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Collective Thomson scattering by using a 77GHz gyrotron for bulk and fast ion measurements in LHD

K.Tanaka [1*], M. Nishiura[1], S. Kubo[1], T. Shimozuma[1], K. Kawahata[1], T. Mutoh[1], H. Igami[1], Y. Yoshimura[1], H. Takahashi[1], T. Saito[2], Y. Tatematsu [2], S. Ogasawara[3], S.B. Korsholm[4], F. Meo[4], M. Stejner[4] LHD experiment group

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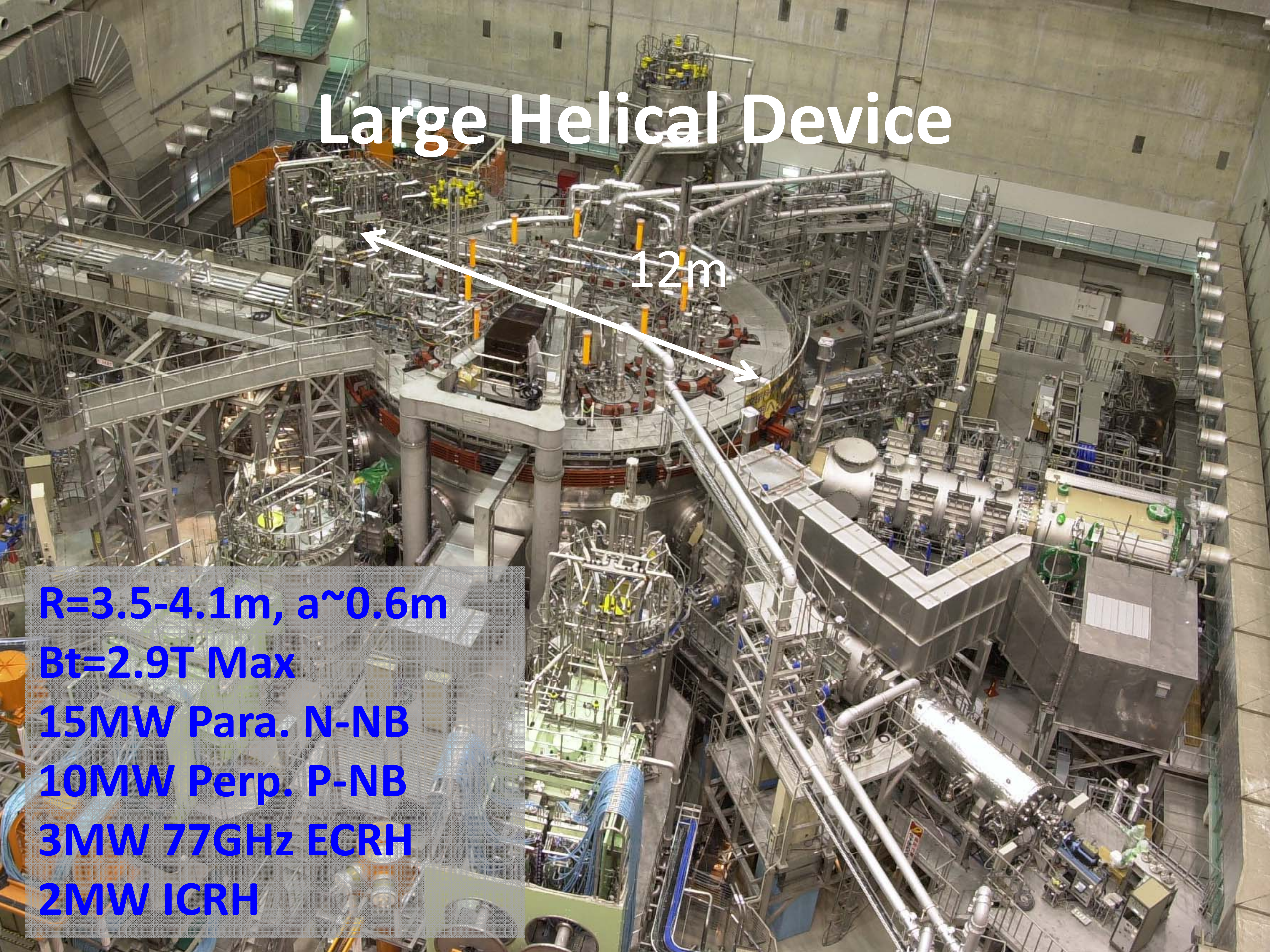
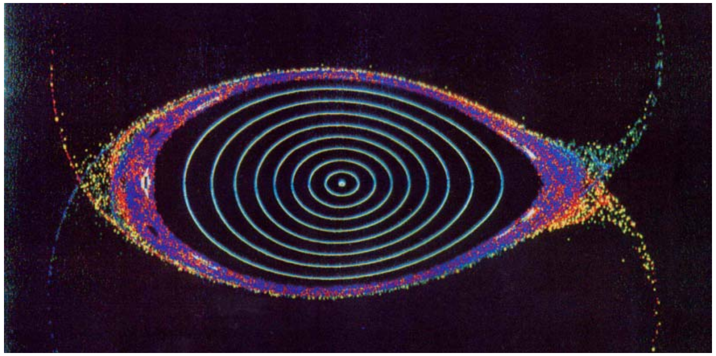
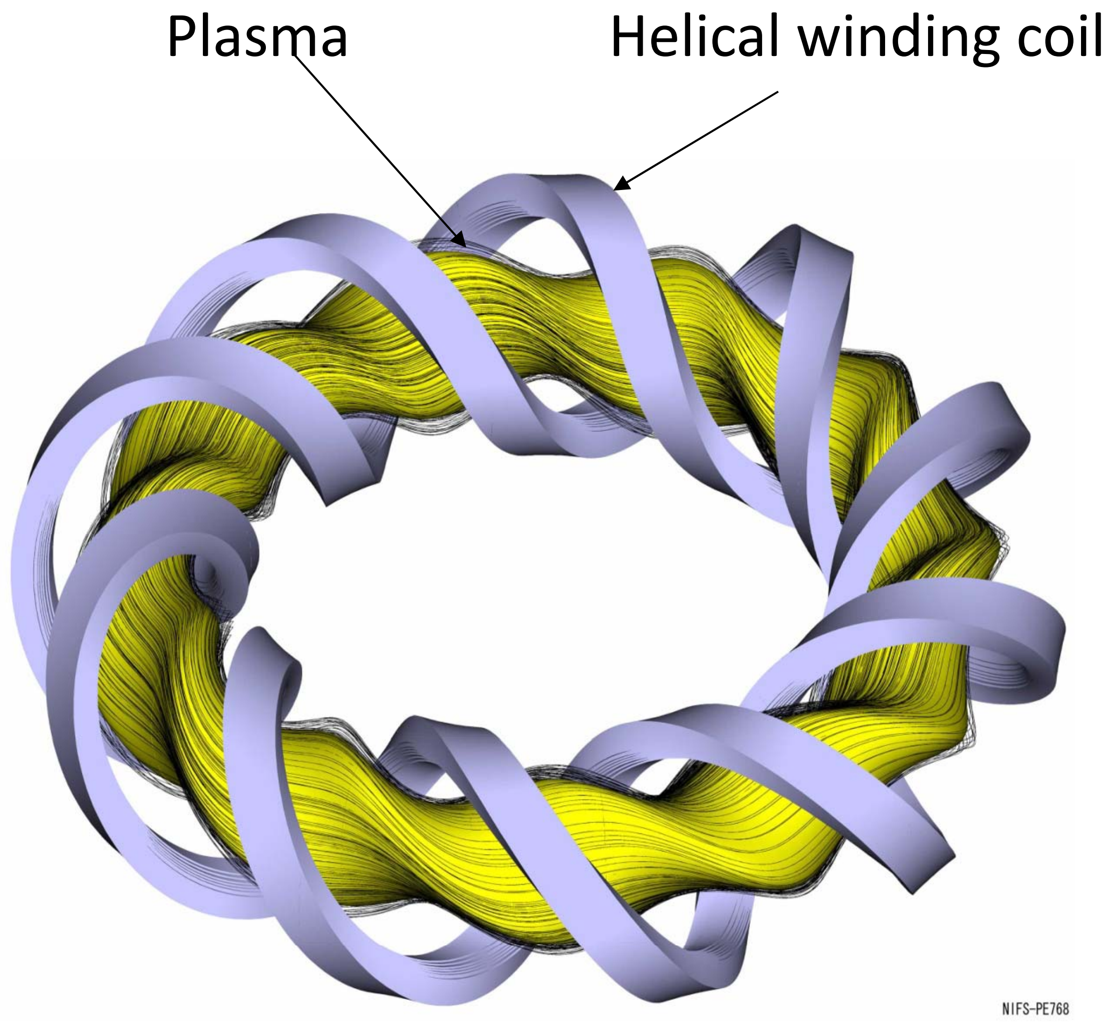
Large Helical Device



R=3.5-4.1m, a~0.6m
Bt=2.9T Max
15MW Para. N-NB
10MW Perp. P-NB
3MW 77GHz ECRH
2MW ICRH

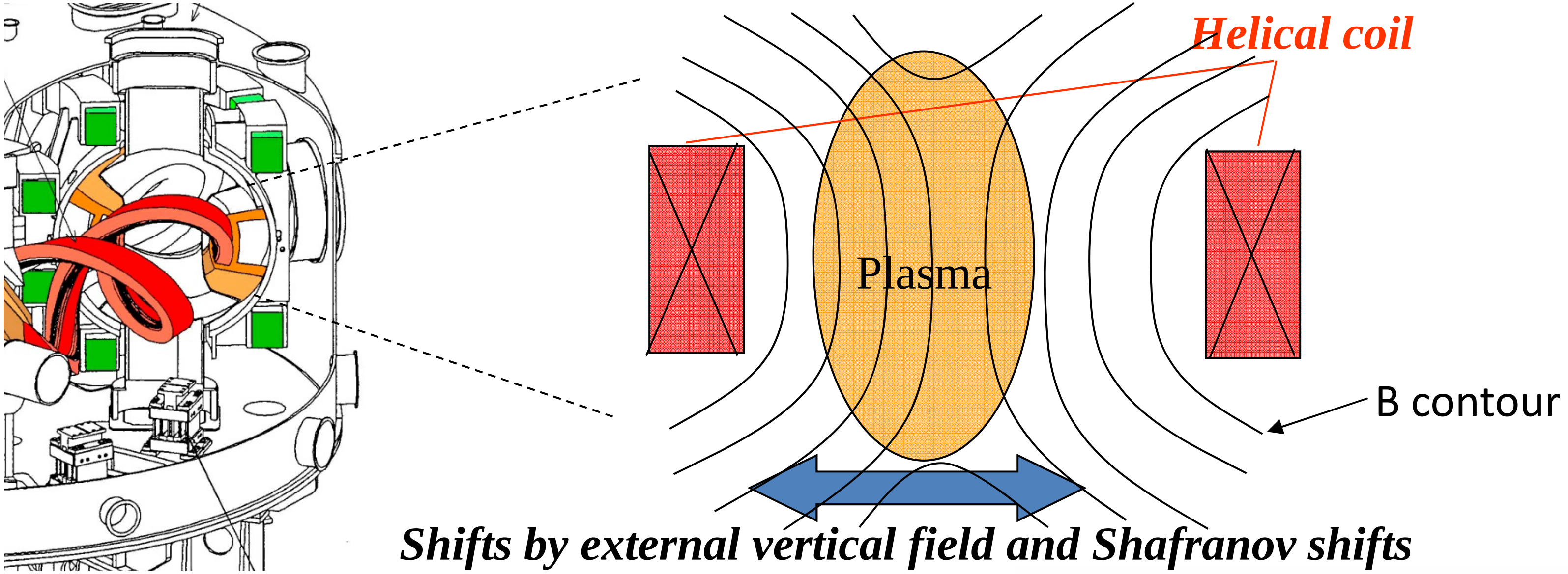




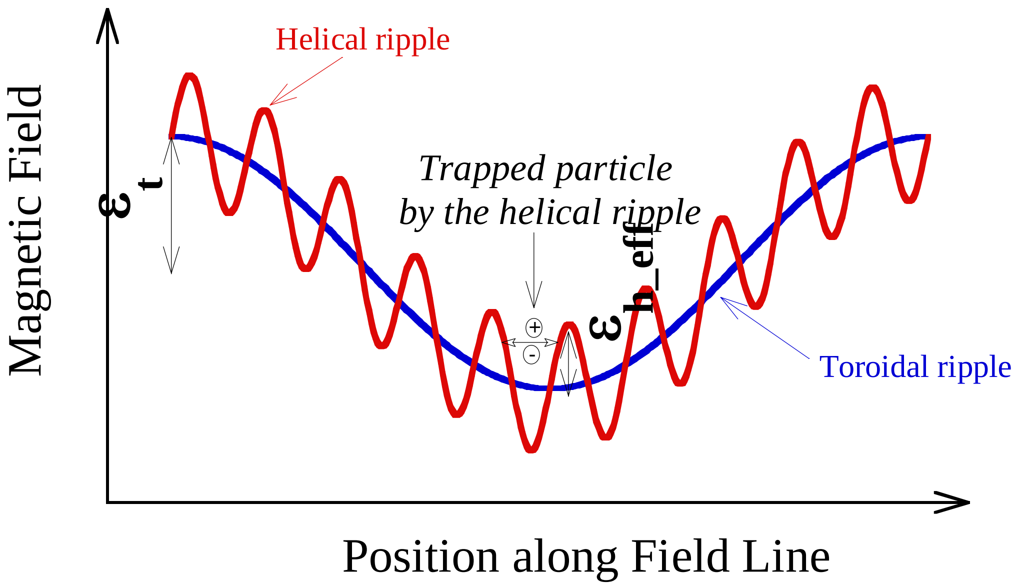
External coils can sustain magnetic flux surface stationary.

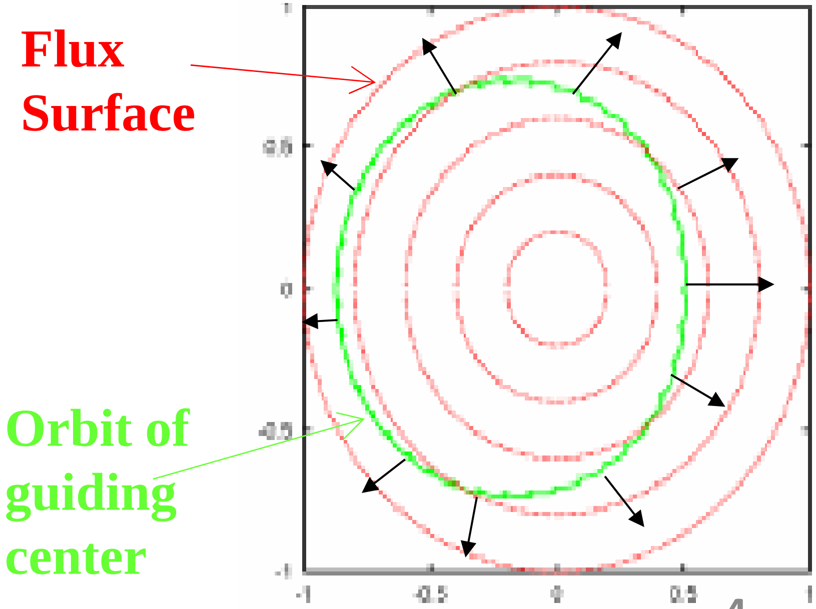
This is a strong advantage for the steady state operation.

Particularity of magnetic configuration in LHD is additional magnetic ripple. This enhances bulk and fast ion transport.



