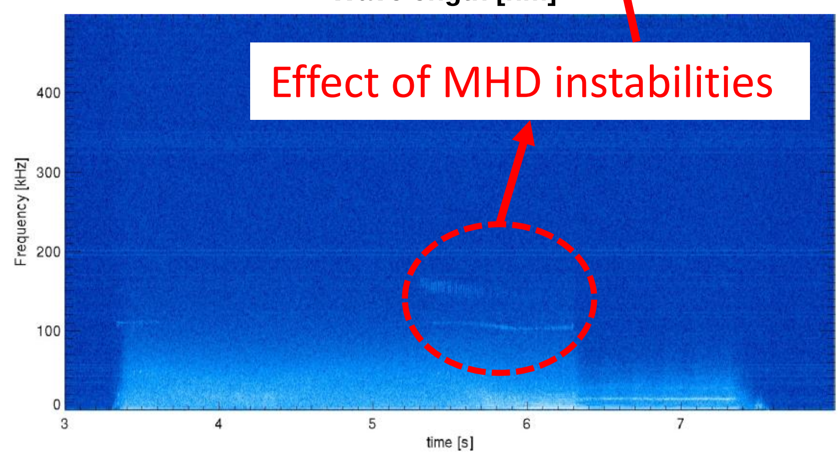
Comparison of FIDA with FIDASIM (large grid) result on NBI #2, #3

Fast ion of NB2 component (ctr-beam)



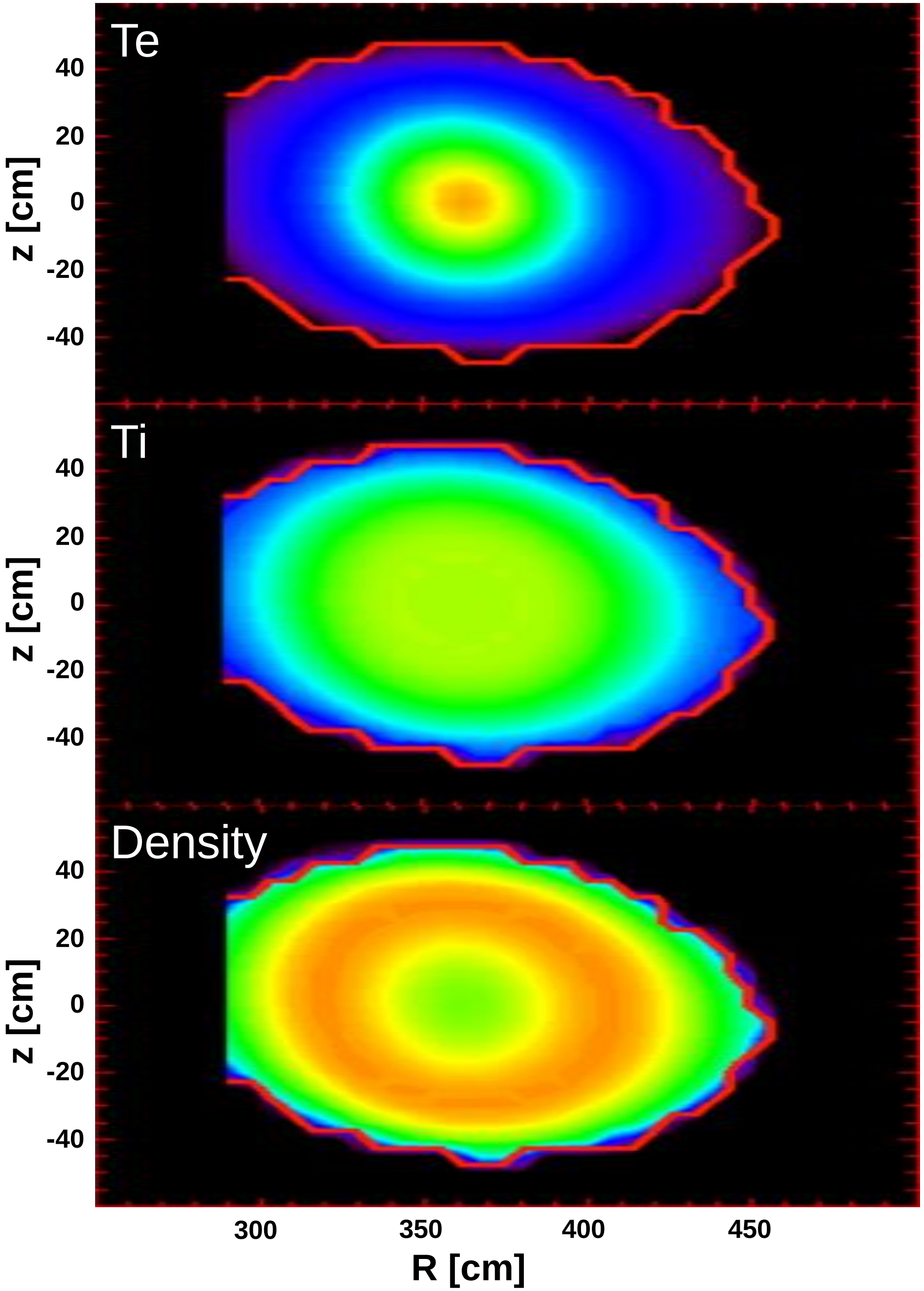
Fast ion of NB3 component (co-beam)

