ICRF long-pulse discharges and ICE measurement in LHD

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Korea-Japan Workshop on Plasma Heating and Current Drive

Korea

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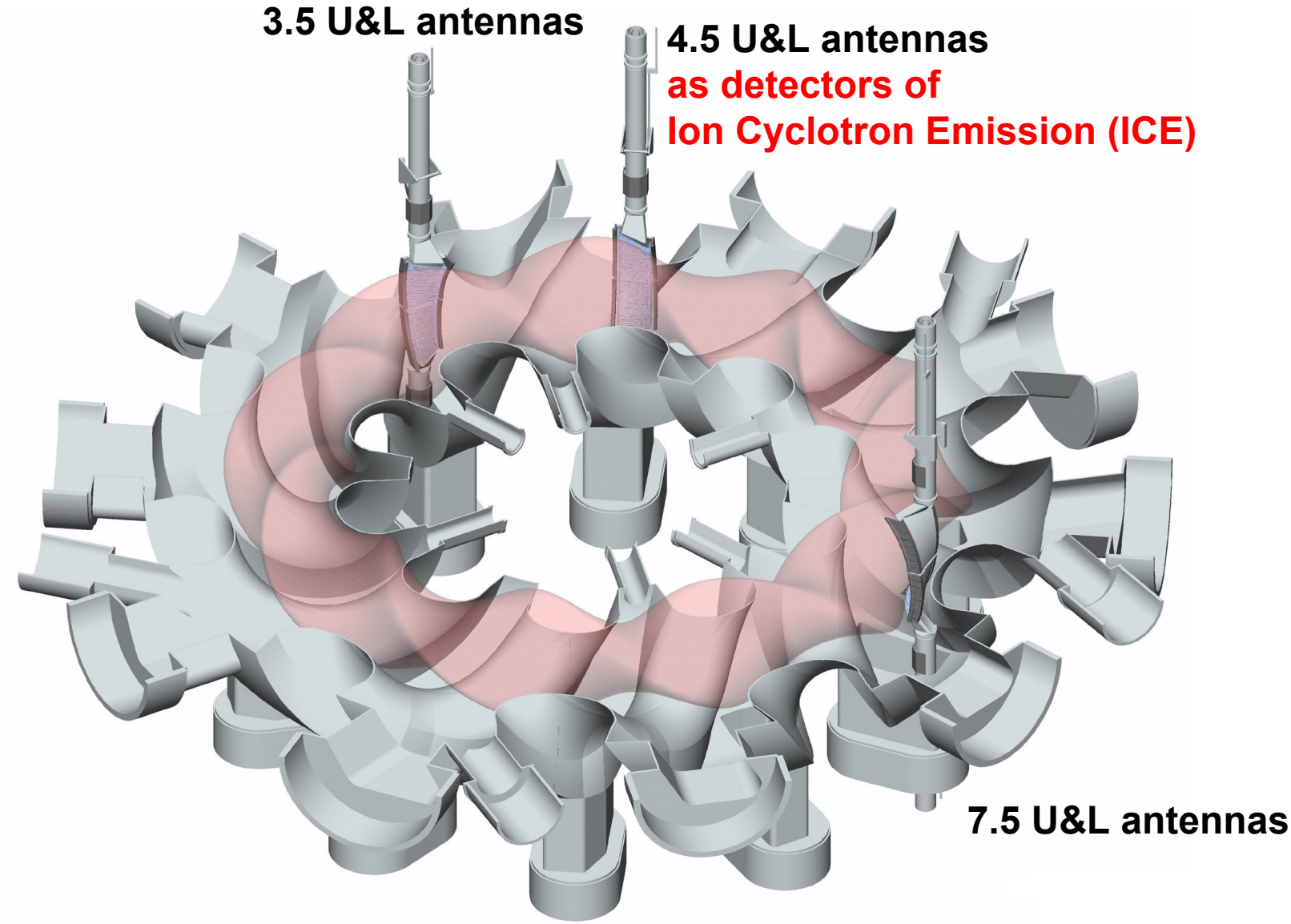
3 pairs of loop antennas



Out line

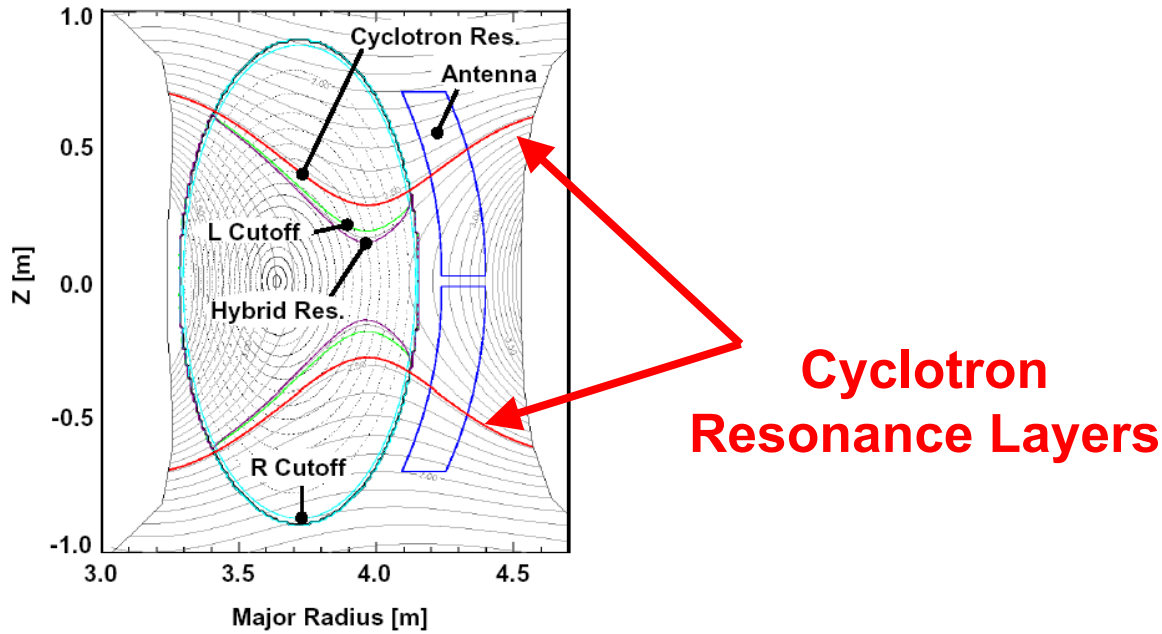
1. Steady state operation
   ①by minority ion heating
   ②by mode conversion heating

2. Ion cyclotron emission measurement by use of ICRF heating antennas

Long pulse operation by minority ion heating

ICRF minority ion heating

He^{2+}:majority ion H^{+}:minority ion

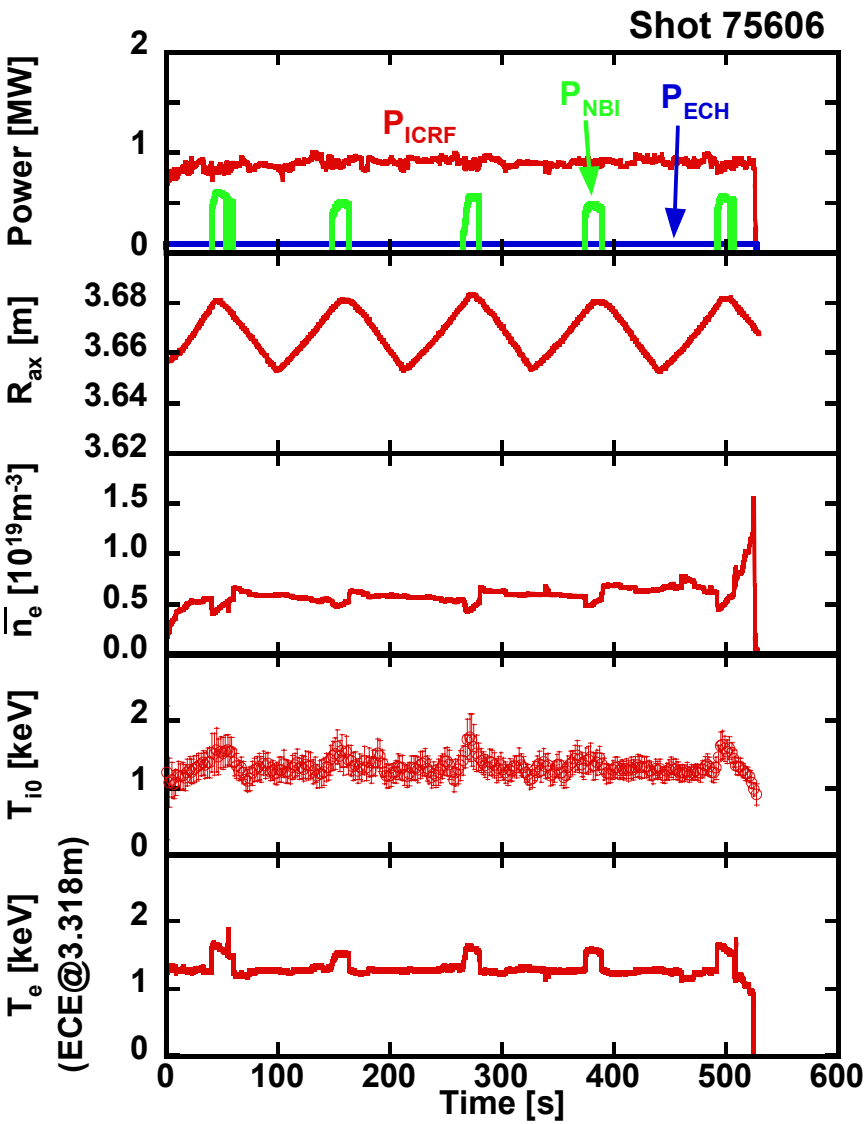


Parameters of calculation

- He plasma with minority H ions
- $n_{H+}/(n_{H+}+n_{He2+})=0.05$, $n_{e0}=1.0\times10^{19}m^{-3}$
- $B_{ax}=2.85T$
- $R_{ax}=3.6m$
- frequency : 38.47MHz
- $k_{//}=5m^{-1}$

Minority ion heating with this configuration of cyclotron resonance layer has a high heating efficiency up to 80%.