Shifts by external vertical field and Shafranov shifts





Outline

1. Introduction of collective Thomson scattering (CTS)

2. CTS system in LHD

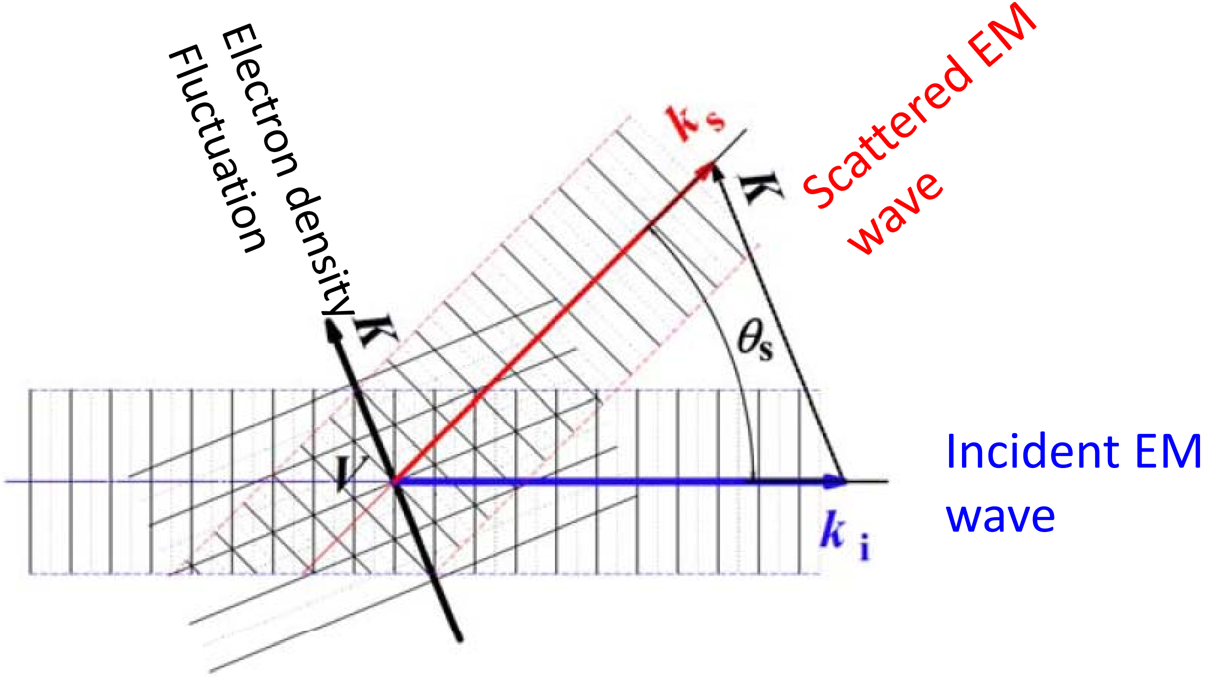
3. Experimental results

4. Summary

Introduction to Collective Thomson Scattering (CTS)

Collective scattering means scattering of electro magnetic wave by collective motion of electron

Scattering condition



Bragg condition $2k_i \cos\left(\frac{\theta_s}{2}\right) = K$ should be satisfied.

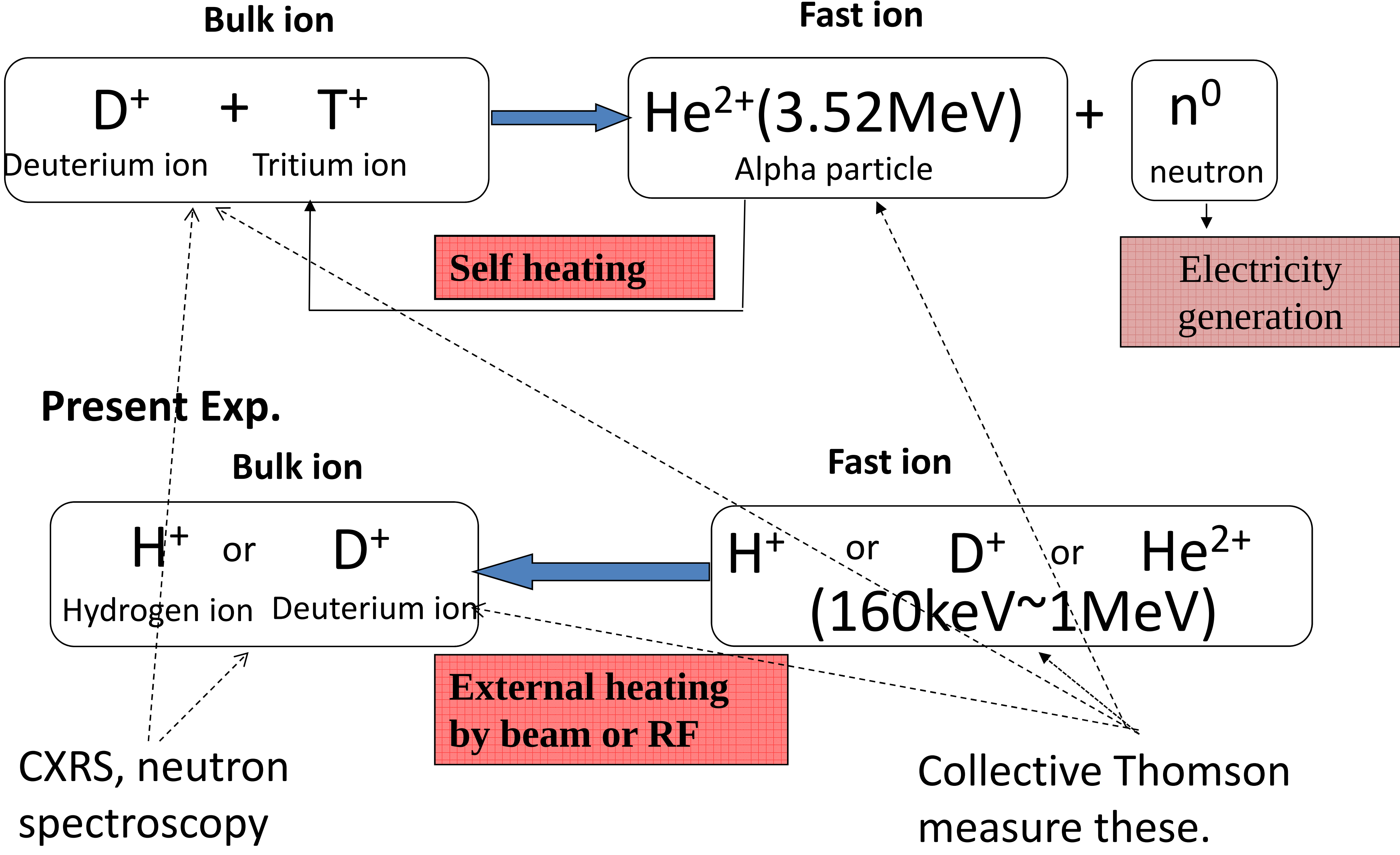
Collective motion of electrons is due fluctuations caused by instability
→ study of macro or micro instability are possible

It is also due to the electron motions shielding local charge of ion (Debye shielding
→ Ion moves thermally, thus, information of ion thermal motion can be extracted

What CTS measures?

Fast ion measurements are weighted by CTS.

Future Exp.



Bulk ion

D^+ + T^+

Deuterium ion Tritium ion

Fast ion

He^{2+}(3.52MeV) + n^0

Alpha particle

neutron

Electricity generation

Self heating

Present Exp.

Bulk ion

H^+ or D^+

Hydrogen ion Deuterium ion

Fast ion

H^+ or D^+ or He^{2+}

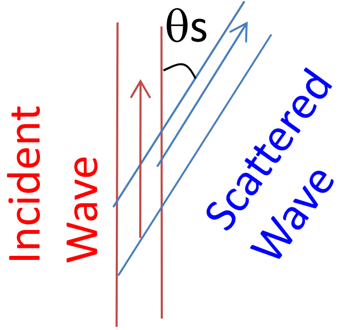
(160keV~1MeV)

External heating by beam or RF

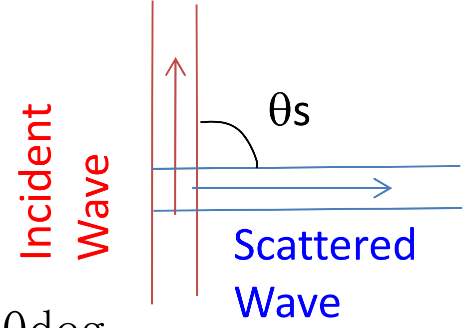
CXRS, neutron spectroscopy

Collective Thomson measure these.

Collective condition is determined by Debye length $(\propto Te^{1.5}/ne^{1.5})$ and fluctuation K($\propto$ scattering angle)

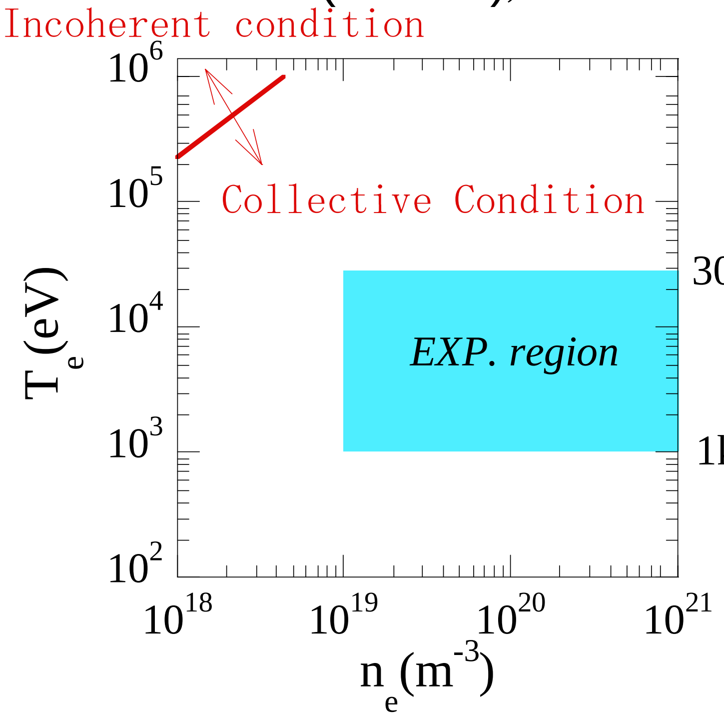


$\alpha=1/K\lambda_d<1$ is required for collective condition.



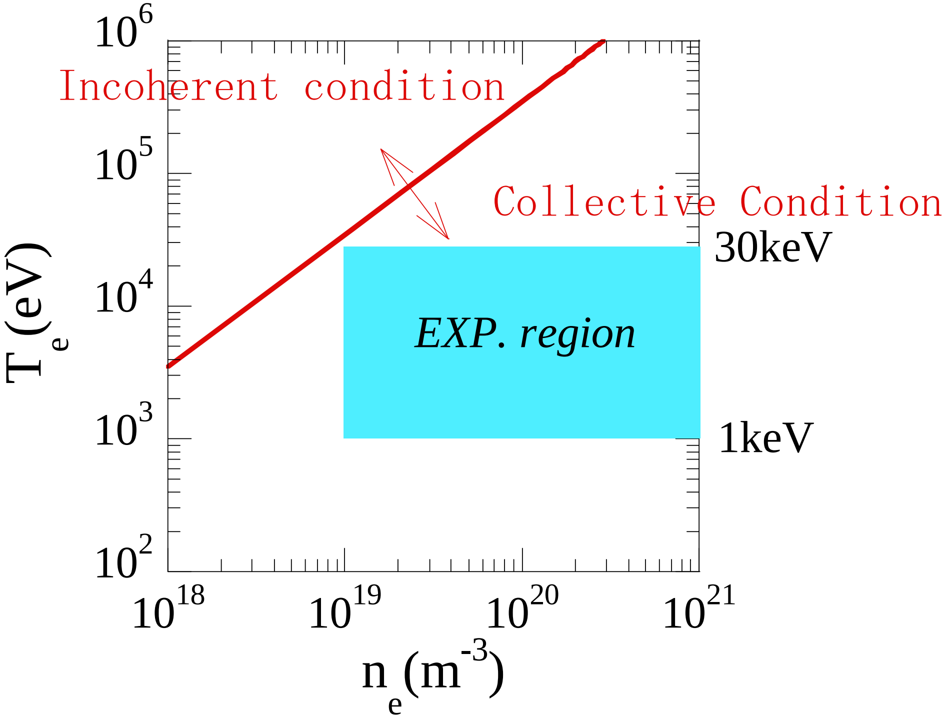
θ_s=10deg.

ki=1.6mm^{-1}(77GHz), K=3.2mm^{-1}

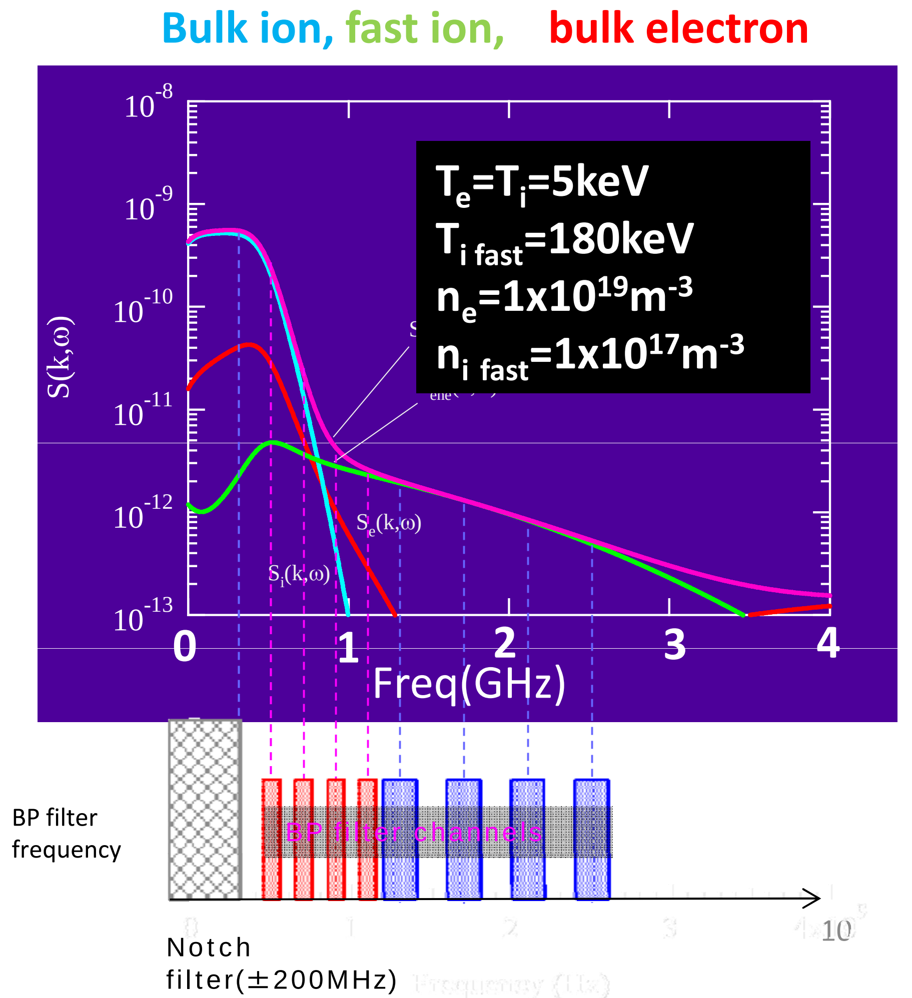


θ_s=90deg.

ki=1.6mm^{-1}(77GHz), K=2.2mm^{-1}



CTS spectrum tells bulk thermalized ion, electron and non thermalized fast ion.



Nishiura et al., RSI(2008)

Electron density and temperature are available from other diagnostic (incoherent Thomson, interferometer), thus ion information is determined as free parameters

Spectrum can be measured either filter bank system or fast digitizer.

The difficulty of CTS for high temperature plasma

1) Microwave high power gyrotron is probably only solution to get reasonable spatial resolution and signal intensity.

2) Even using high power microwave (~100kW), scattered power is order of nW.

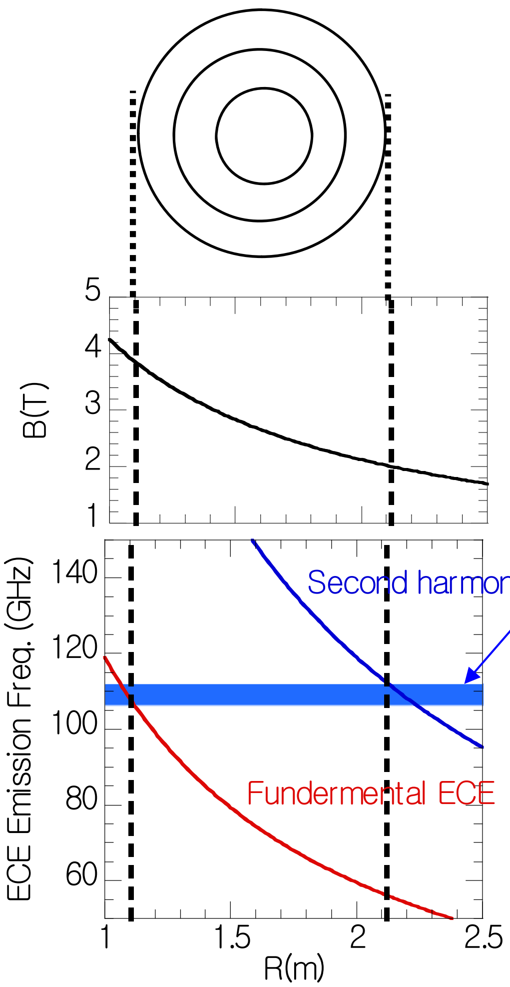
3) Small noise can easily hide the real signal.