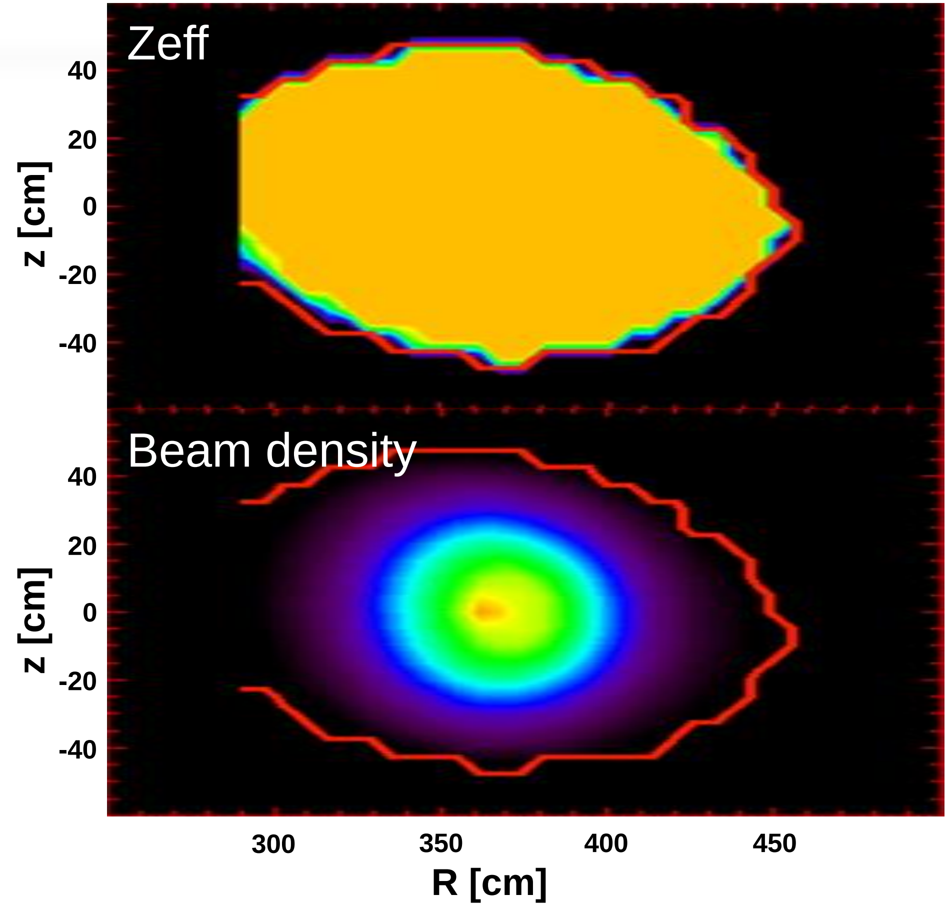




- FIDA component result of FIDASIM does not agree with FIDA measurement on NBI #2. (Figure out why happed)
- FIDA component result of FIDASIM does not agree with FIDA measurement on NBI #3. However, the MHD instabilities were observed at the NBI #3 injection timing. It seems that effect of MHD instabilities.