Achievement of 525 seconds long pulse with more than 1MW

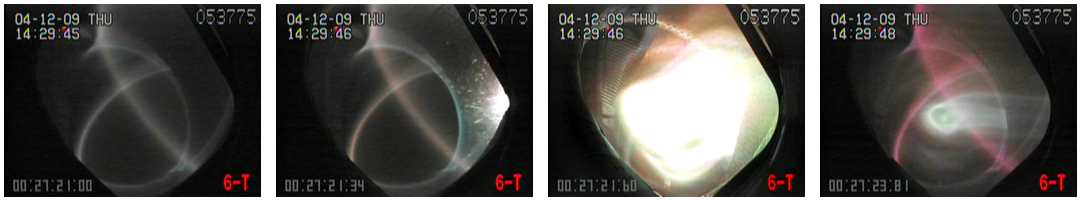


B=2.85T(@R=3.6m), f=38.47MHz

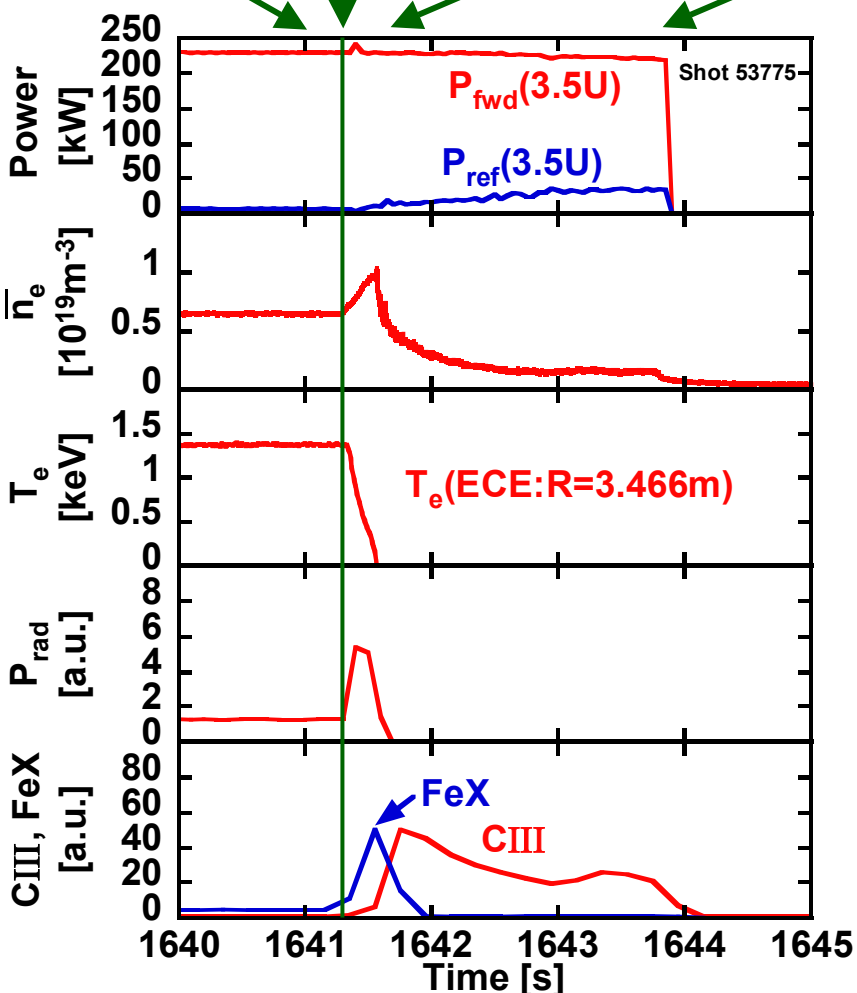
P_{ICRF}=894kW (3.5U, 7.5UL antennas)
P_{NBI}=75kW
P_{ECH}=90kW
P_{total}=1059kW
$T_{duration}$=525sec

- **Magnetic axis was swept to disperse heat load on divertor plates.**
- **Finally plasma collapsed due to density increase.**

Plasma collapse by sudden influx of Fe impurity



Spark

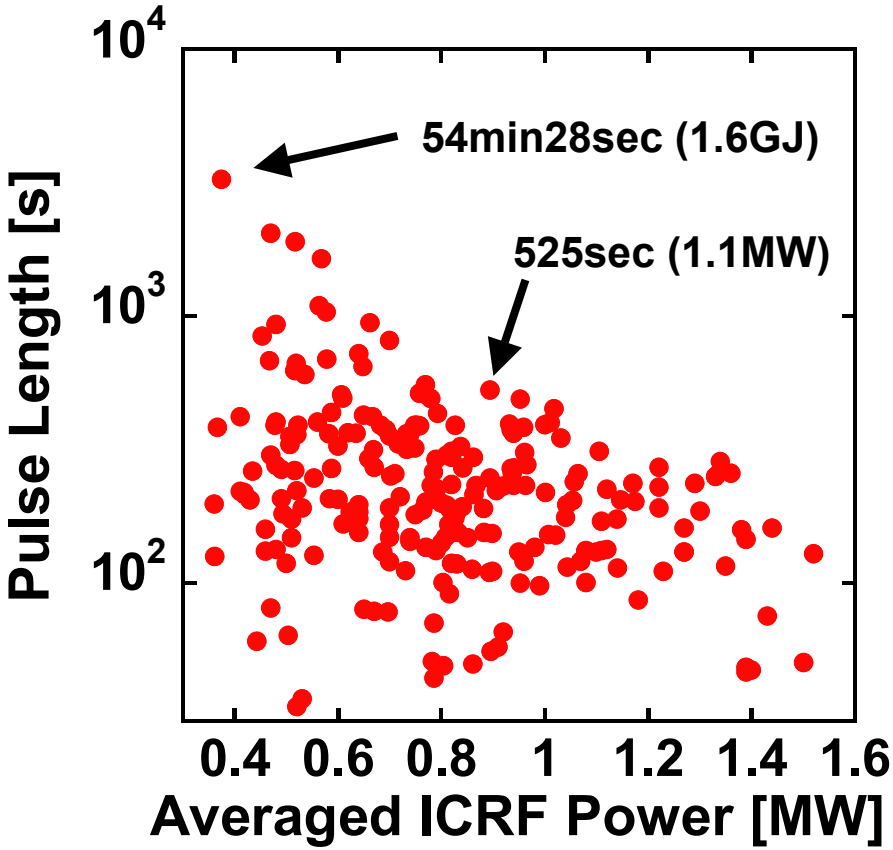


B=2.75T@R3.6m
R_{ax}=3.67-3.70m
P_{ICRF}=570kW
$\bar{n}_e$=0.7×10^{19}m^{-3}

- **Radiation power and electron density increased and electron temperature decreased immediate after a spark from inner side of torus.**
- **FeX intensity increased at this timing.**

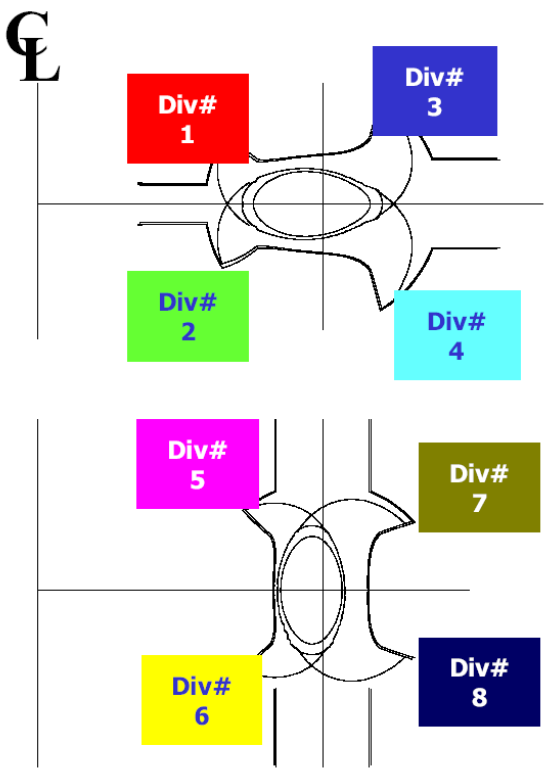
Front view of spark (shot 65983)

Pulse length increase with decreasing ICRF heating power

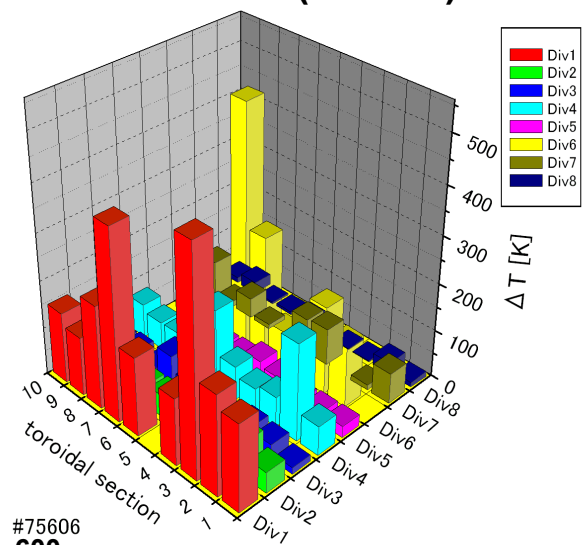


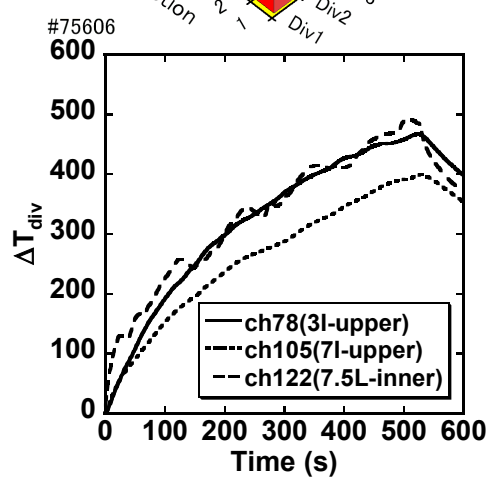
- Pulse length increase with decreasing ICRF heating power.
- Duration time are mainly limited by the outgassing and sudden influx of iron impurity.