4) Good band reject filter to remove stray radiation is essential.

5) Fighting against ECE noise is pretty tough.

In present tokamak, frequency between fundamental and 2nd harmonics EC is selected in order to reduce ECE background noise

Tokamak Flux surface



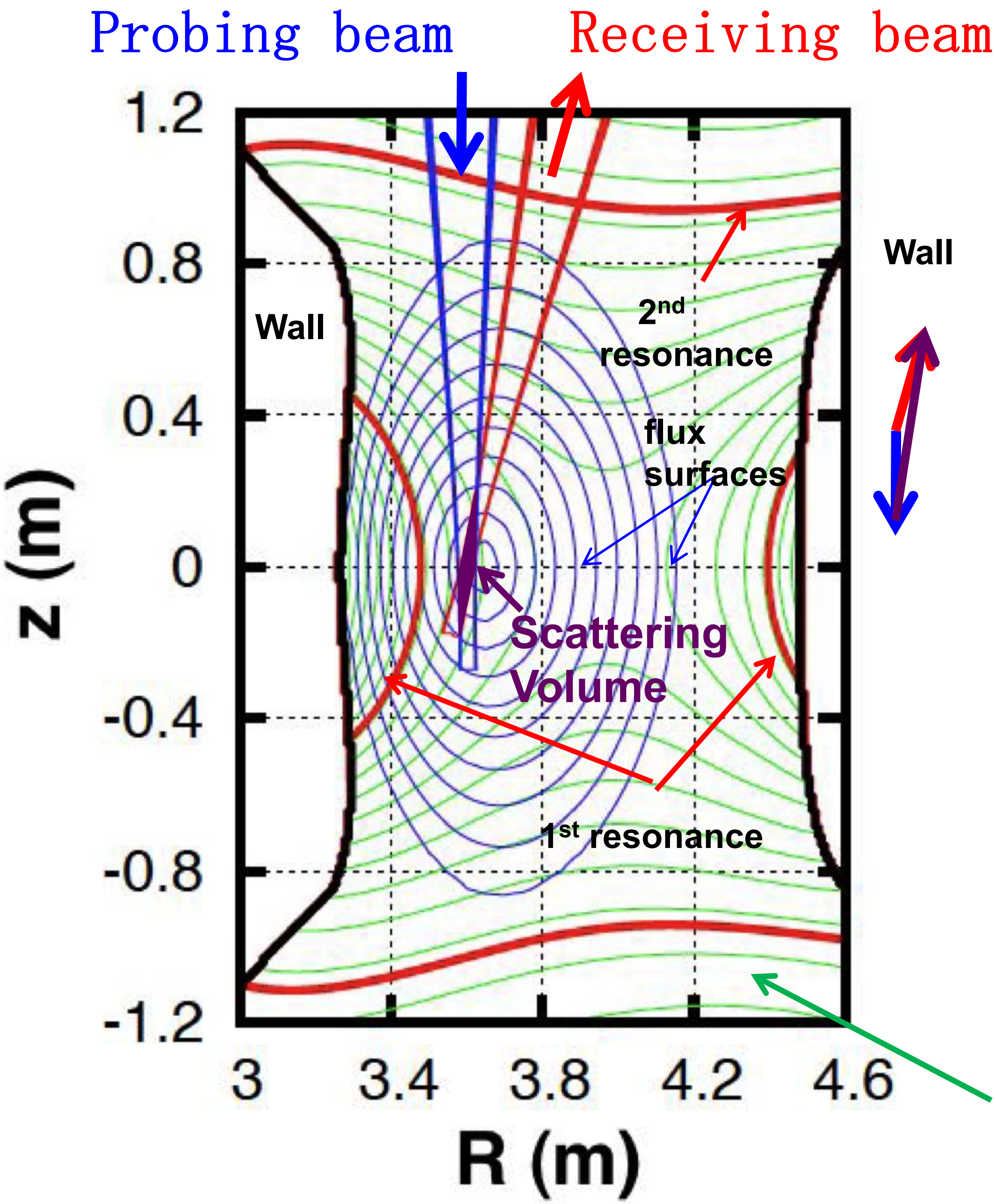
Freq. window between 1st and 2nd resonance

Max freq of n th EC freq. < source freq. < Min of n+1th EC freq.

$$28n\,B_{\max} < f(\mathrm{GHz}) < 28(n+1)\,B_{\min}$$

$$\frac{B_{\max}}{B_{\min}} < \frac{n+1}{n}$$

In LHD, Bt cannot be tuned to expel resonance

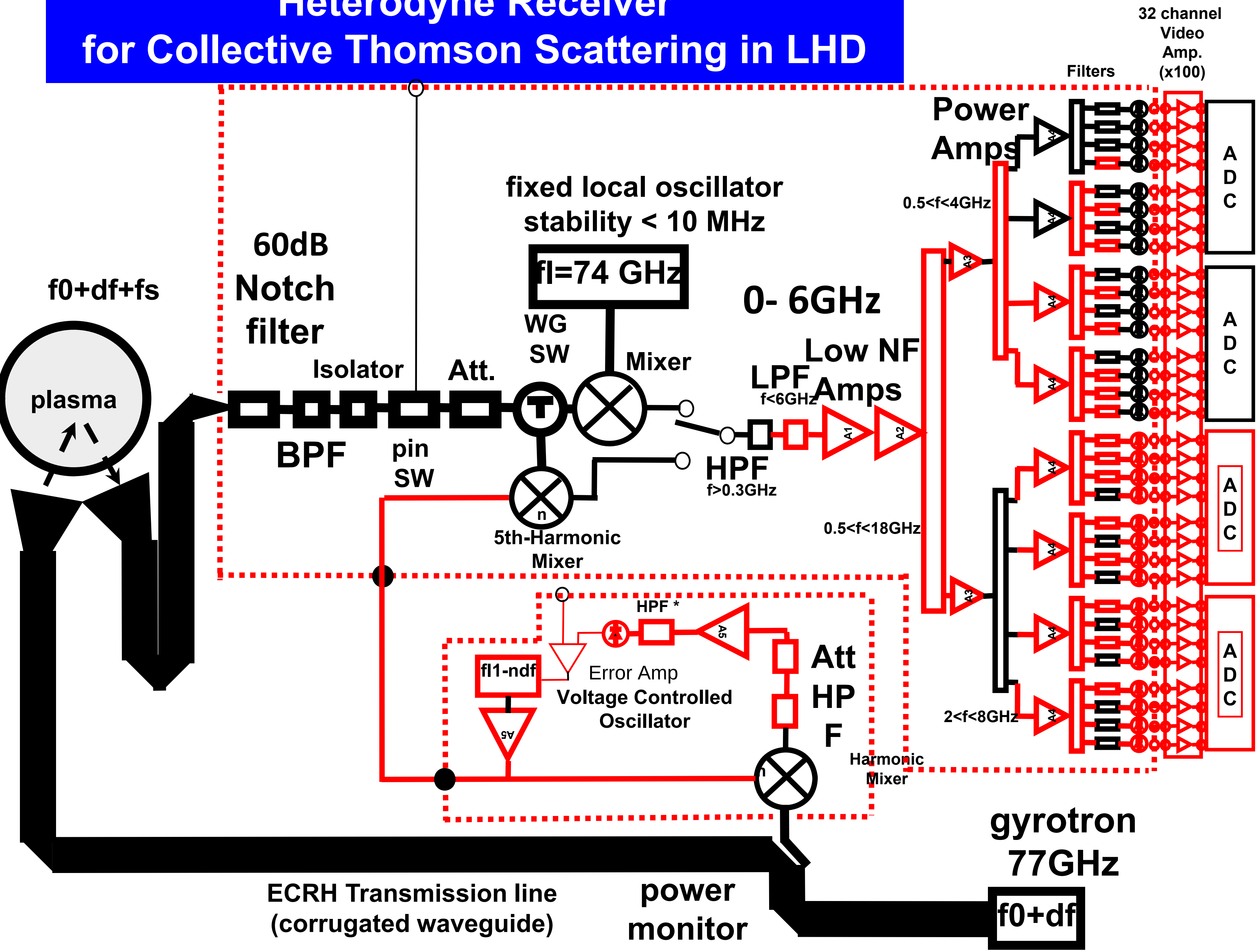


i) This causes technical difficulty to reduce ECE background noise.
ii) Beam is modulated to extract ECE back ground noise
iii) Put fundamental resonance away from the sight light
iv) Put 2nd harmonic resonance out of plasma

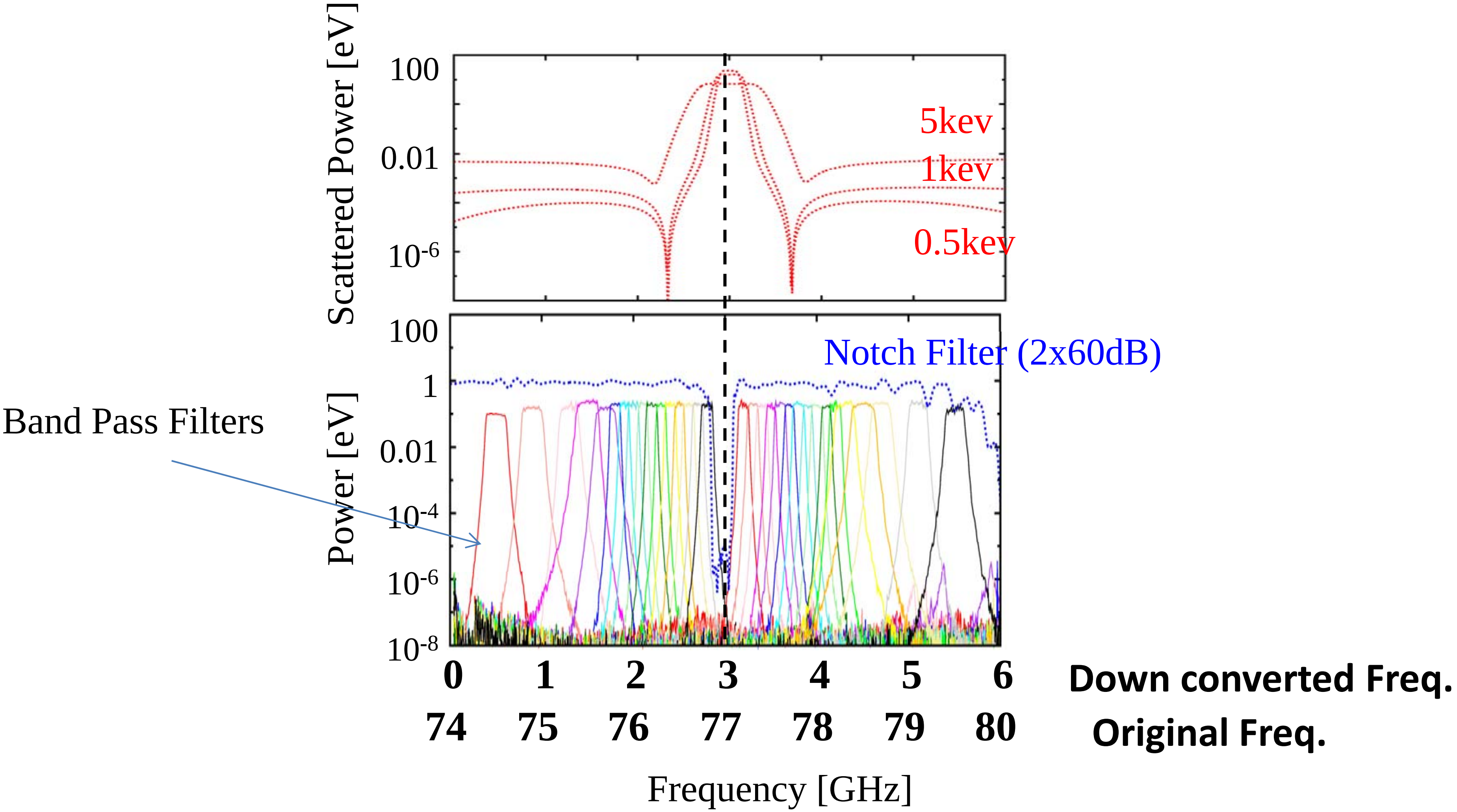
Green curve ; magnetic strength contour

LHD CTS system

Heterodyne Receiver for Collective Thomson Scattering in LHD



Spectrum is measured by filter bank system. Stray radiation around gyrotron frequency (76.95GHz)+-100MHz is cut by Notch filter (-120dB)



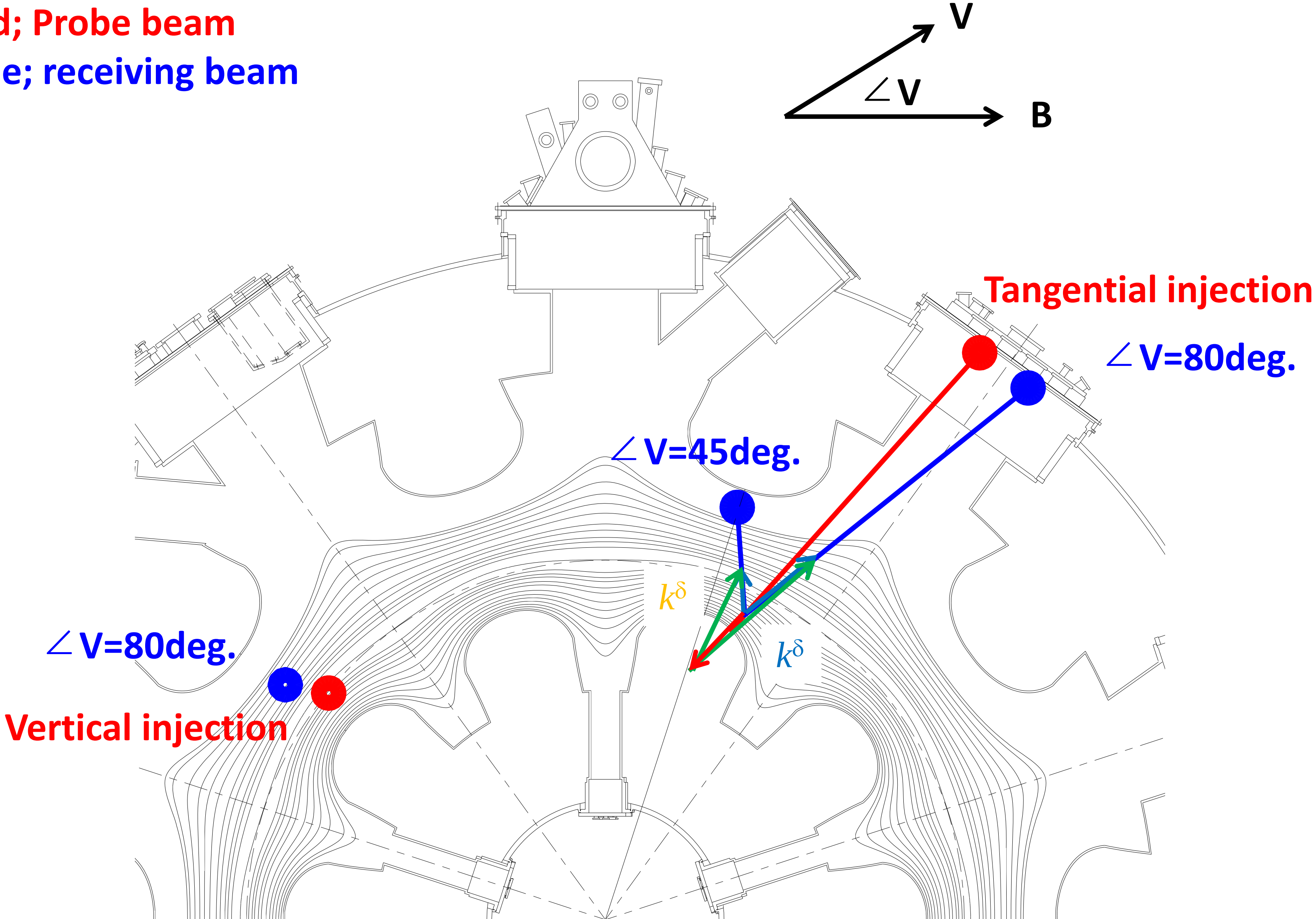
Spectrum and filter characteristics

Calibration and keeping linearity are necessary.