Visualize inputs data of FIDASIM (using measurements Ti)





Te_max = 7.64 keV

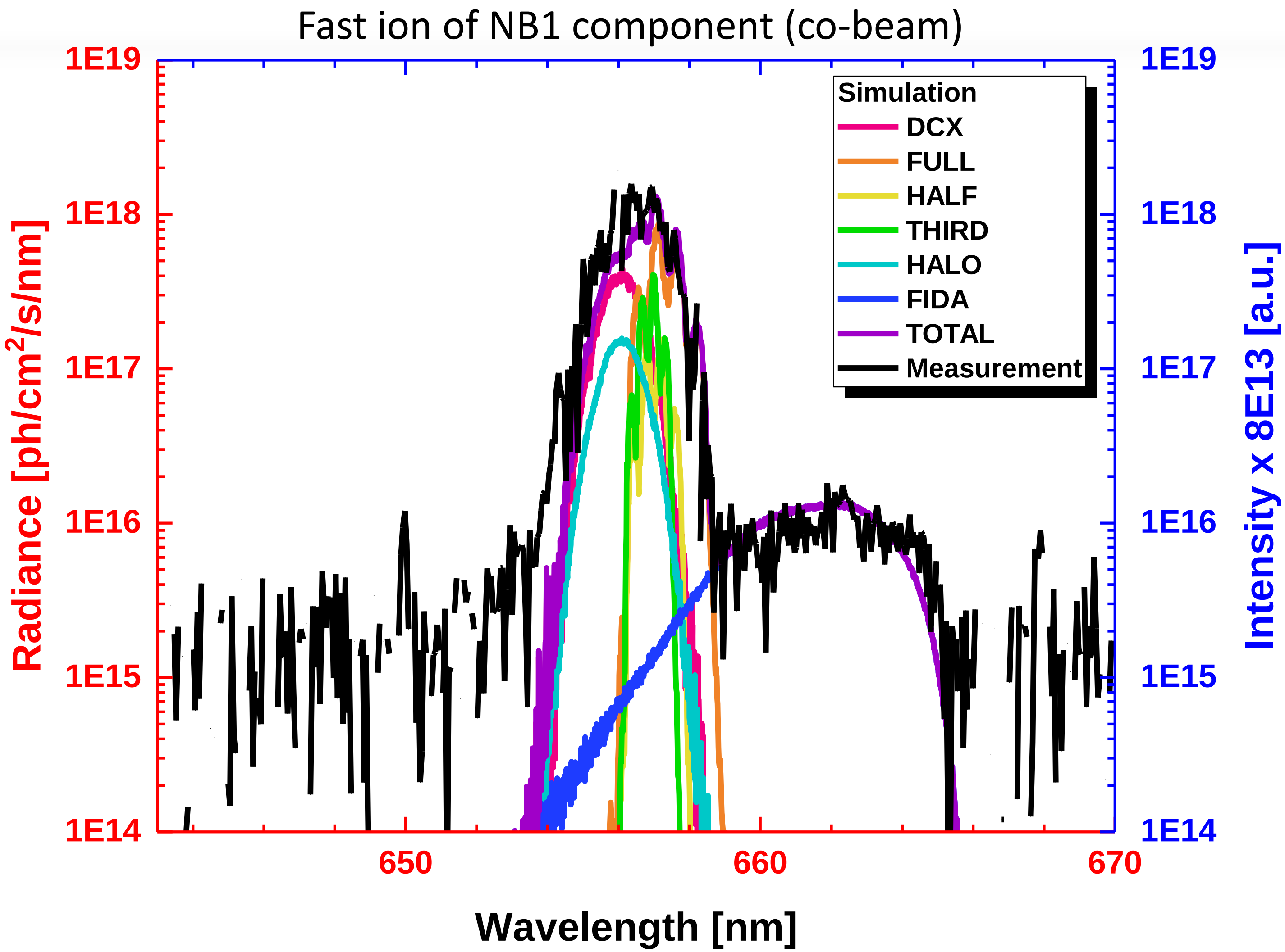
Ti_max = 1.51 keV

Density_max = 7.15E12 cm^{-3}

Zeff_max = 1.12

Beam density_max = 1.33E12 cm^{-3}

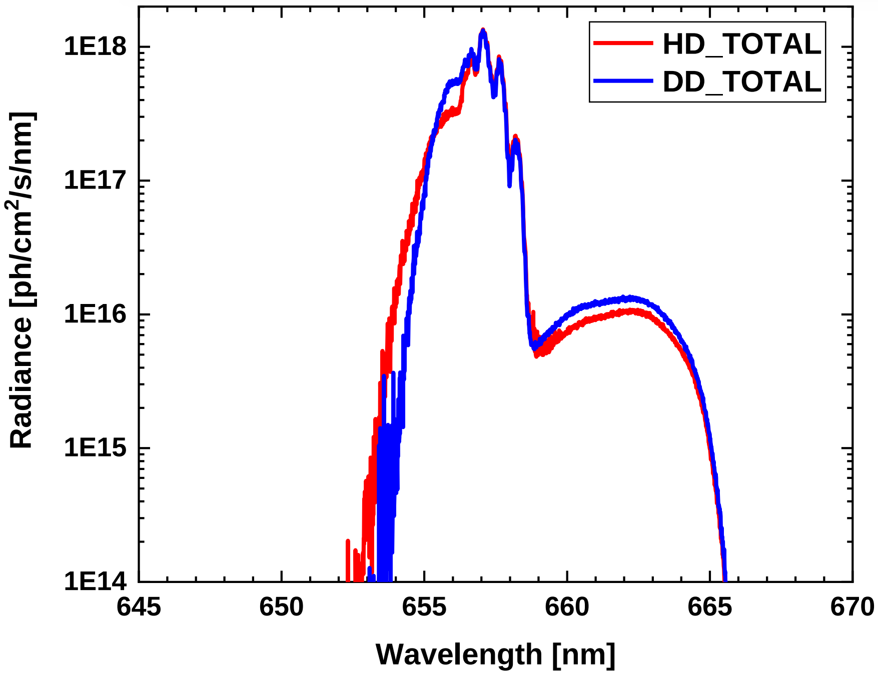
Comparison of FIDA with FIDASIM (using measurements Ti)