Temperature distribution on divertor plates



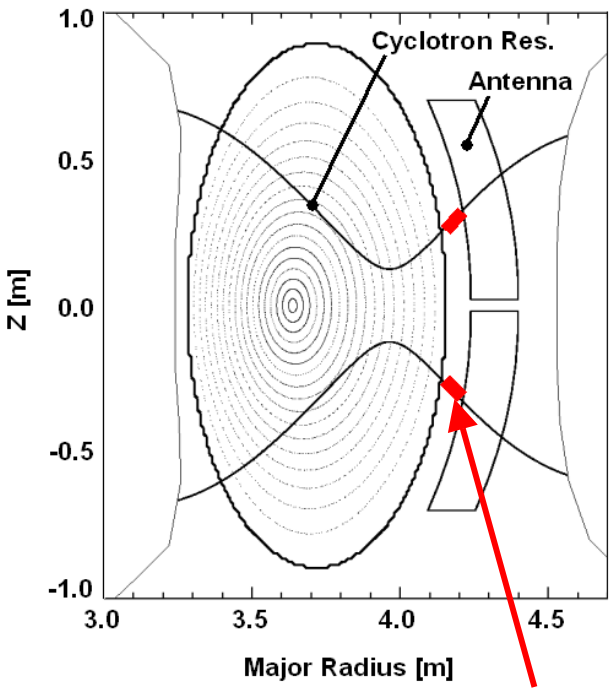
Shot of 525sec (1.1MW)





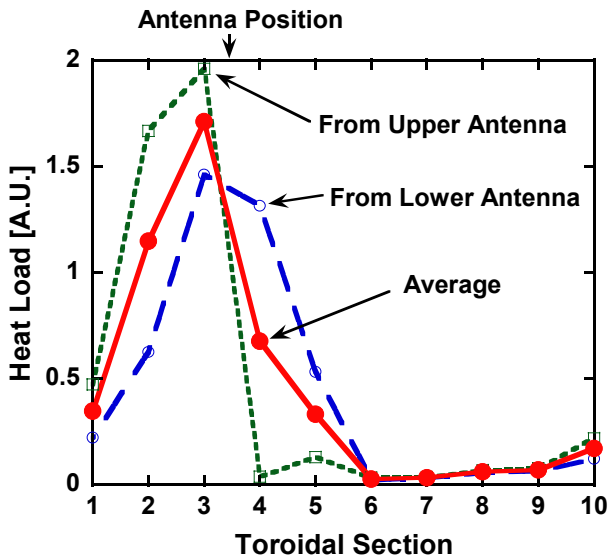
- Temperature on divertor plates is locally high around ICRF antennas.

Local heat load due to resonance layer in front of ICRF antenna



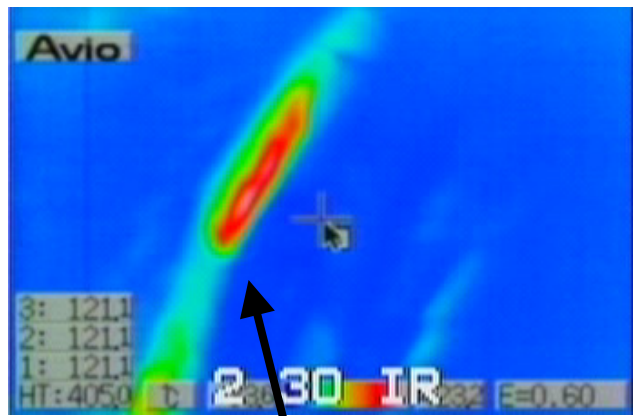
start position of particles

Result of calculation



IR camera image

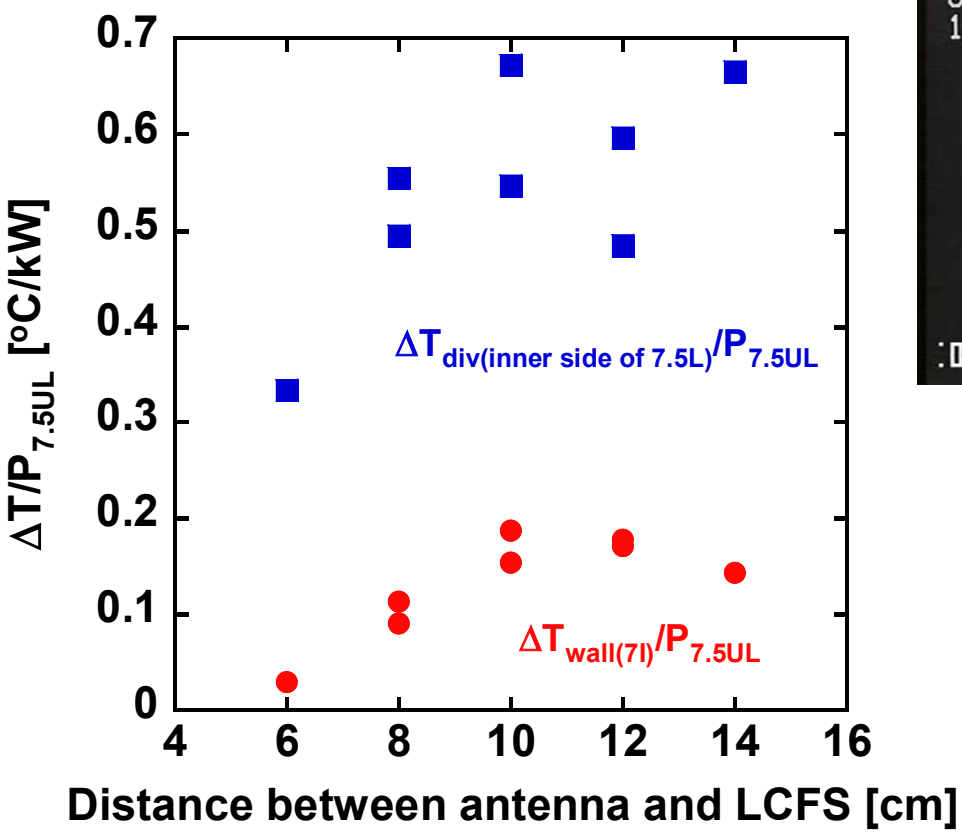
shot76944

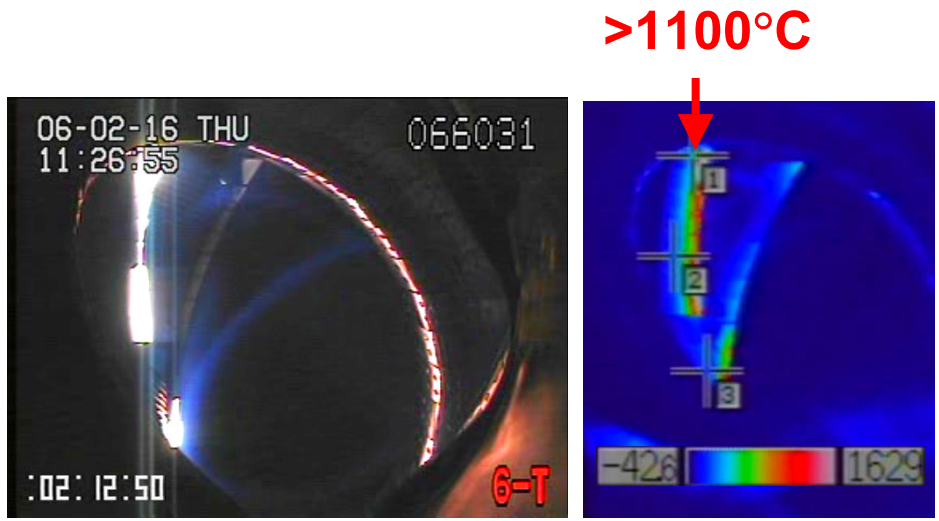


Divertor Plate at inner side of No.3 toroidal section

- Calculated heat load on divertor plates is locally high near ICRF antennas.