Three versions of scattering geometry were tried in order to measure different fast ion velocity components

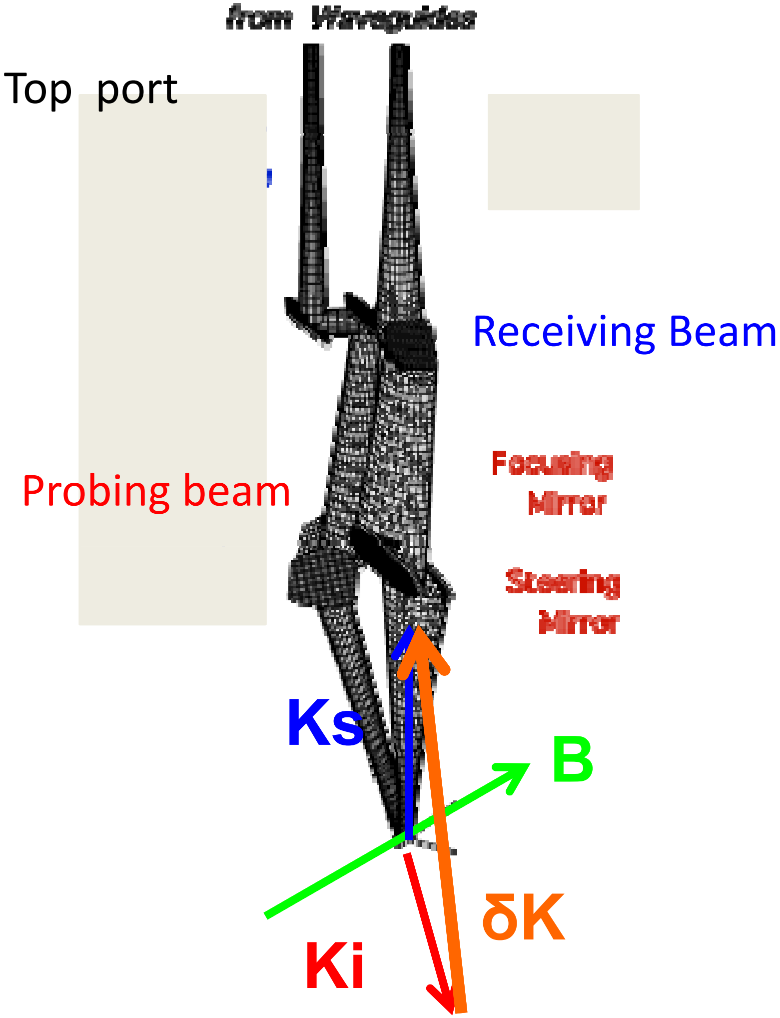
Red; Probe beam

Blue; receiving beam



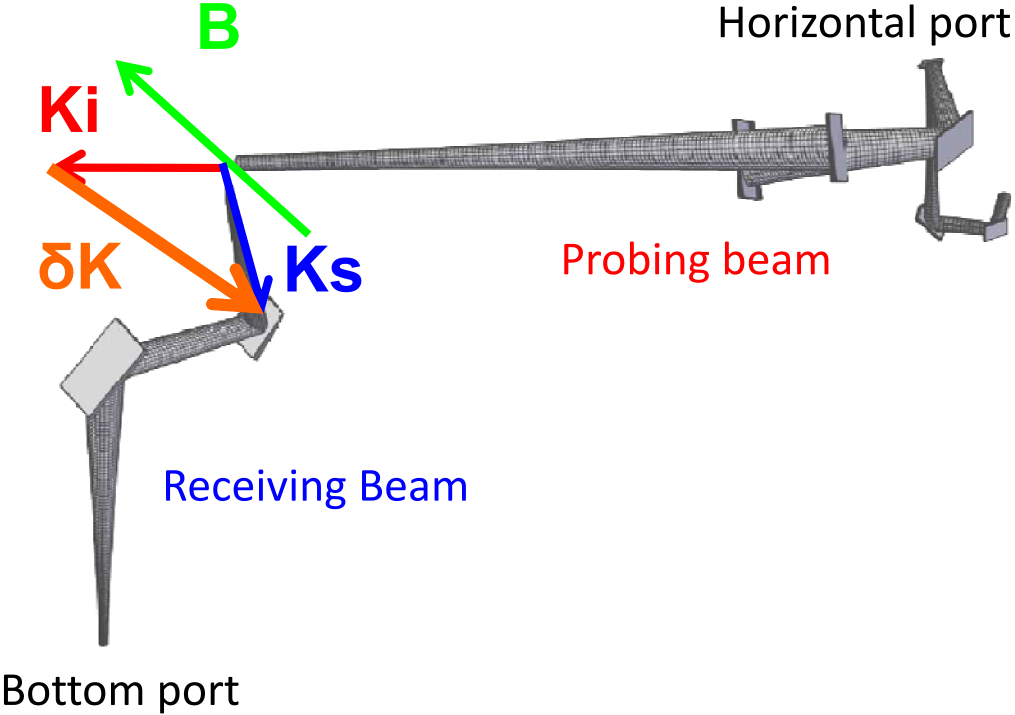
Change of geometry

2008~2010



Kperp is dominated.

2011~



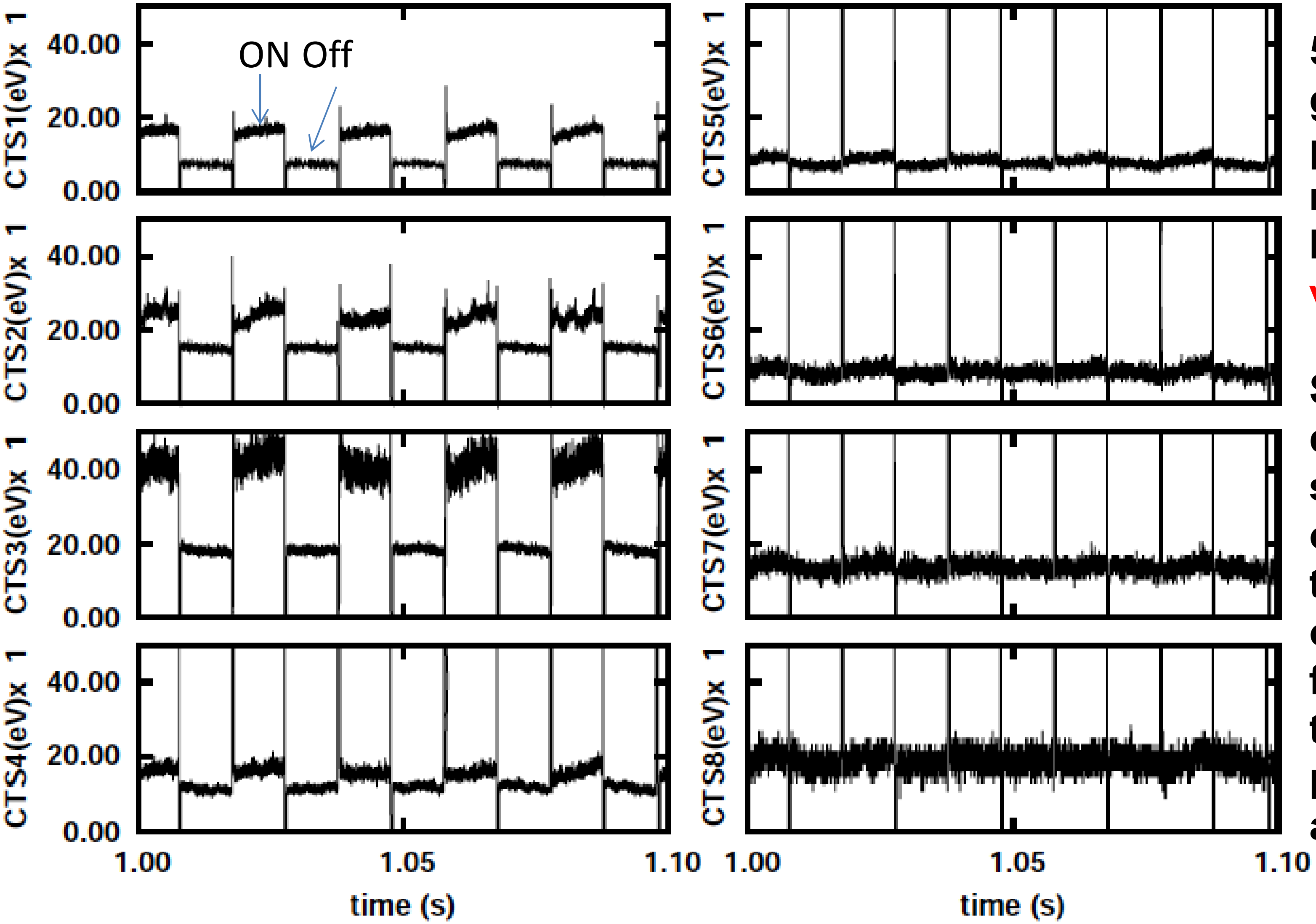
Kpara contribution lager

Experimental results

Raw signals of CTS. Gyrotoron was modulated in order to extract ECE background noise

LHD CTS #91758

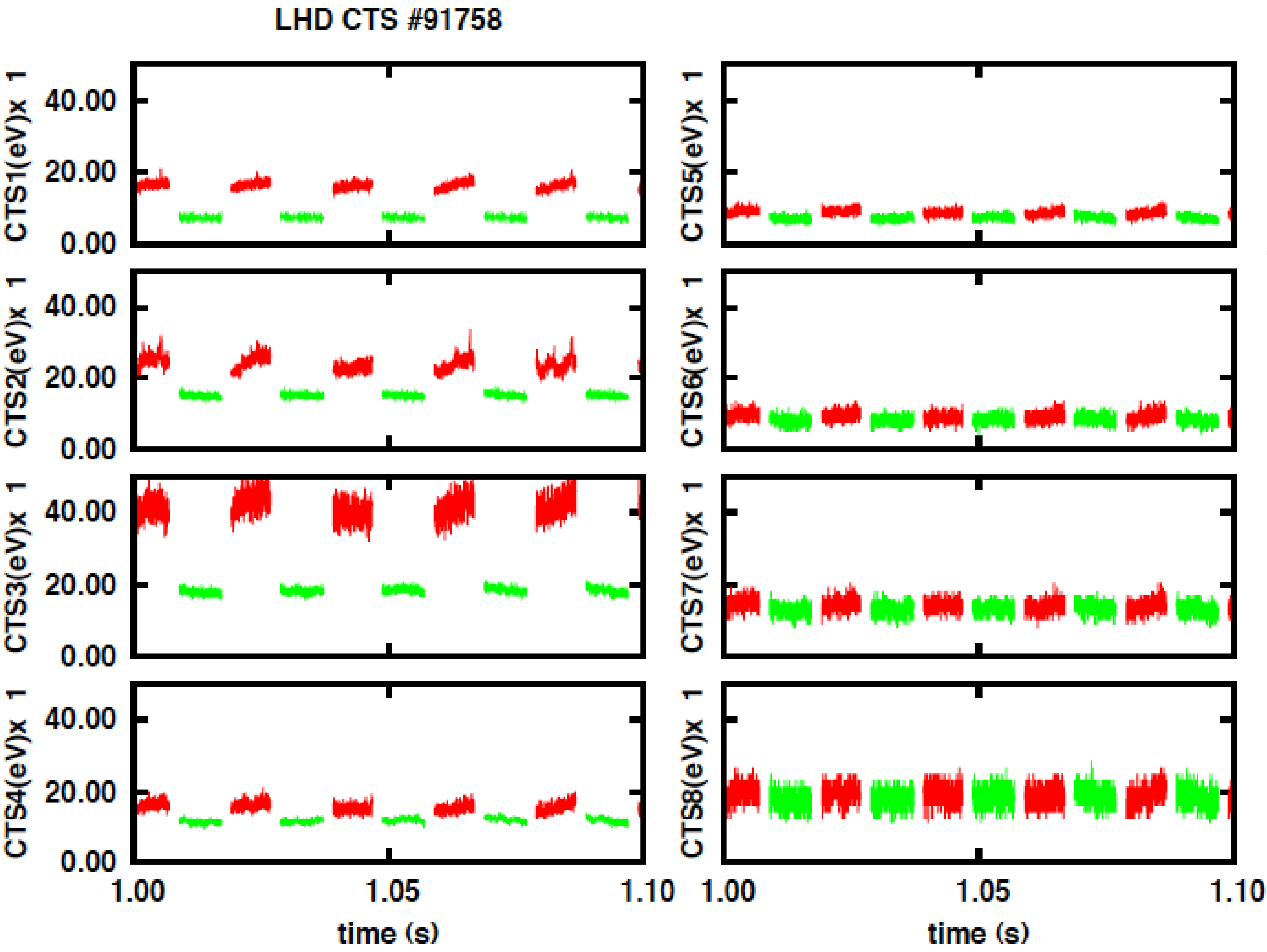
On timing ; Signal +ECE, Off timing ; ECE



50 Hz gyrotron power modulation by anode voltage

Spikes are due to the spurious oscillation of the gyrotron out of notch frequency at transient phase of anode voltage

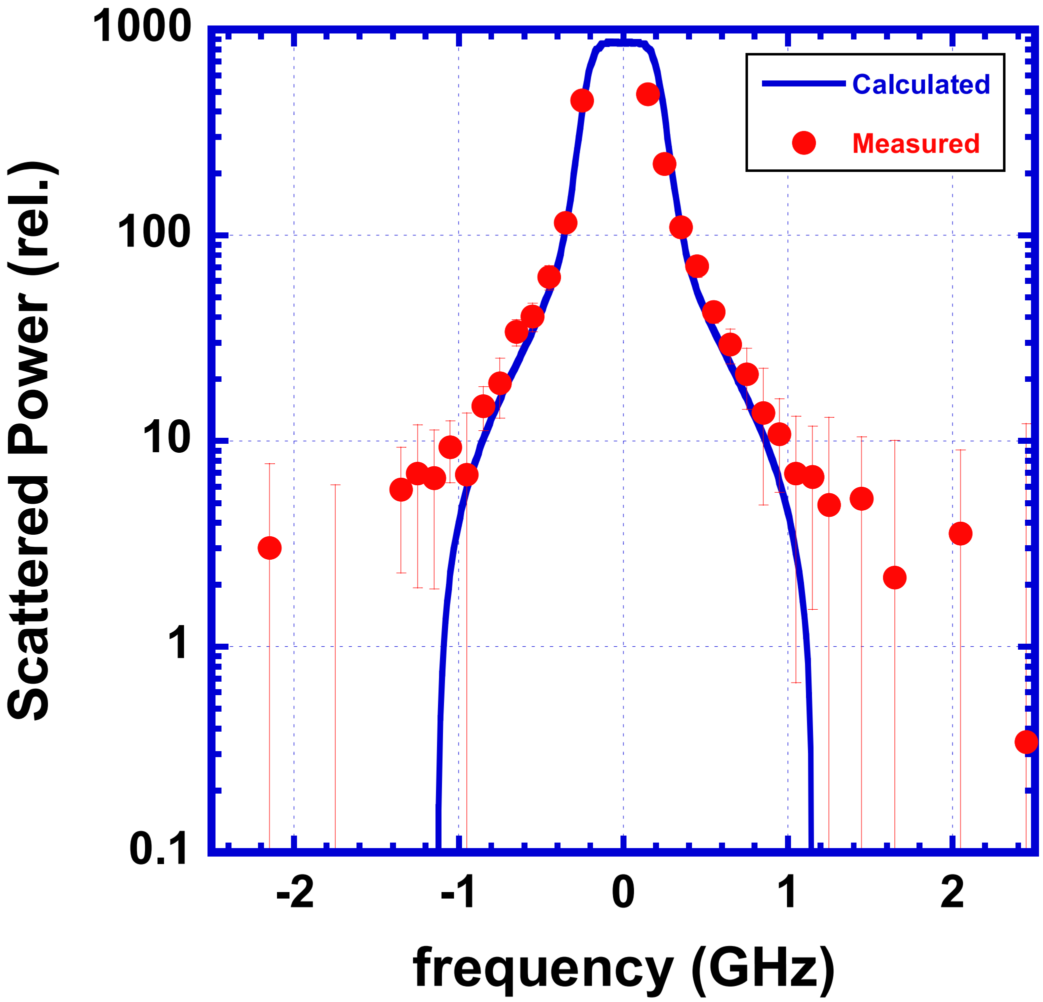
Spikes are removed numerically and separated on/off phase



Spikes are removed and separated to on and off phase.

Changes in slope are due to heating and diffusion effect of the background ECE.

Spectrum shape was fitted with bulk temperature



Spectrum is not absolutely calibrated.