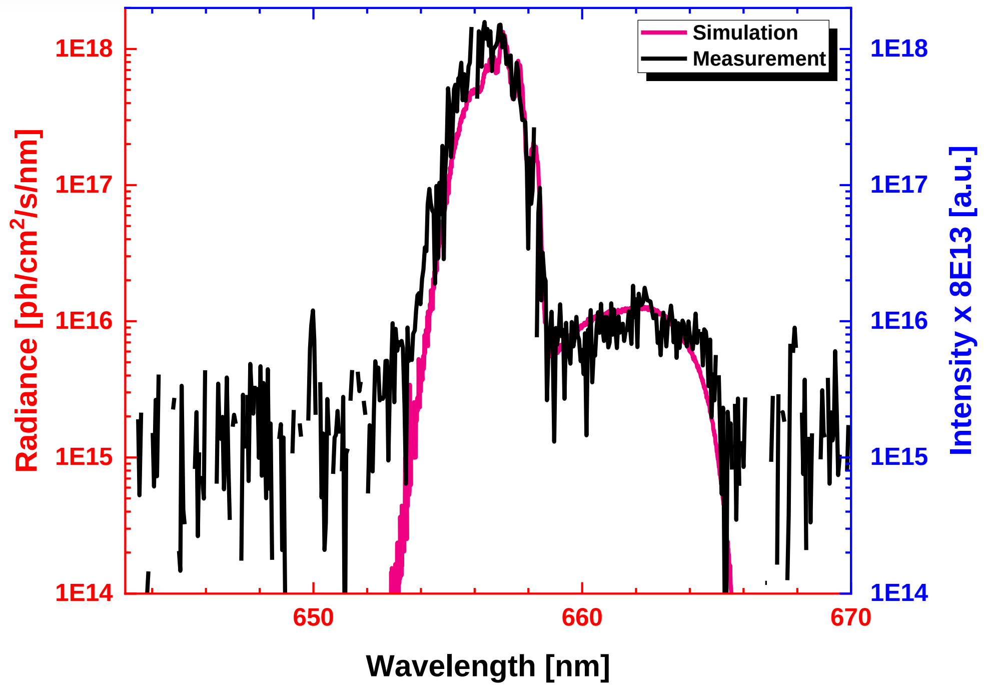


- In order to obtain more realistic FIDA measurement result, we input the measured Ti data produced by the CXS.
- However, intensity of DCX and HALO were getting smaller than before.

Effect of H/D ration on FIDASIM (using measurements Ti)

Fast ion of NB1 component (co-beam)





Red line : 100% H plasma and D NBI

Blue lien : 100% D plasma and D NBI

In this experiment, H/D ratio was 0.23/0.77 that was measured by Hα and Dα intensity.

- To consider H/D ratio on plasma, intensity of DCX and HALO were increased.
- The result shows H/D ratio is important to simulate the FIDA.

Conclusion

- In order to analyze the FIDA measurement for the LHD, enhanced FIDASIM was applied. We show enhanced FIDASIM is possible to simulate the FIDA measurement in the 3D magnetic fields devise such as LHD.

- FIDA measurement and simulation results are good agreement in MHD-quescient plasmas.

- We obtained the strong tool to understanding fast-ion behavior with the MHD instabilities.

- We recognized FIDASIM need more large grid in the low electron density situation.

- We shows H/D ratio is important to simulate the FIDA.

Future Works

- We need to elucidate the reason of differences between FIDASIM and FIDA measurement.

- In order to understanding fast-ion behavior with the MHD instabilities, we need to make database on MHD-quescient plasmas.