Local heat load depends on antenna-plasma distance



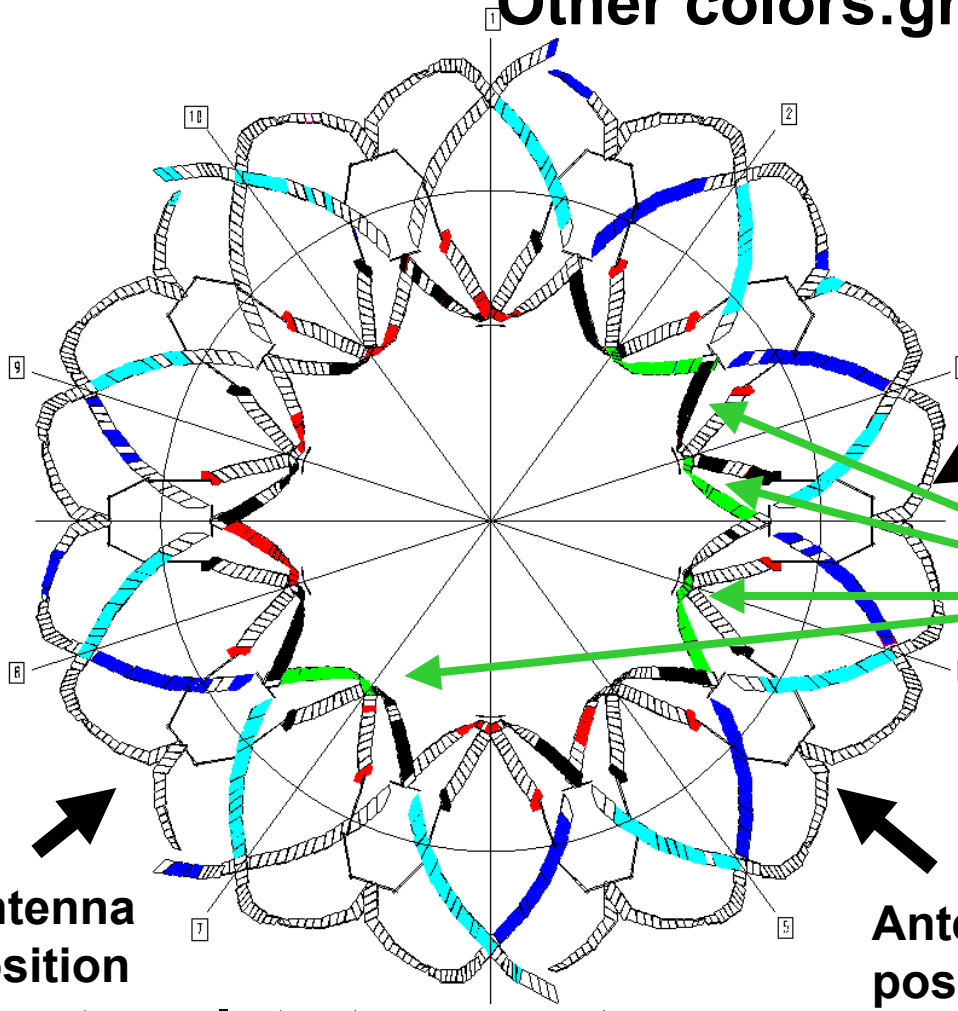


Temperature rise in ICRF antenna (distance 6cm)

- Temperature on divertor plates and wall near ICRF antenna decreases with decreasing antenna plasma gap.
- This suggests peripheral plasma heating was suppressed by decreasing peripheral region.
- But temperature of antenna side limiter reached more than 1100°C.

Temperature reduction on divertor plates

Light green:new divertor plates
Other colors:grinded to remove layer of Fe



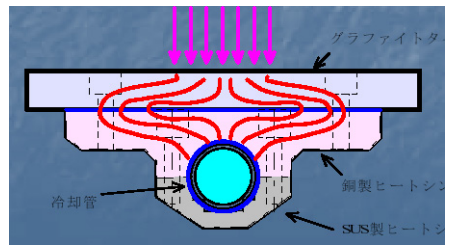
Antenna position

Antenna position

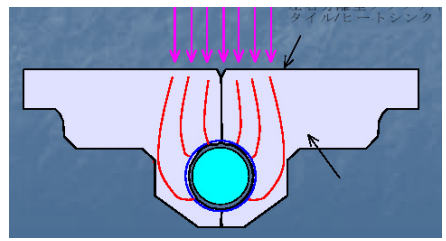
Antenna position

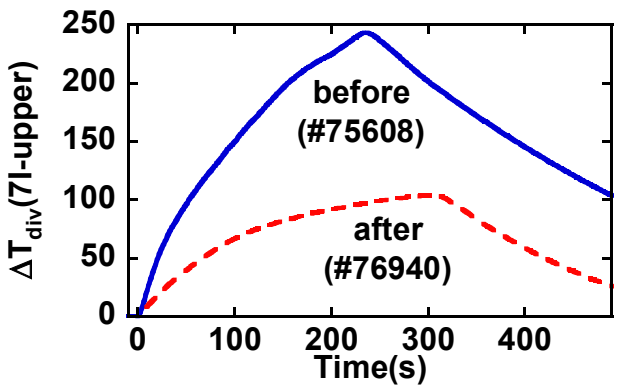
Improvement of divertor plate

old



new

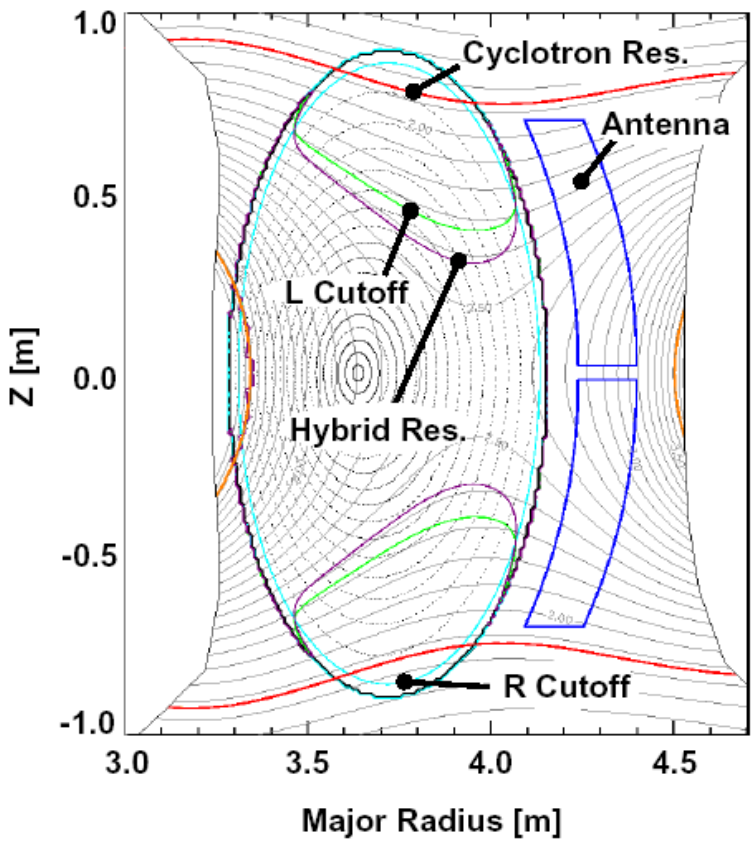




Divertor plate temperature decreased more than half.

Long pulse operation by mode conversion heating

Electron heating by mode conversion



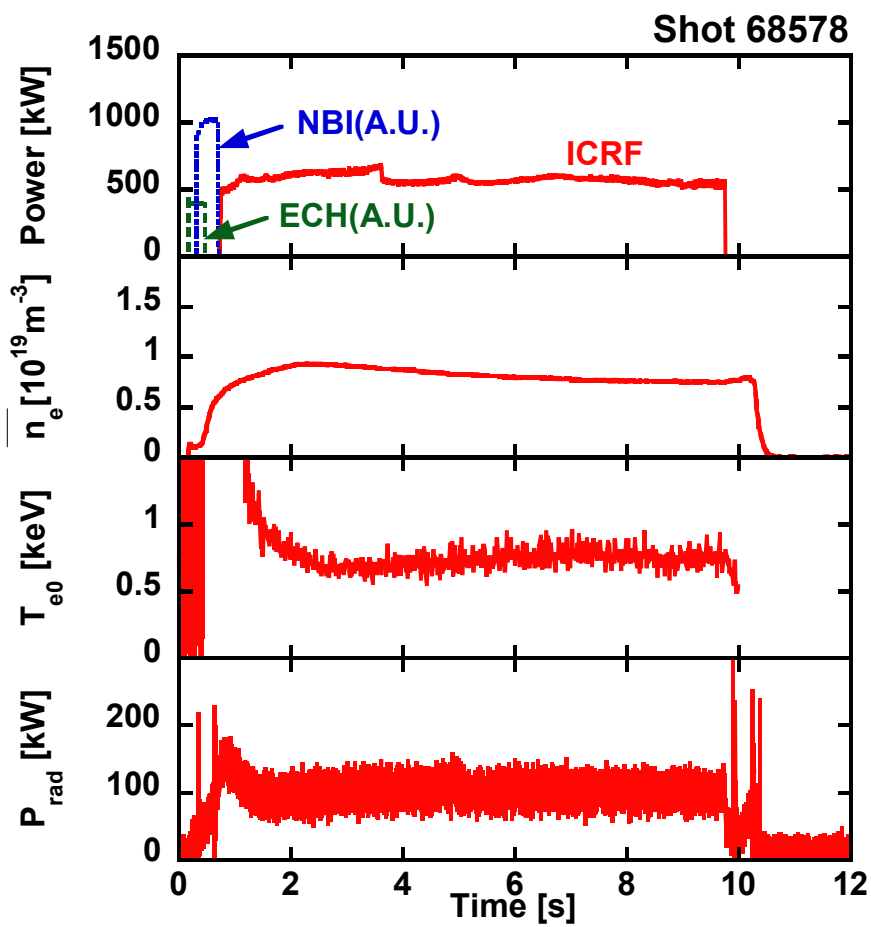
Parameters of calculation

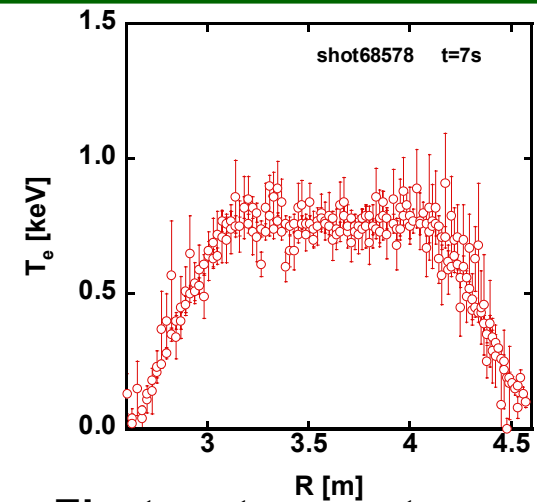
- He plasma with minority H ions
- $n_{H+}/(n_{H+}+n_{He2+})=0.6$, $n_{e0}=1.0\times10^{19}m^{-3}$
- $B_{ax}=2.75T$
- $R_{ax}=3.6m$
- frequency : 28.4MHz
- $k_{//}=5m^{-1}$