Measured data are used for calculation.

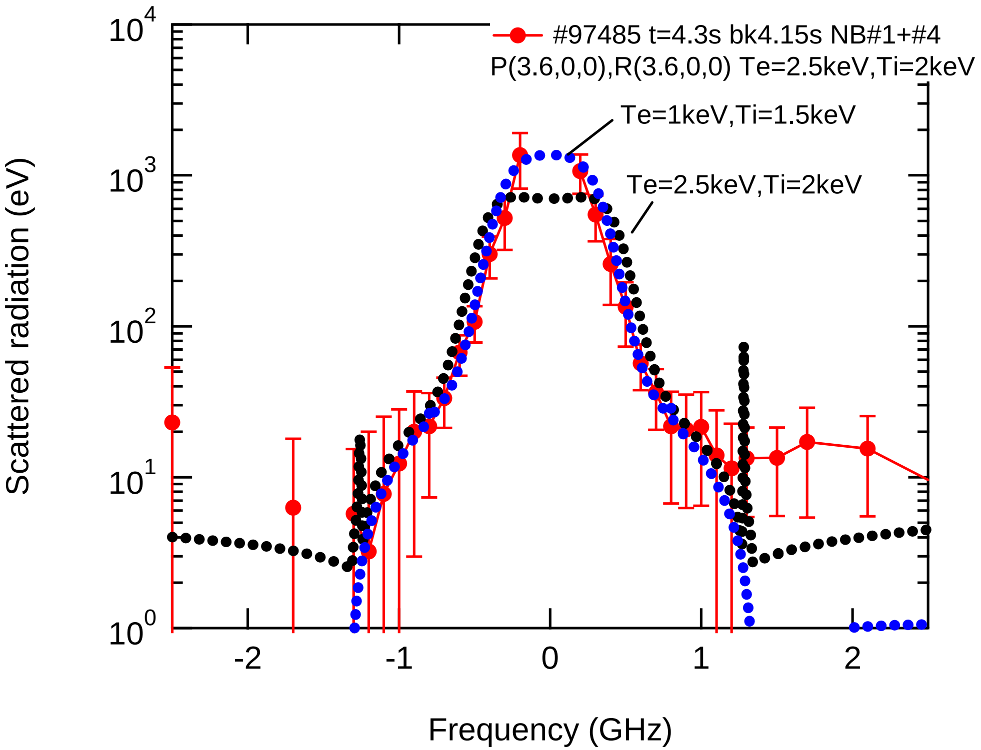
T_e=0.8keV
(from YAG TS)

T_i=0.7keV
(from Ar broadening)

n_e=2.5x$10^{19}$$m^{-3}$
(from FIR interferometer)

$N_{\text{fast 40keV}}$ =0.25x$10^{19}$$m^{-3}$
(Fitted)→ 10% of bulk density too high?

Sensitivity of fitting with calibrated data



Black (Exp. Data from YAG TS and CXRS); Te=2.5keV, Ti=2kev

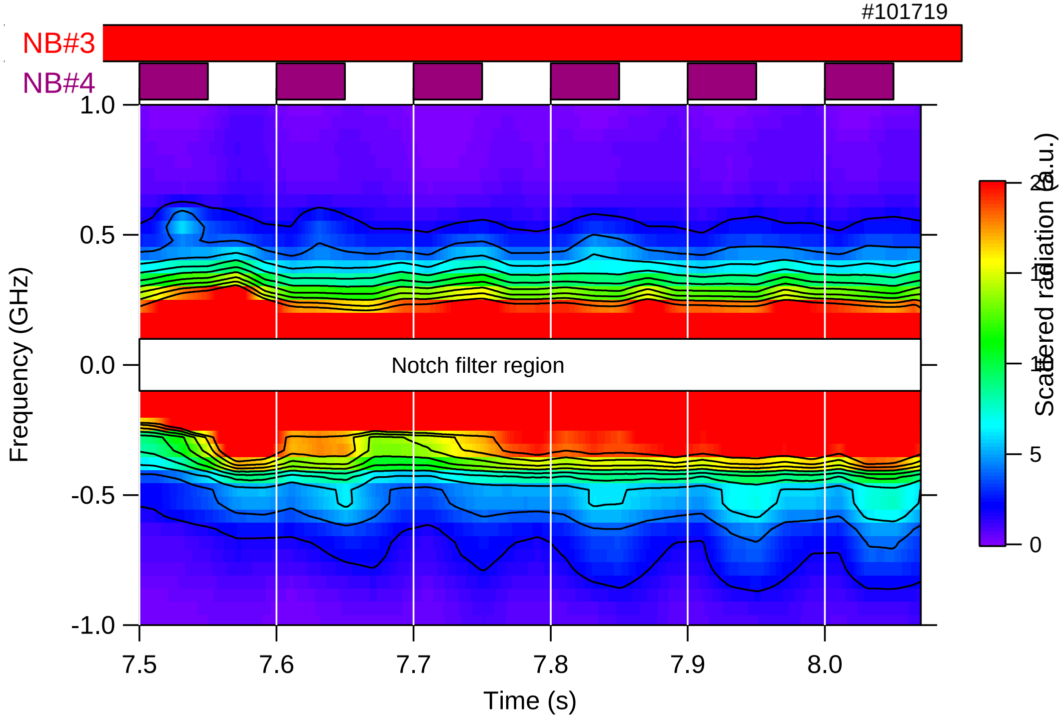
Blue (other candidate of parameter); Te=1keV, Ti=1.5kev

Blue is more likely to fit experimental data than black, but blue is unlike parameter compared with YAG TS and CXRS.

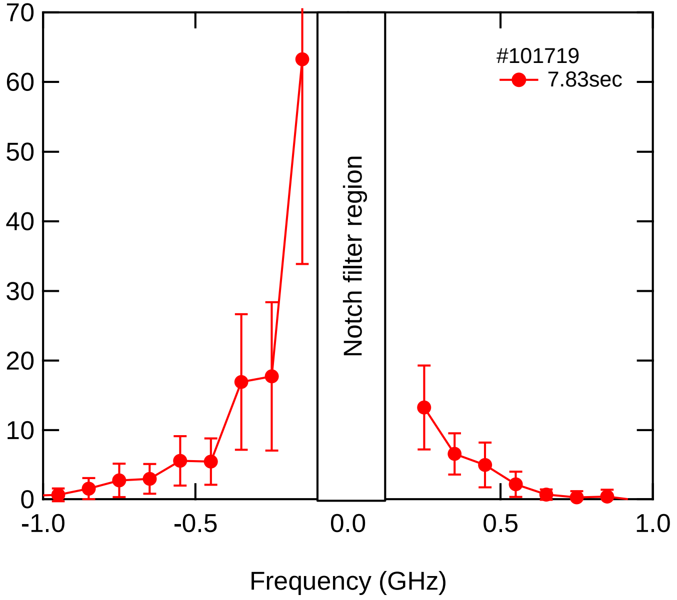
Increase of bulk channel and check of the calibration data is necessary. Especially, numerical FFT by using fast digitizer will help

Signature of fast ion components

#3, para, #4 perp.



Scattering geometry is sensitive to perp. components



When perpendicular NBI is injected, components higher than 0.5GHz are observed. This is likely to be fast ion components.

Signal is weak. Asymmetry of spectrum is unlikely for perpendicular beam.→This might be caused by the drift of gyrotron frequency.

In campaign of 2011 ,in order to improve the signal quality, we tried

i) checking of gyrotoron frequency and fine spectrum measurements using a fast digitizer

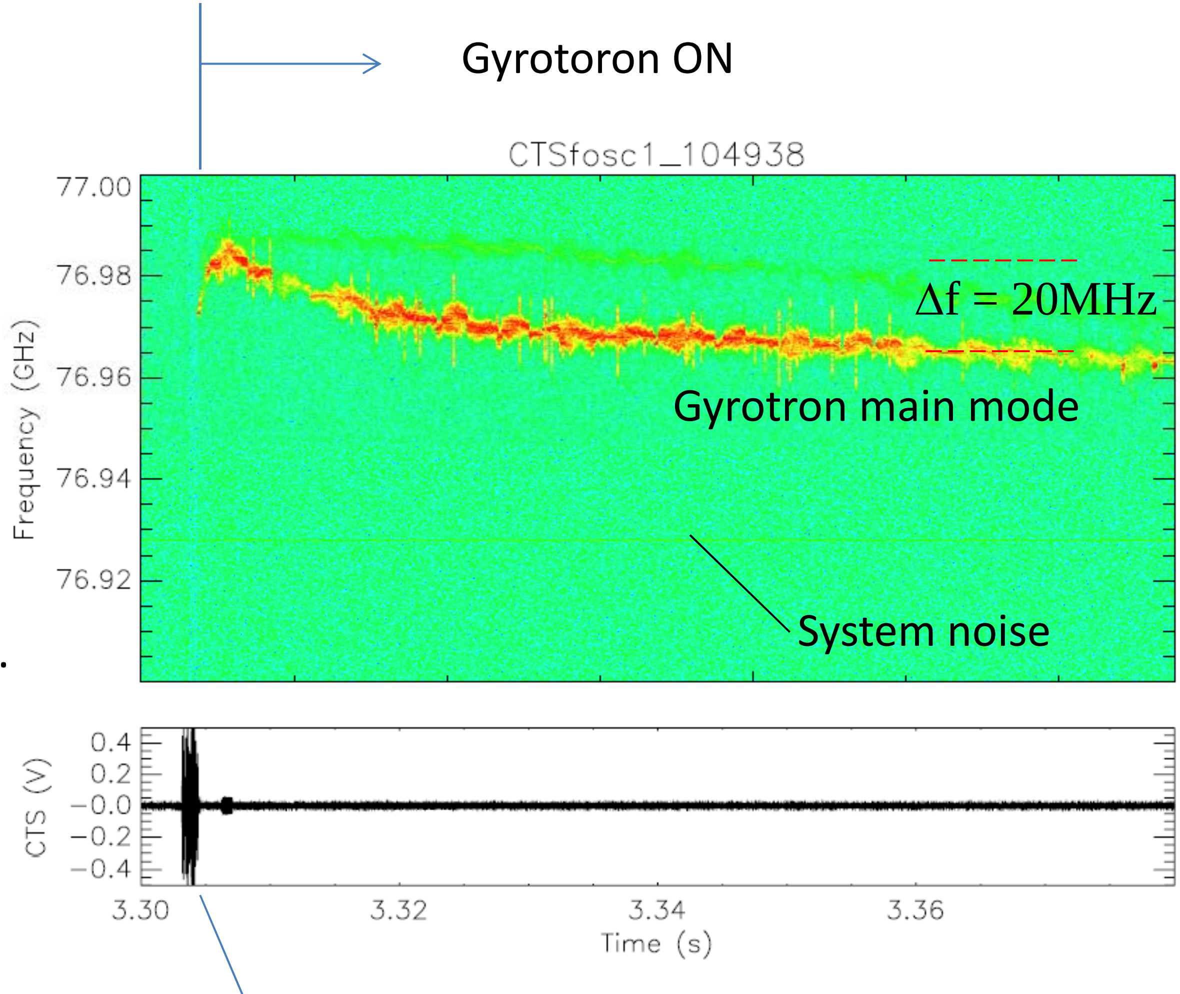
ii) Scan of scattering volume using fast sweeping mirror system to confirm scattering position

Gyrotron frequency was measured by fast digitizer

The gyrotron output is introduced into the CTS receiver .
The nominal frequency is 76.95GHz. The actual frequency depends on the gyrotron operation.

The frequency shift is about 20MHz at 80 ms pulse. The shift comes from the thermal expansion of the gyrotron cavity.
➡The gyrotron frequency exists inside the notch filter.

The time constant for the above shift is about 30~40ms.
➡The CTS probing beam is modulated with the frequency of 50Hz. The frequency shift has to be taken care of for CTS analysis.



Gyrotoron ON

Δf = 20MHz

Gyrotron main mode

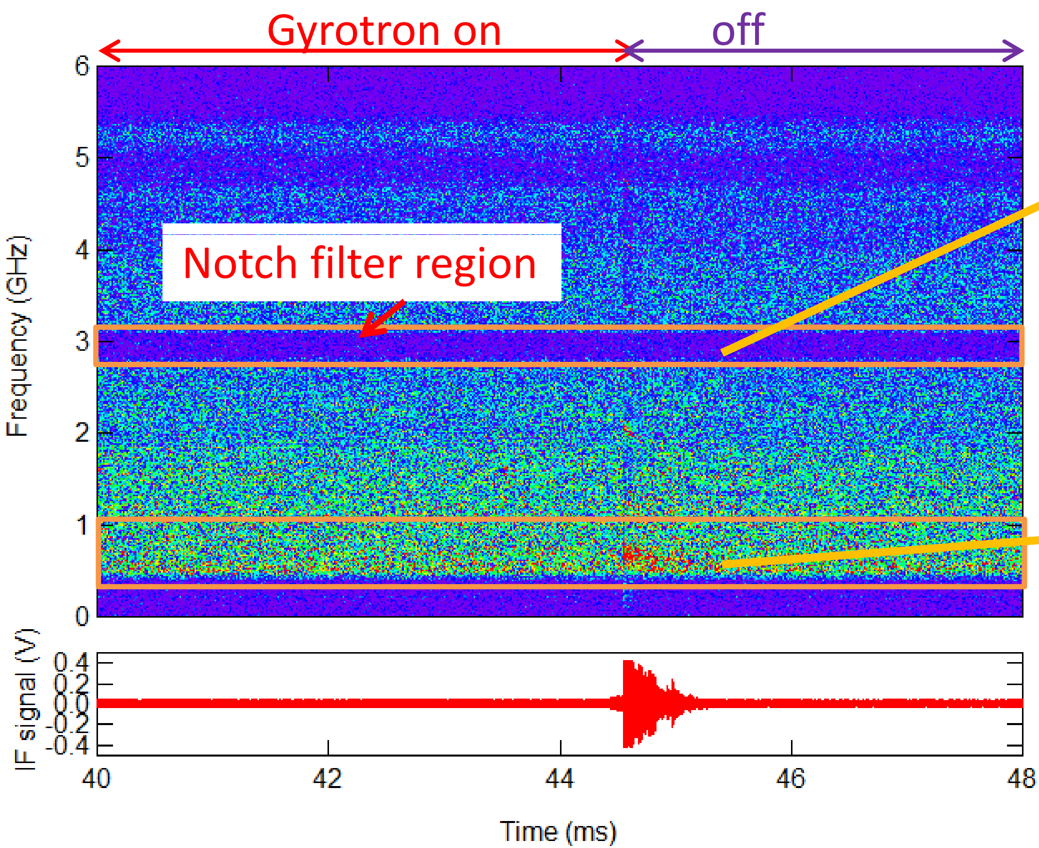
System noise

Spurious signal ~74.7GHz

Frequency shifts may cause the asymmetry of spectrum.

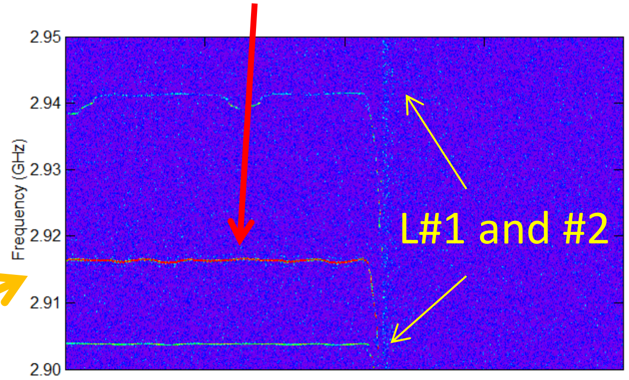
Spuripus mode was observed. This distorts spectrum.

At the gyrotron output ON timing and OFF timing, the spurious mode appeared. This mode should be removed for CTS measurement.