- **Fast wave is converted to ion Bernstein wave at ion-ion hybrid resonance layers.**
- **Pure electron heating.**
- **Cyclotron resonance layer locates up and bottom in plasma far from antenna tip.**

600kW injection for 9seconds

f=28.4MHz, B_{ax}=-2.75T

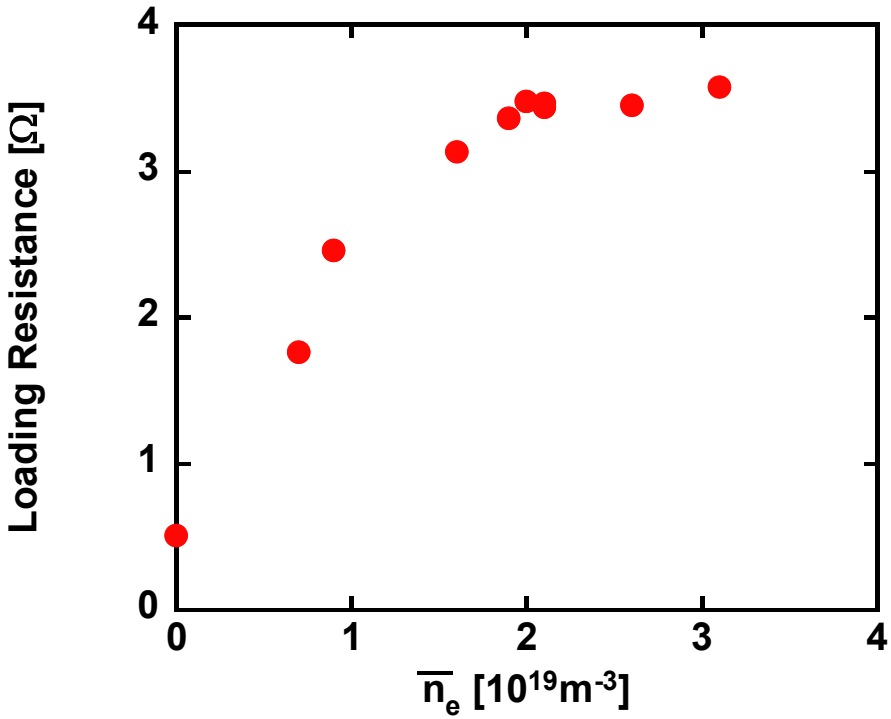




Electron temperature profile

- Injection of 600kW was successfully conducted.
- Plasma sustained for 9 seconds.
- Loading resistance is low (less than 2Ω)
  →high voltage in transmission line.

Loading resistance
- mode conversion heating -

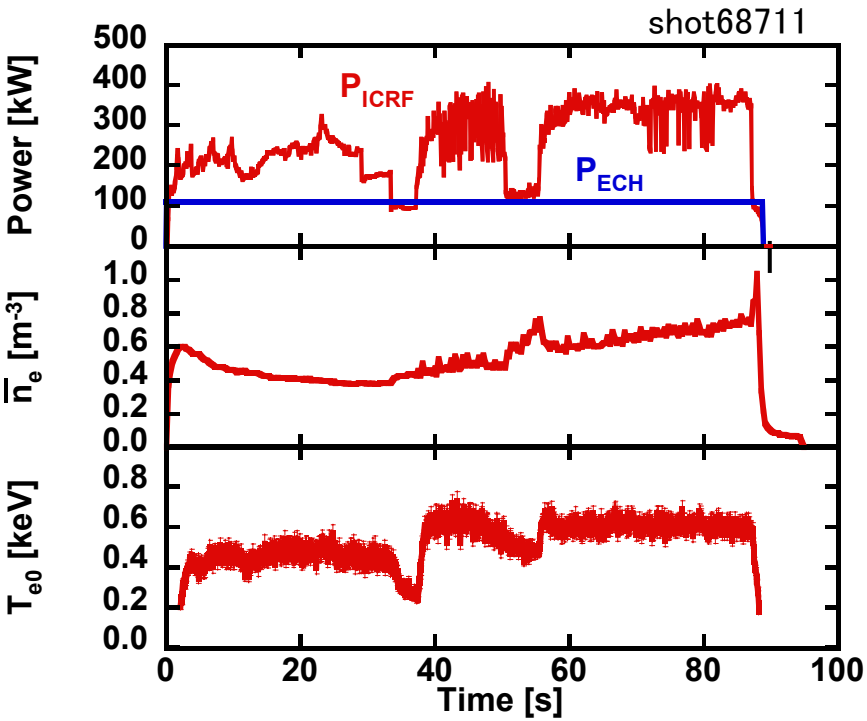


Antenna-plasma distance: 8cm
B=-2.5T
f=25.3MHz

- Problem of low loading resistance can be avoided by higher electron density.
- 3.5Ω is possible when n_e>2×10^{19}m^{-3}.→630kW /antenna can be injected with the voltage of 30kV in the coaxial line.

Long-pulse operation with electron heating

Plasma was sustained for 88sec with the power of 0.26MW(average) of mode conversion heating and 0.11MW of ECH



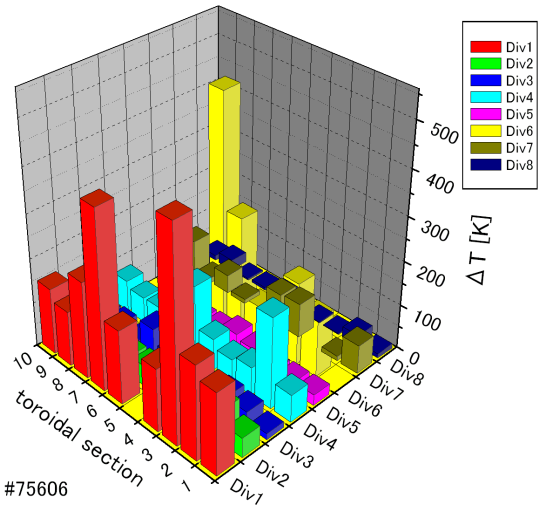
B=-2.75T, R_{ax}=3.6m
f_{ICRF}=28.4MHz

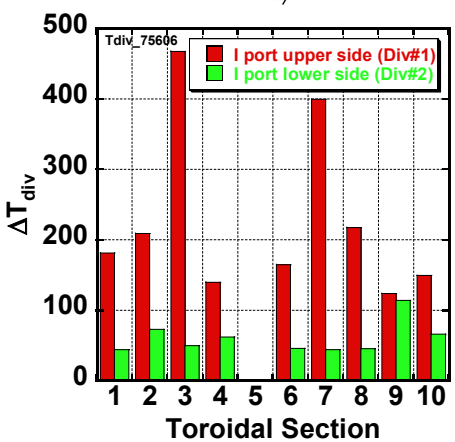
- **Pellets were injected repetitively to supply hydrogen.**
- **Plasma collapse is due to down of amplifier.**