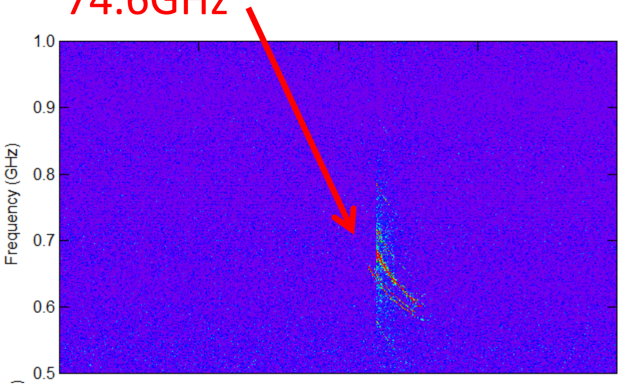
The time and frequency domain signal is measured by CTS receiver at LHD#101711.
L#1,L#2,L#7, all 77GHz gyrotron
IF frequency = 0~6GHz

Probing beam L#7
Nominal frequency is 76.95GHz



Inside the notch filter

Spurious lines at the trailing edge
~74.6GHz

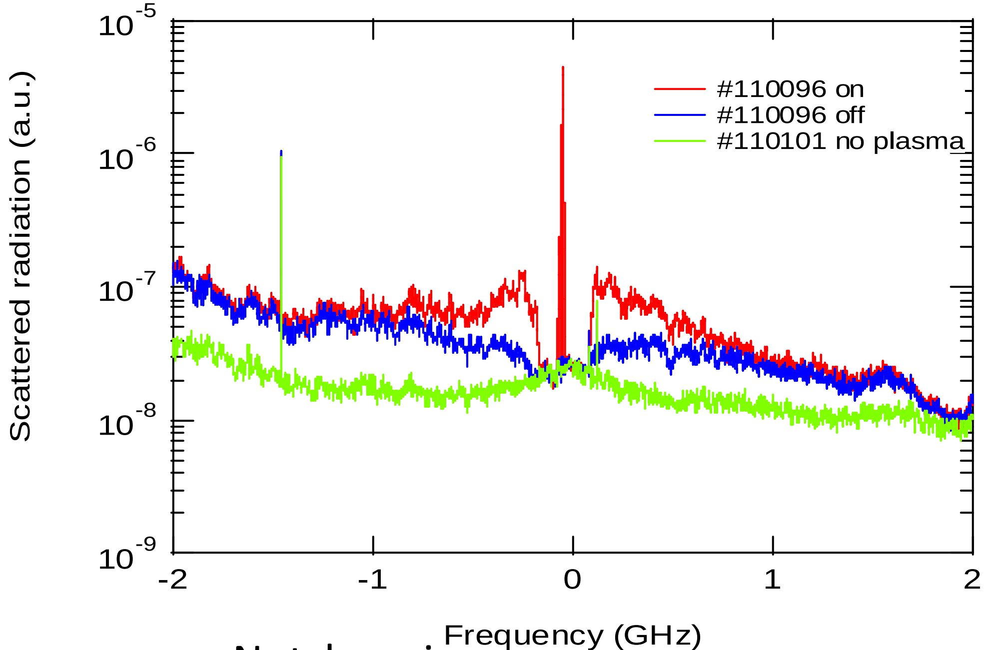


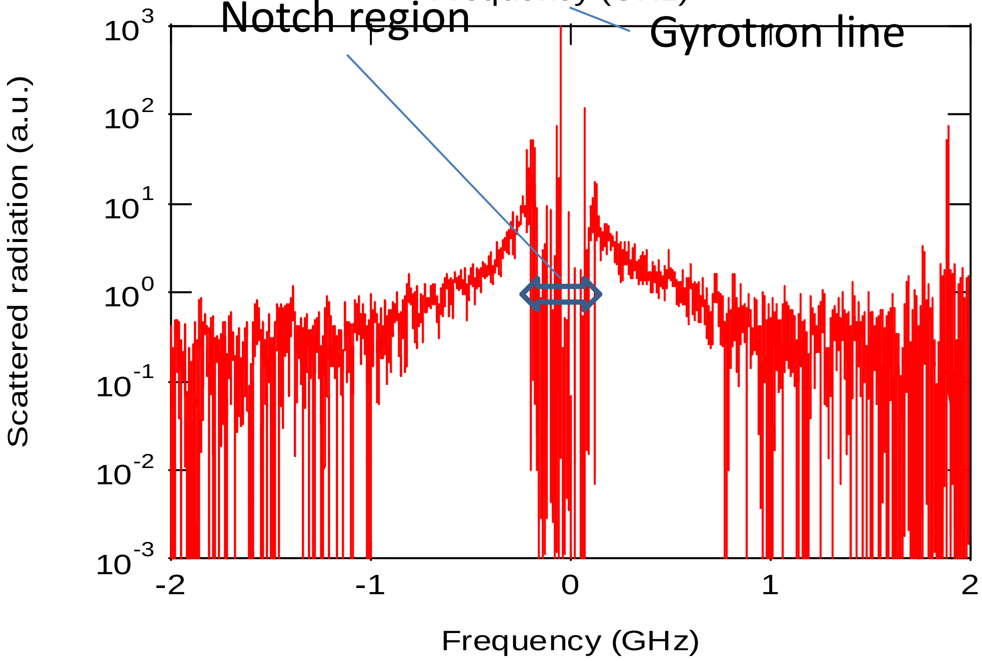
Outside the notch filter

Fine spectrum was measured by fast digitizer

Fast digitizer
National Instruments,
NI-PXIe 5186
- **BW: 5 GHz**
- **Sampling rate: 12.5 GS/s**
- **Resolution: 8-Bit**
- **Memory: 1GB (80ms duration)**

The 77GH range signal is down converted to the IF signal from 0 to 6GHz, which is directly calculated and transformed by FFT.

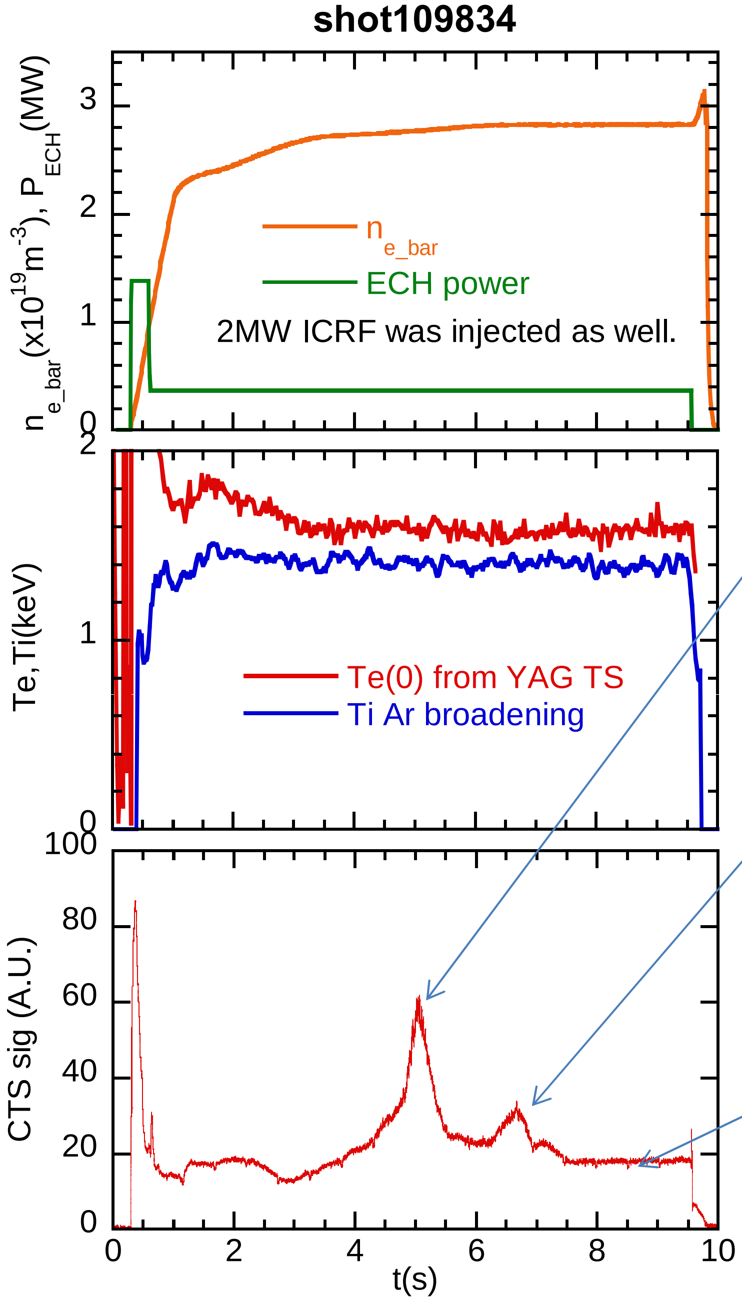




Notch region

Gyrotron line

Fast sweeping mirror system enabled to check antenna alignment.



Preliminary

Signal becomes strongest at around maximum scattering volume. This peak is observed only in bulk channel

The second peak is observed. This may be due to stray radiation or multiple reflection.

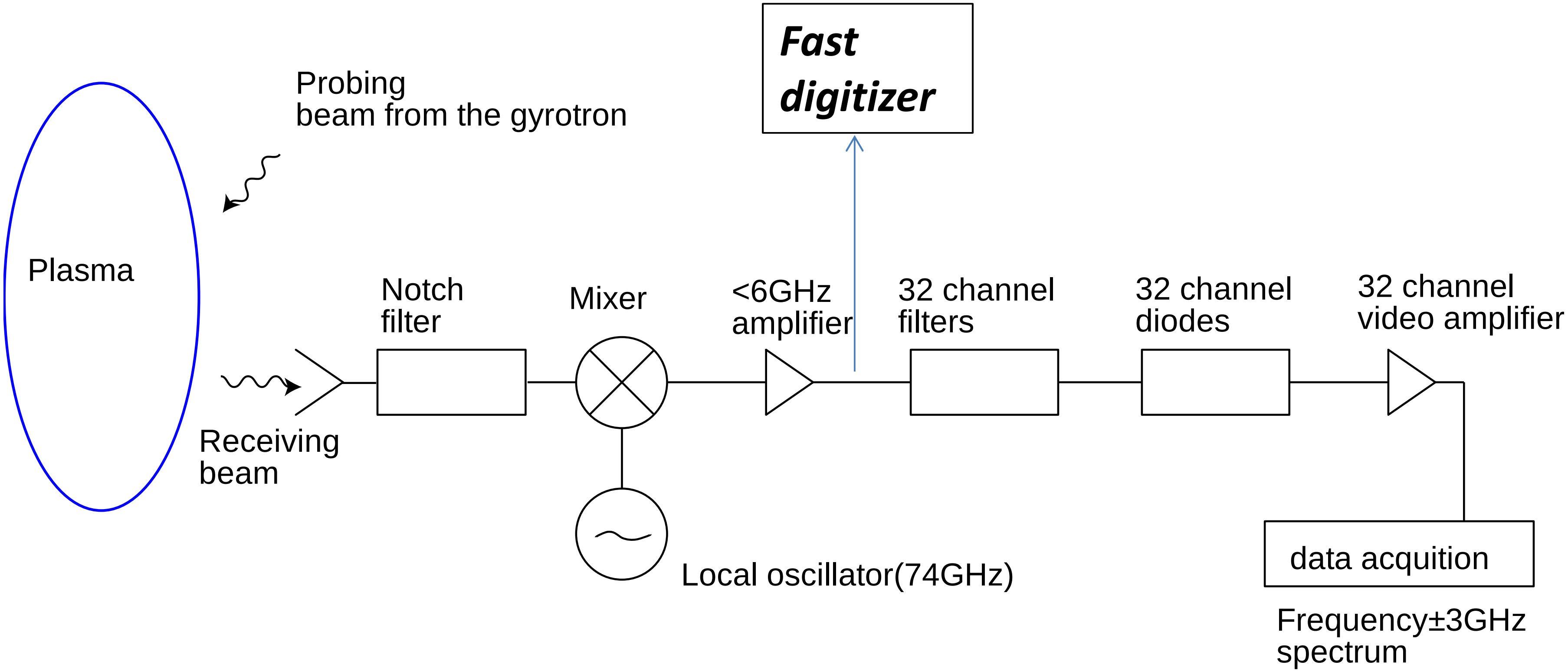
ECE background radiation is still significant. This can be excluded ECH modulation.

Summary

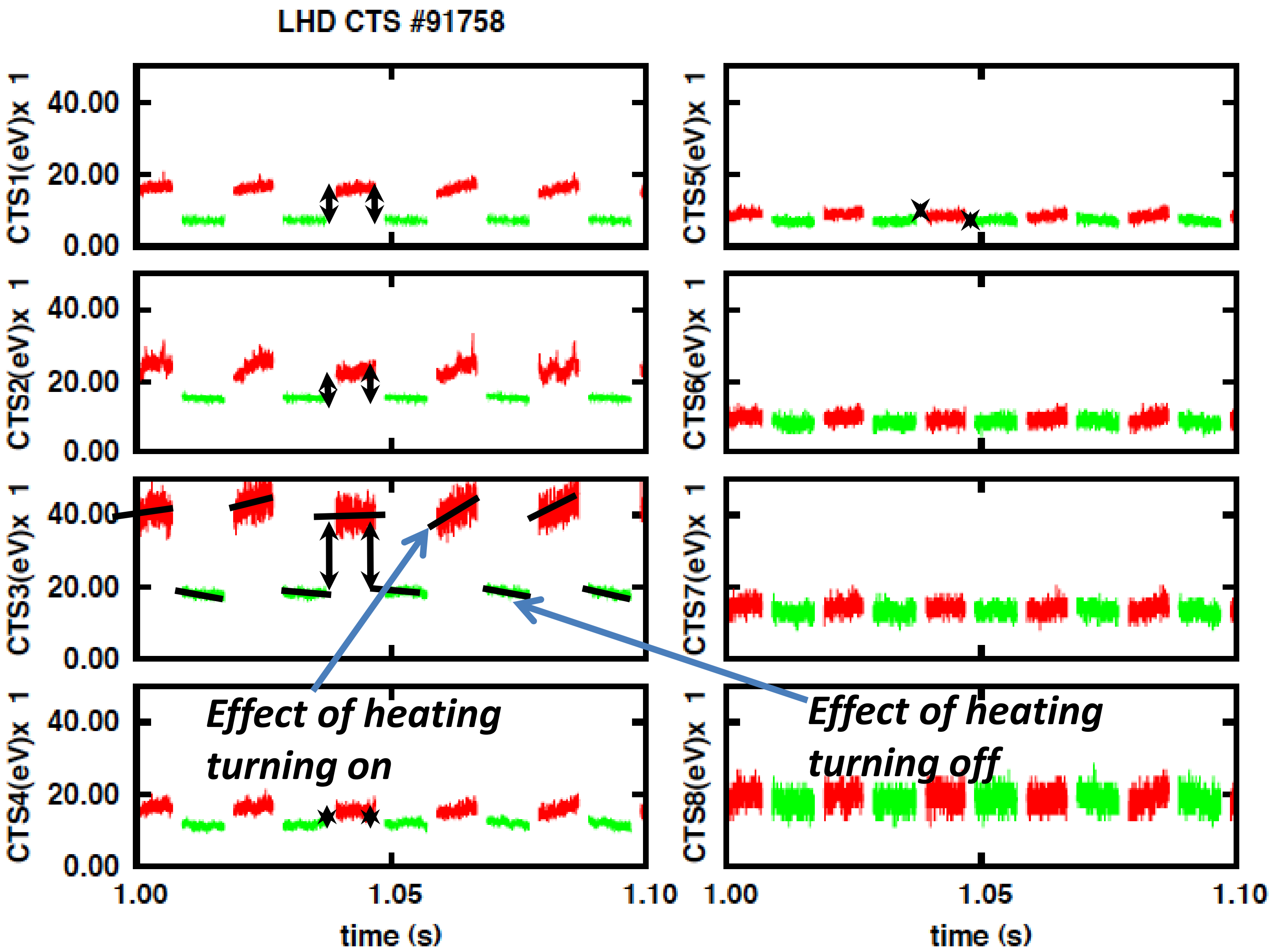
1. In LHD, collective Thomson scattering system is being developed to measure bulk and fast ion density and temperature.
2. 32 ch filter bank system (bulk 16ch, fast ion 16ch) and fast digitizer system are routinely working.
3. Fast digital oscilloscope and fast digitizer enables to measure fine structure of the spectrum.
4. Bulk ion and fast ion density were estimated from the fitting of filter bank system output.
5. Fitted values were unlike values.
6. Signature of the fast ion was observed.
7. Fast sweeping mirror system was installed to check antenna alignment. Preliminary data showed maximum signal at around maximum scattering volume position.
8. Further developments are necessary, to confirm the data.