Temperature distribution on divertor plates

Minority ion heating

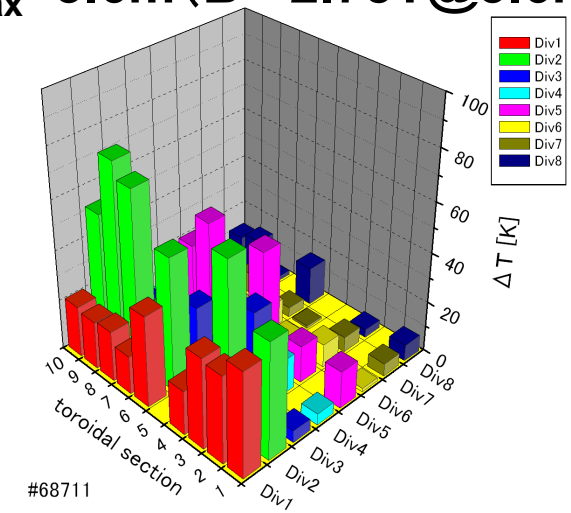
R_{ax}=3.64-3.67m（B=+2.85T@3.6m）

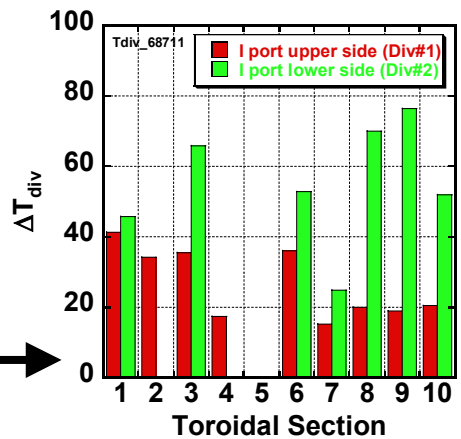


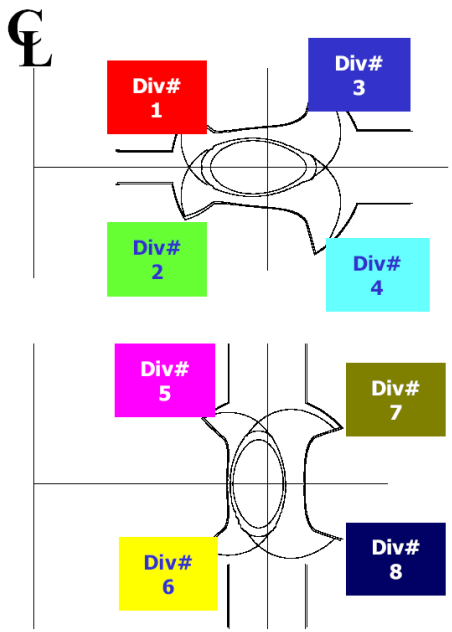


Electron heating

R_{ax}=3.6m（B=-2.75T@3.6m）







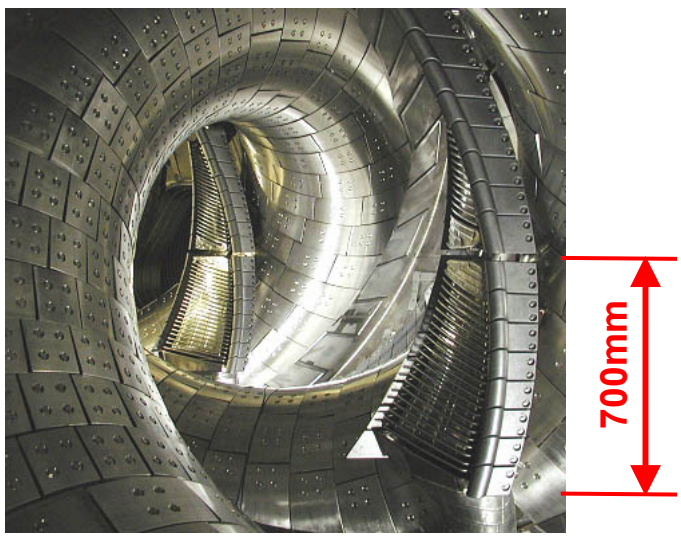
← Antennas loccate at 3.5 and 7.5 ports →

- **Temperature distribution on divertor plates is less peaked with mode conversion heating.**
- **Mode conversion heating can be useful for steady-state operation.**

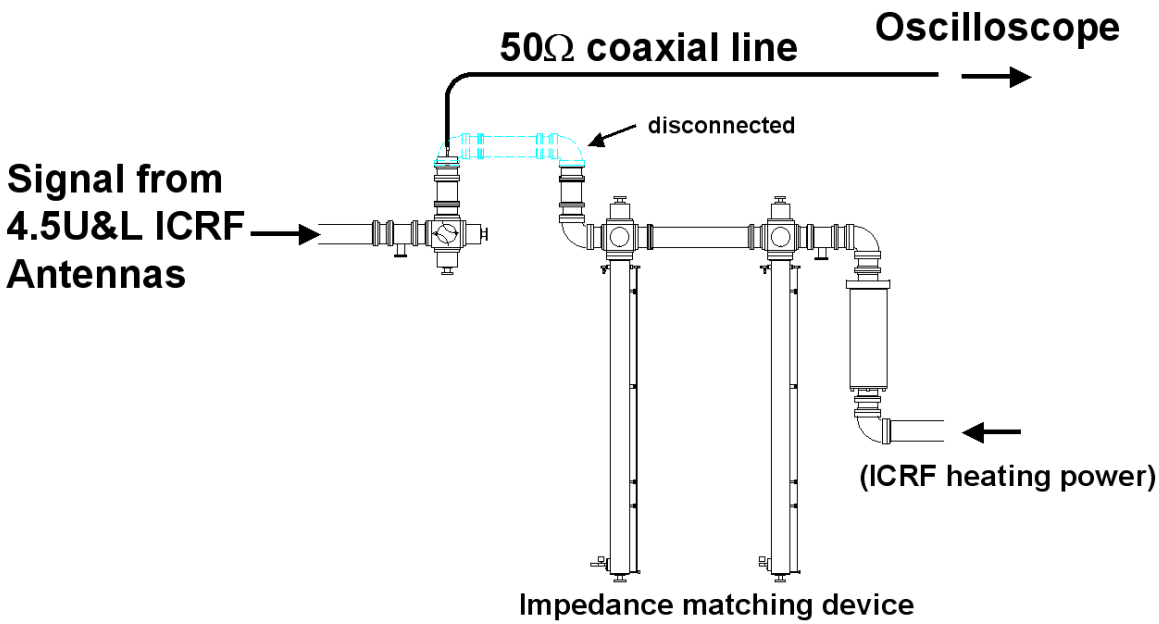
ICE measurement by using ICRF antenna

ICRF heating antennas as detectors

- ICE is caused by the reversed distribution of ions ($\partial f/\partial v_{\perp}>0$).
- ICE frequencies are approximately $f \approx n\, f_{ci}$
- By using large heating antennas as detectors,small ICE signal could be measured.



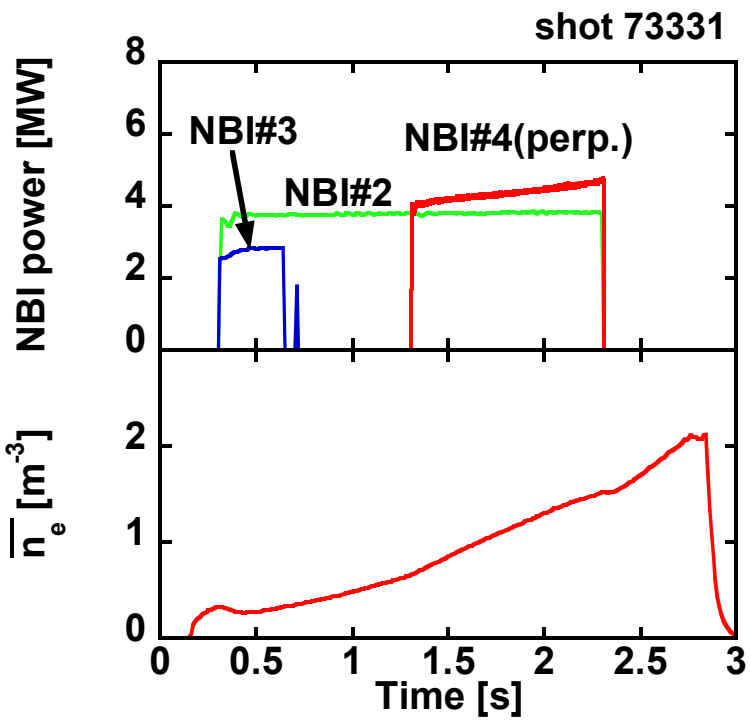
large heating antennas



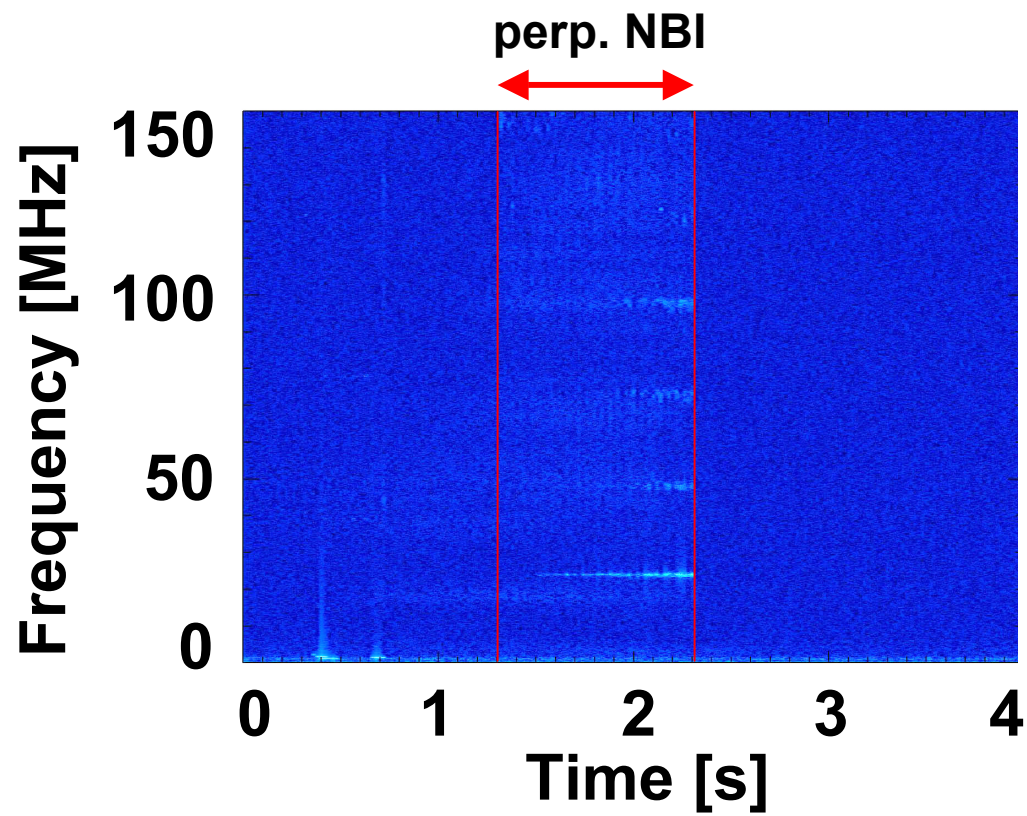
- 3.5UL & 7.5UL antennas were connected to oscilloscope via impedance matching device.

Detection of ICE in LHD

B_0=2.75T,R_{ax}=3.6m

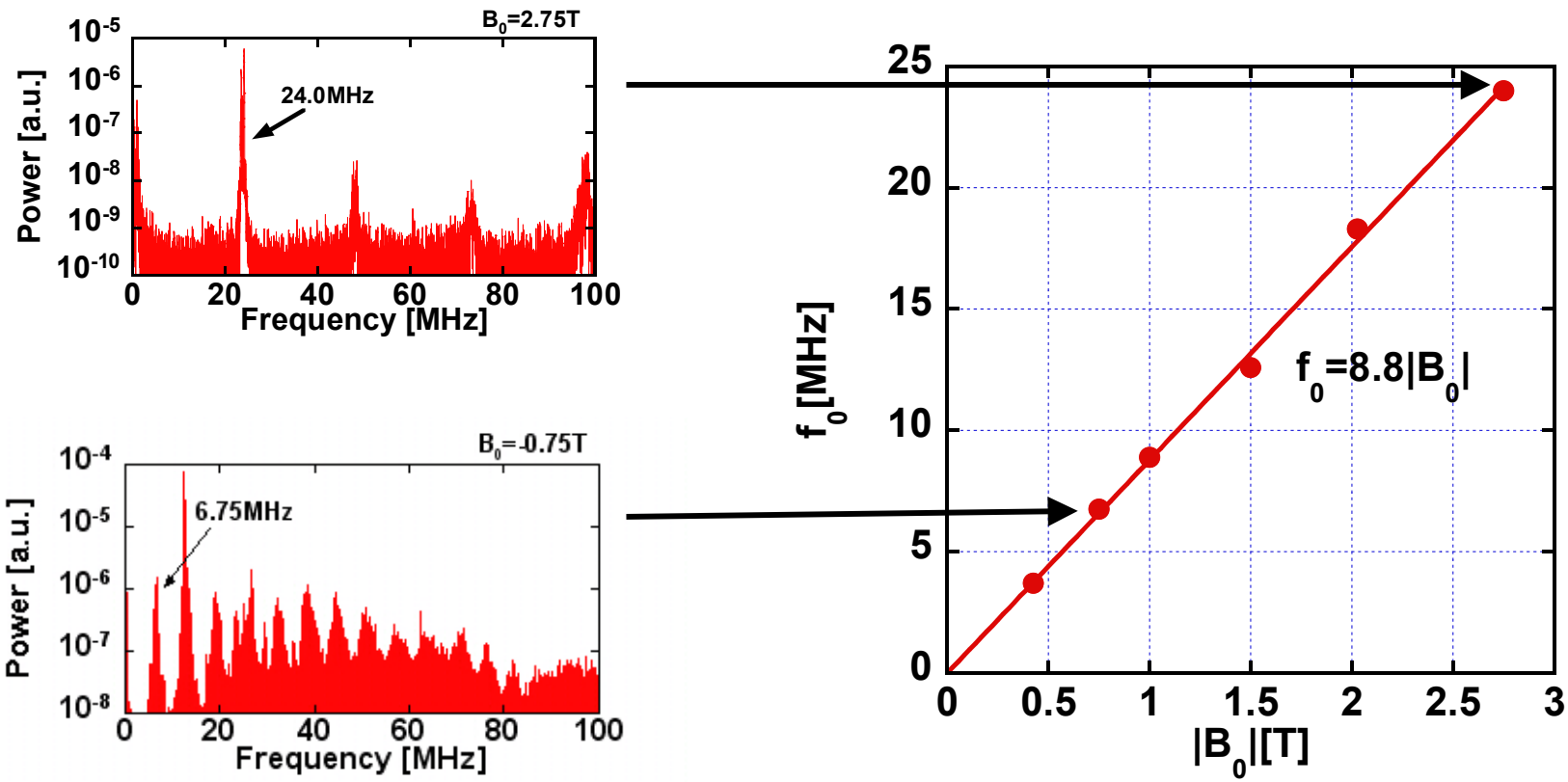


Signals detected by 4.5L antenna



- ICE was observed during perpendicular NBI.
- ICE frequency is written by f=n×24.0MHz where, n is integer.

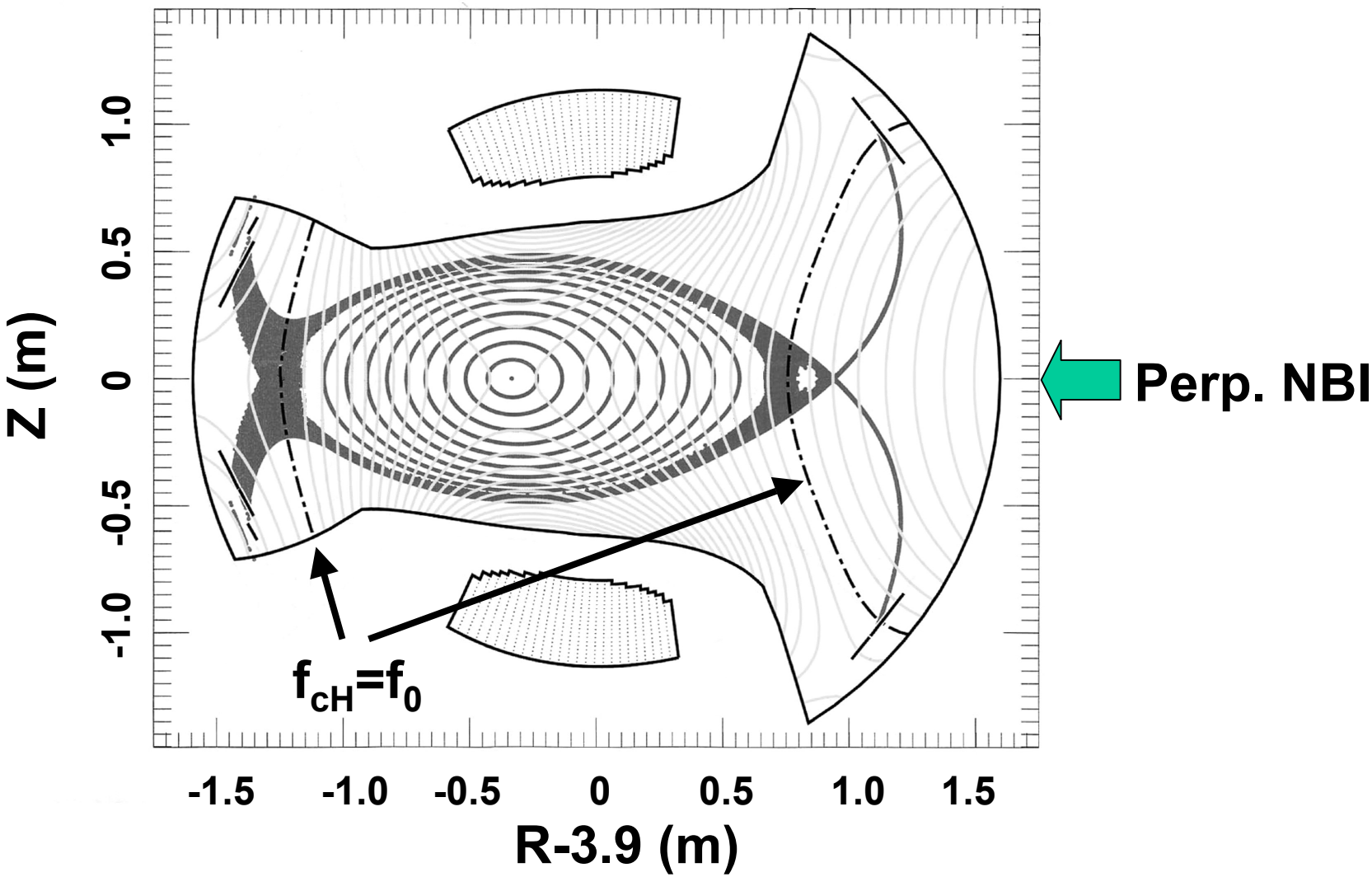
ICE frequency is proportional to magnetic field strength



ICE frequency is proportional to magnetic field strength.

Location of ICE source is fixed.

Location of ICE source



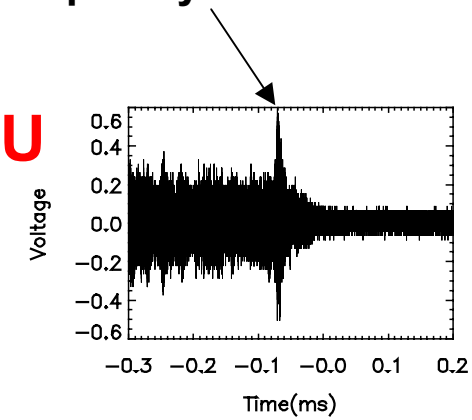
- ICE source locates at peripheral region of plasma. Inner resonance is not the source of ICE since ICE was observed even at $n_{e0}>5\times10^{20}m^{-3}$, where beam penetration to inner side is impossible.