Supplement

CTS heterodyne receiver system



Analysis excluding heating effects

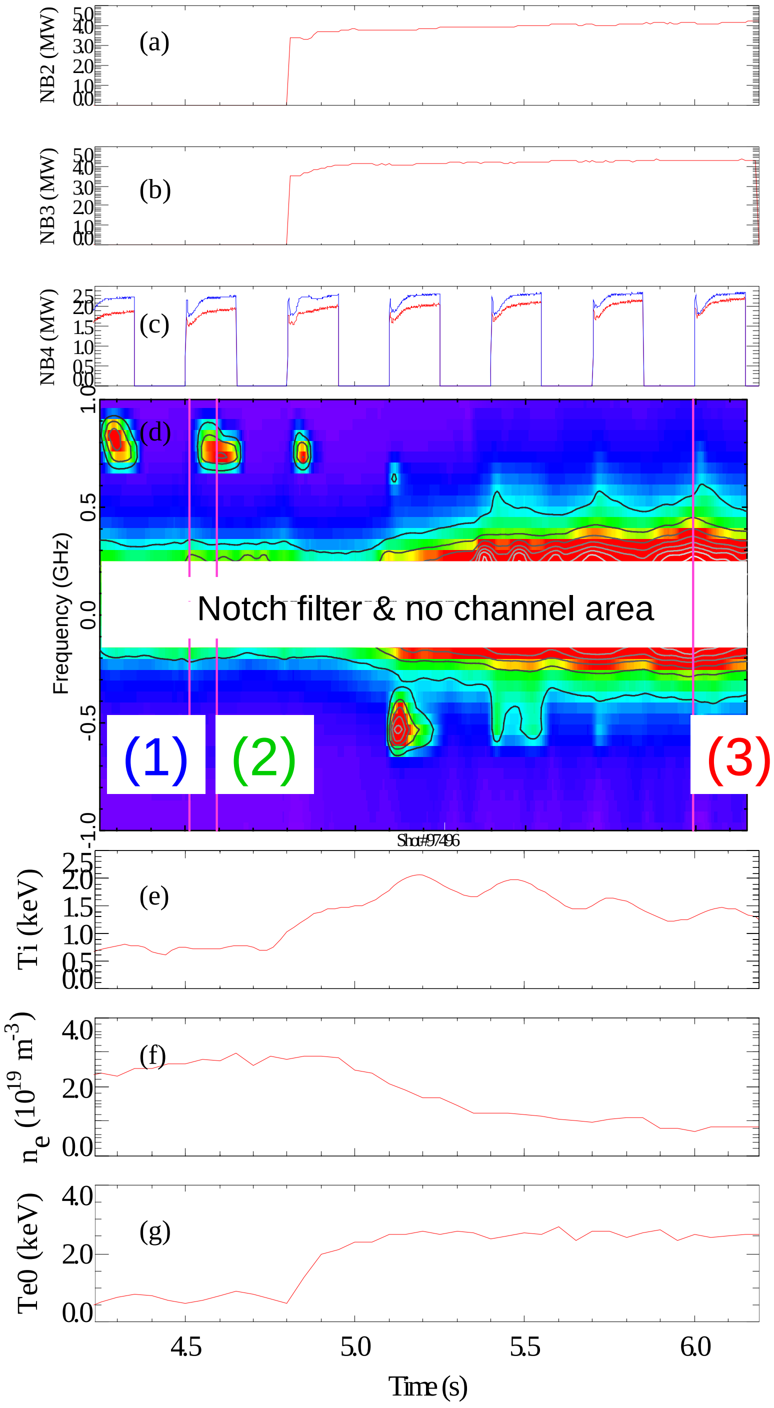


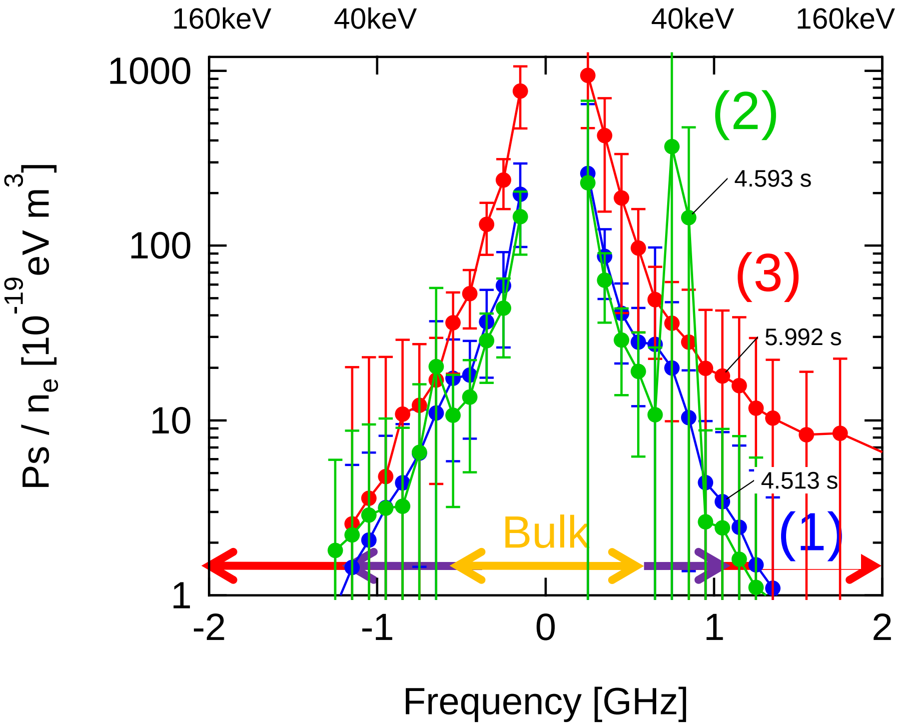
Effect of heating turning on

Effect of heating turning off

Signal of 1~2ms just after turning ON and OFF of gyrotoron was used. Step function was fitted for this time window . (Kubo et al.; 2010 RSI)

Time evolution of normalized CTS spectrum





Snap shots of CTS spectrum at t=4.513, 4.5992 and 5.93 s.

- The CTS spectrum responses to NB#4(40keV) injection

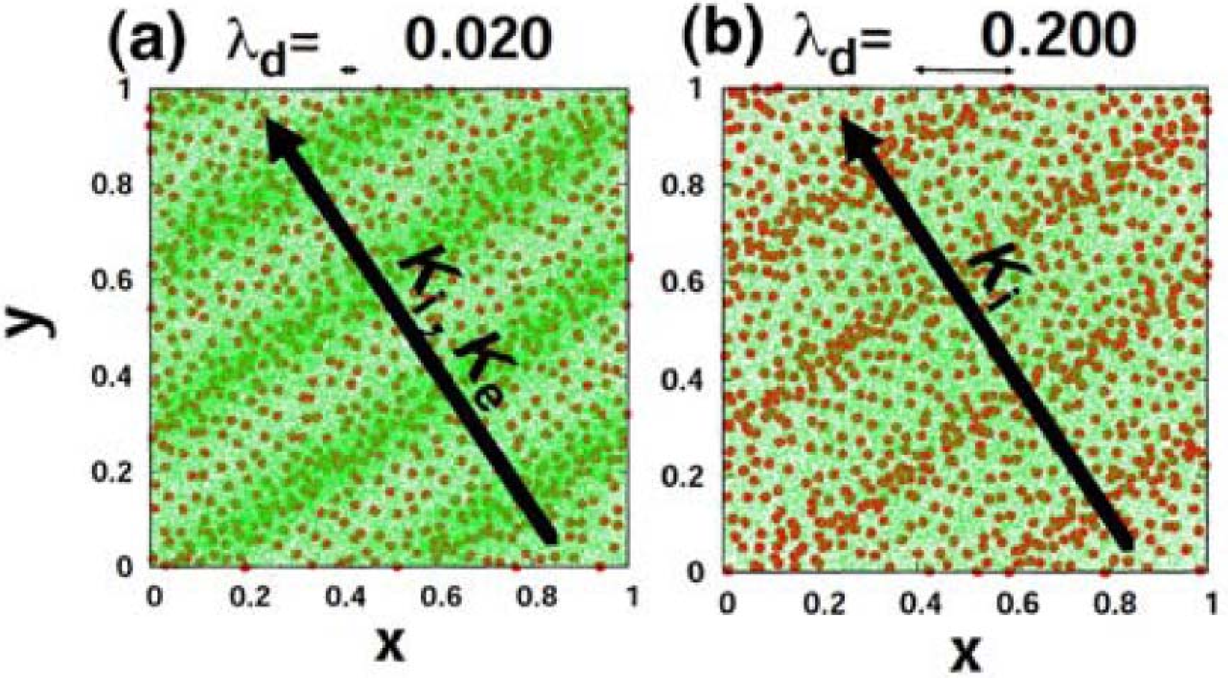
$\alpha=1/K\lambda_d<1$ ($K\lambda_d>1$) is required to see ion thermal motion from the scattered radiation

Small green dot; Electron

Large Red point; ion

Electron shields ion charge

Ion move toward the arrowed direction,



$$K\lambda_d > 1$$

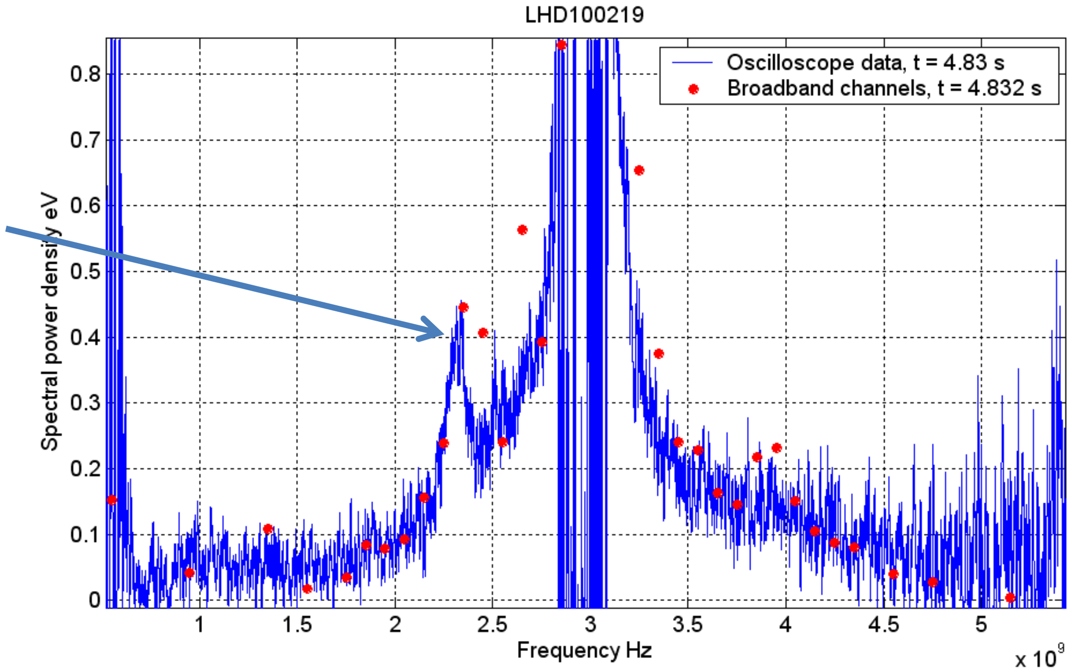
Electron follows ion movements. (Collective motion)

$$K\lambda_d < 1$$

Electron does not follows ion movements. Moves independently (incoherent motion)

Fine spectrum measurements by using high speed sampling digital oscilloscope (6GHzBW Tectronics) and digitizer (NI). （Collaboration with Fukui Univ. and RISO.）

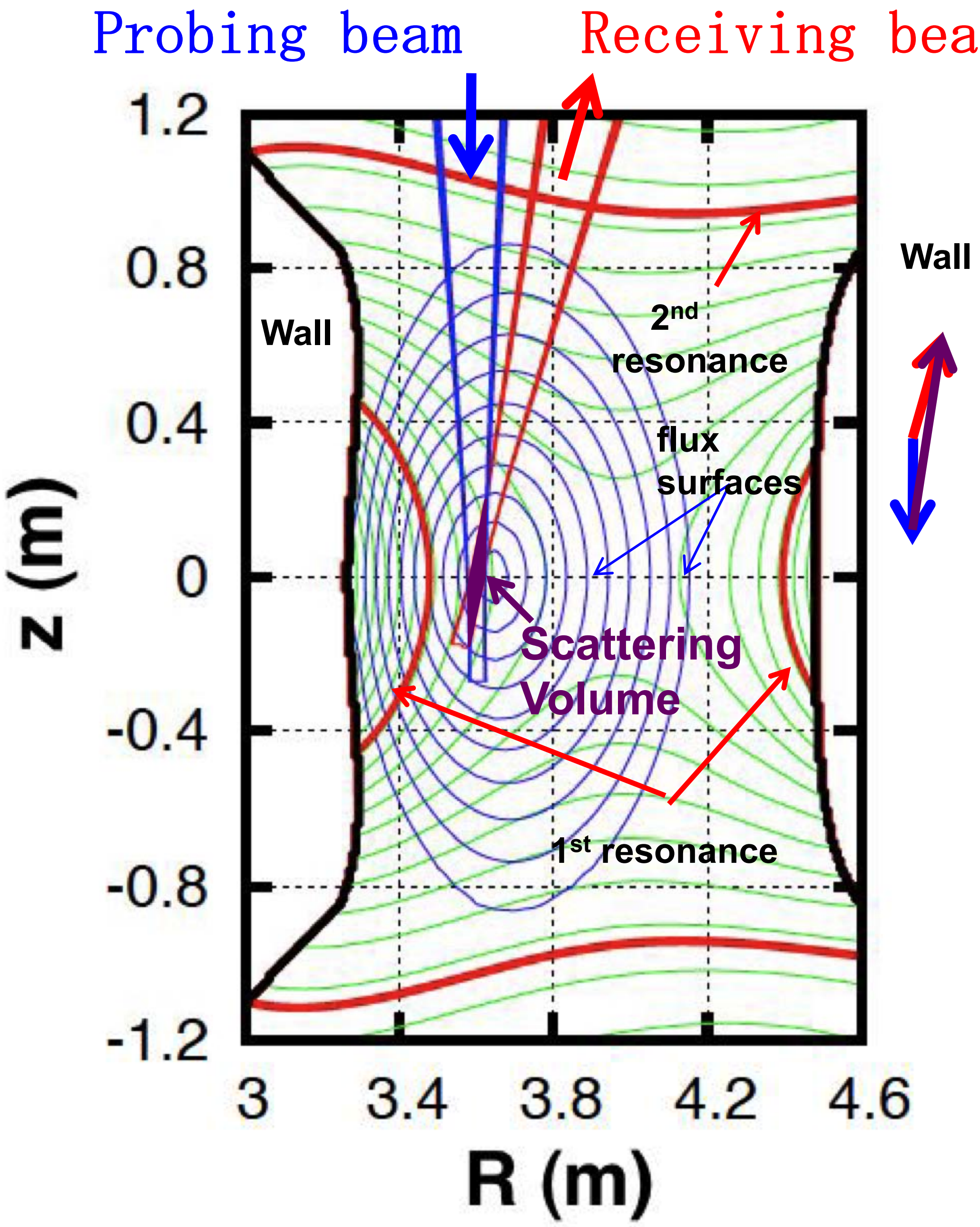
- Altough data length and resolution is limited (5ms for oscilloscope , 50ms for digitizer, bith 8bit), fine structure of spectrum of bulk components can be measured.
- Especially, this is powerful to monitor shift of gyrotron frequency and parasitic oscillation.



Spurious mode?

Comparison of CTS spectrum from digital oscilloscope (blue line) and filter bank output (red point)

Measured Scattering Configuration



B=2.40 T
R=3.6 m

k^{δ} ~ near perpendicular

k^{δ} ∠B ~ 80 degree

1st resonance exists in the confinement region even avoiding it on the line of sight.

O-mode for both probing and receiving beams.

History of collective Thomson scattering. This diagnostic had a hard time.

Collective Thomson scattering has sensitivity to ion thermal motion. From late 1970's, the developments started. However, it was not very successful (pioneer works were done by Woskov, Behn). This is because good source was not available for collective Thomson (λ>0.5mm). This is big contrast to incoherent Thomson scattering. Good source are available around 600nm (Ruby laser) from 1960's. In 1980's, charge exchange spectroscopy (CXRS) using heating NBI appeared and it provided "*impurity*" ion temperature with good spatial resolution (~cm) and reasonable time resolution (~100msec). People started use CXRS.

However, in the end of 1980's, collective Thomson was proposed to measure fusion product in the future reactor (by Costley, Bindslev). Also, in the experimental device, it was proposed to measure externally injected fast ion, which can simulate fusion products.

Preliminary data was obtained in JET in the beginning of 1990's. In 2000's, excellent data was obtained in TEXTOR and ASDEX-U. In LHD, collective Thomson started since 2008.

Upgrading after last LAPD

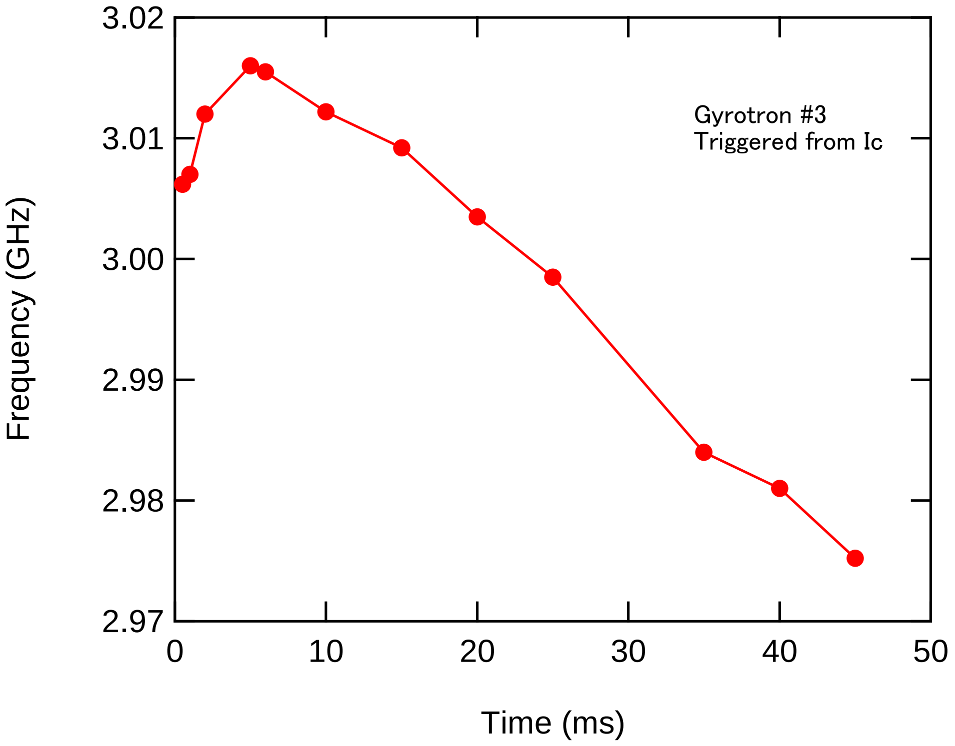
1. Increase of channel of filter bank from 8 to 40.

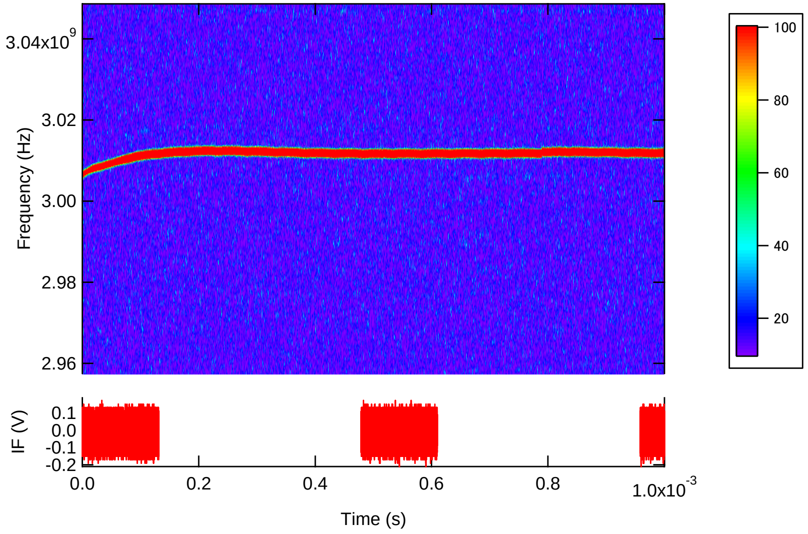
2. Install of fast digital oscilloscope and fast digitizer

3. Change of scattering geometry
   Tangential viewing to increase contribution of parallel moving fast ion

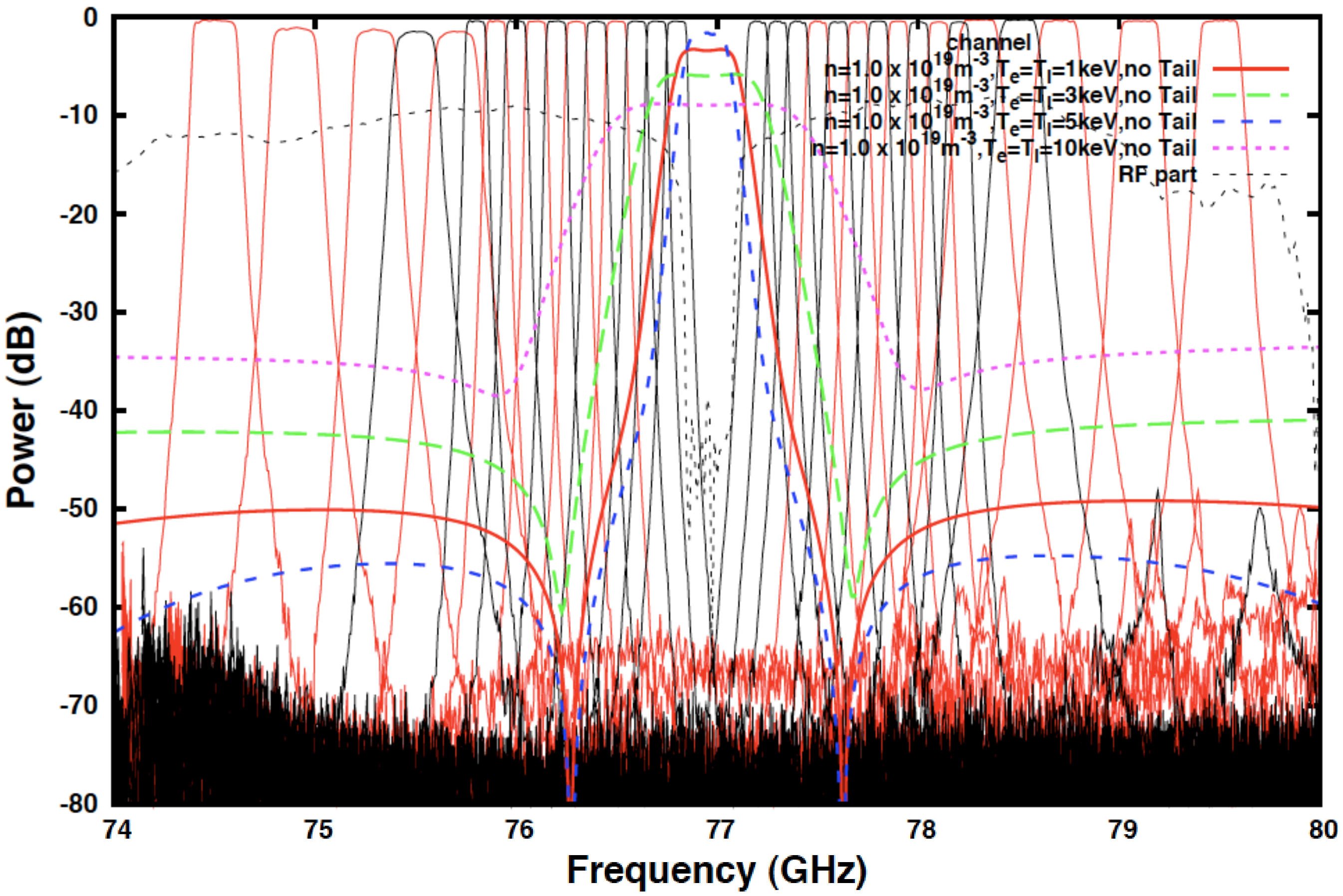
4. Fast sweeping antenna to check antenna alignment

Change of the gyrotron frequency was measured fast sampling digitizer





RF & IF filter characteristics



All RF & IF components used are measured by Vector Network Analyzer (VNA)

Central dense channels give bulk ion temperature. Sparse channels of both side give high energy ion.

Velocity distribution function g(u)

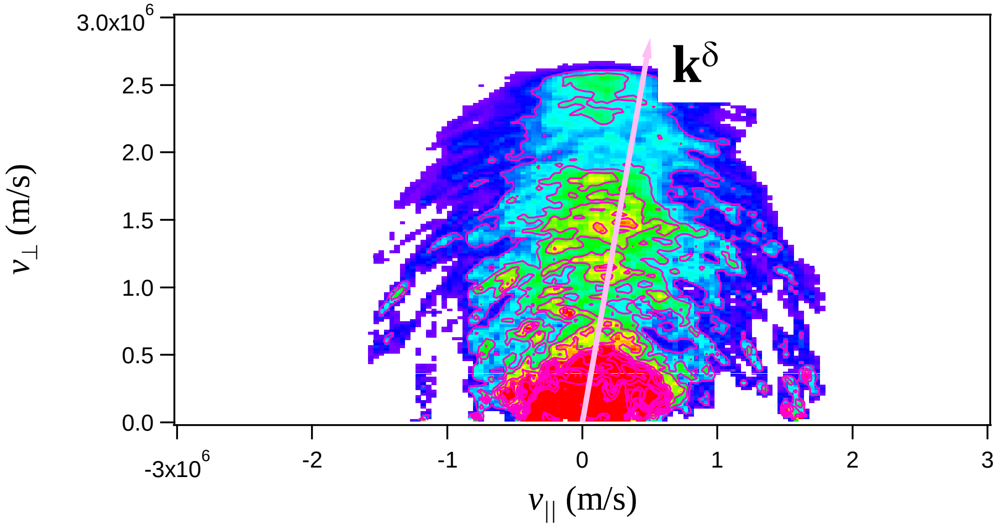
$f(v_{||},v_{\perp})$ is projected onto fluctuation $\mathbf{k}^{\delta}$

- For understanding the measured CTS spectrum, distribution function $f(v_{||},v_{\perp})$ is calculated by GNET code with measured T and n.

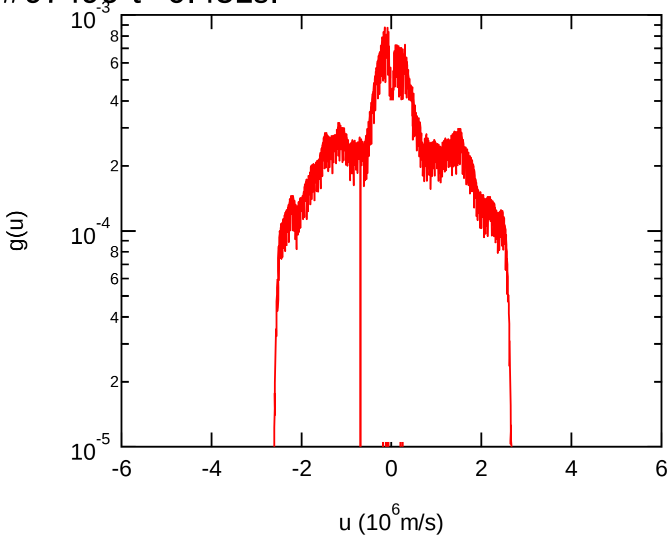
$$g(u,\emptyset)=\int\int_{-\infty}^{\infty} f(v_{\parallel},v_{\perp})\,\delta\left(\frac{\boldsymbol{v}\cdot\boldsymbol{k}}{|\boldsymbol{k}|}-u\right)dv_{\parallel}dv_{\perp}$$

- Fast ion density of ~$10^{17}\mathrm{m}^{-3}$

- We have just started the calculation, and will compare between the experimental and the calculated results.

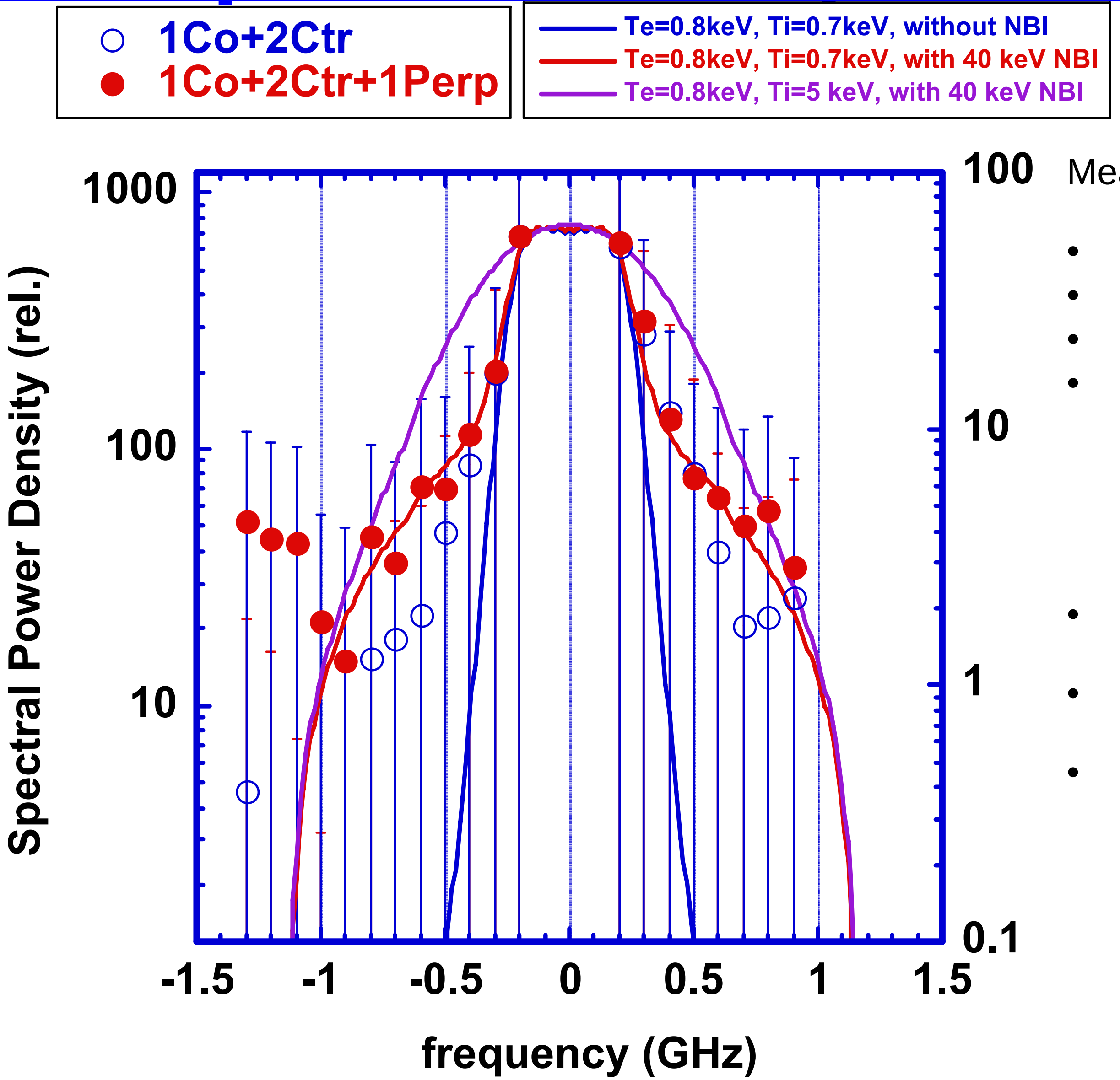


Calculated distribution function $f(v_{||},v_{\perp})$ for LHD#97496 t=0.451s.



Distribution function g(u) projected onto $\mathbf{k}^{\delta}$.

Comparison of Exp. / Cal. Spectrum



Measured data are used for calculation.

- T_e=0.8keV
- T_{Ar}=0.7keV
- $n_e=2.5x10^{19}m^{-3}$
- $n_{fast}=0.25x10^{19}m^{-3}$

- T_i=0.7keV is better fitting than T_i=5keV.
- Measured data seems to have an offset of +0.1GHz.
- P(3.6,0,0), R(3.6,0,0)

Method of analysis

- Raw data of several modulation periods are rearranged in time relative to the turn on/off time
- These rearranged data are fitted with the function

$$V_i = \underline{(a + \boxed{\delta a} \cdot H(t))}t + \underline{b + \boxed{\delta b} \cdot H(t)}$$

Here, $a, \delta a, b, \delta b$ are fitting parameters and $H(t)$ is Heaviside step function defined by

$$H(t) \equiv \begin{pmatrix} 1 & \text{for} & t \geq 0 \\ 0 & \text{for} & t < 0 \end{pmatrix}$$

□ • δa corresponds to background increments/decrements due to heating (change in slope)

□ • δb corresponds to increment/decrement due to scattered signal over background (stepwise change)