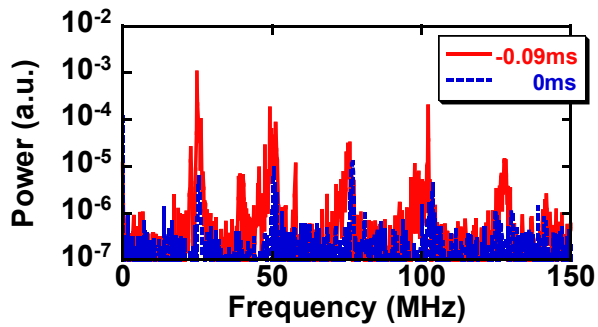
Comparison of decay times measured with different antennas

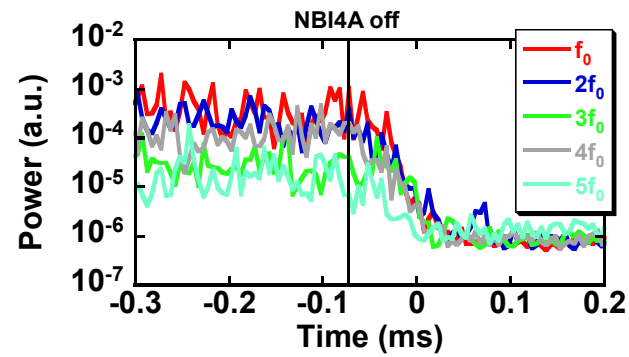
Shot #79264(B_0=-2.712T R_{ax}=3.65m) Ion source:NBI4A

Low frequency noise at NBI off

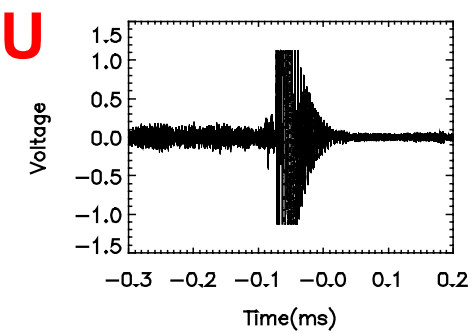
4.5U

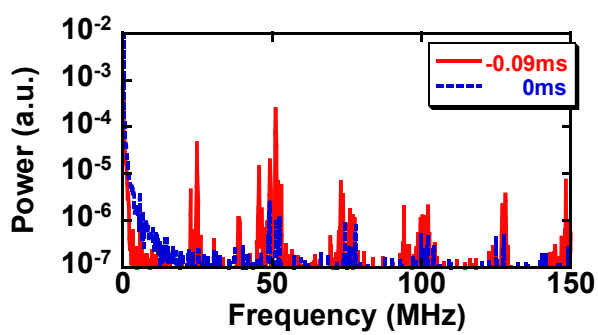


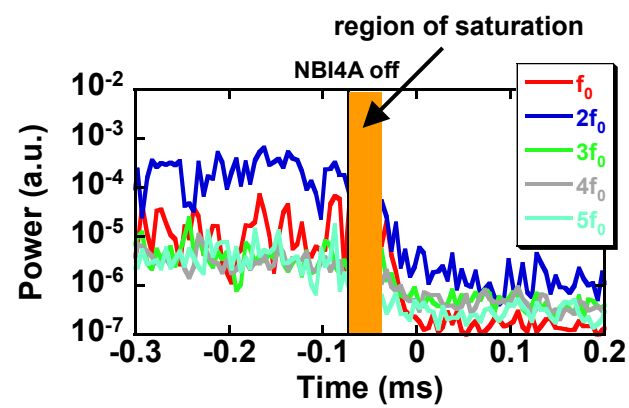




3.5U







- 3.5U decay time is the same with 4.5U decay time.
- They are less than 100μs.

Calculation of orbit

Start from outer side resonance

R=4.56m-4.76m (22.2-25.9MHz) 11points

Pitch angle=87,90,93deg.

Energy=40keV

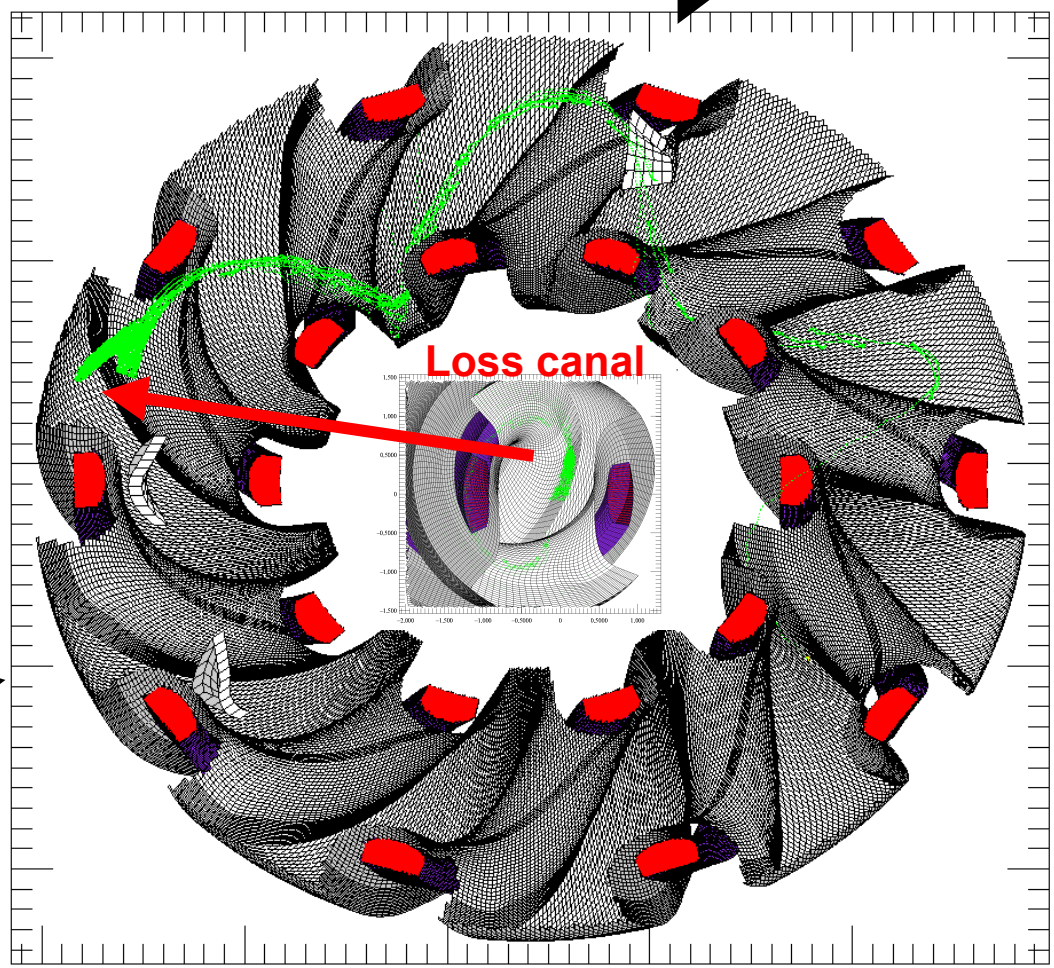
R_{ax}=3.6m, B_0=-2.75T

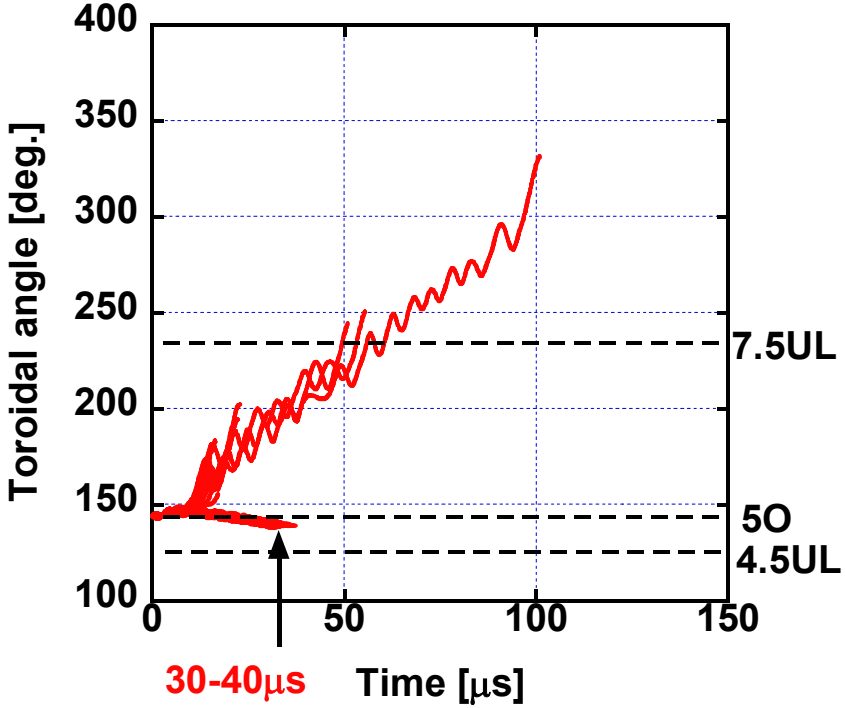
7.5 ICRF antenna

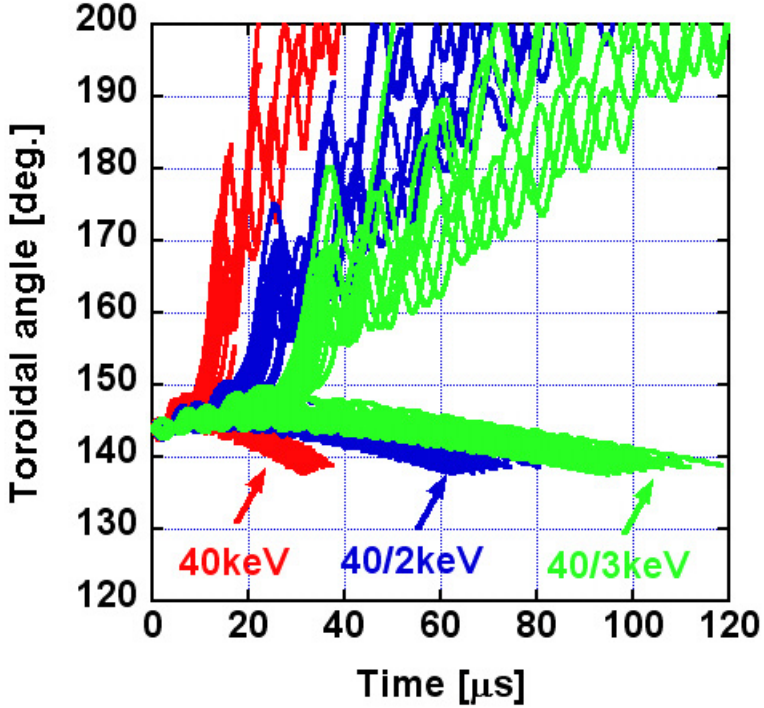
Perp. NBI (5O)

4.5 ICRF antenna

3.5 ICRF antenna





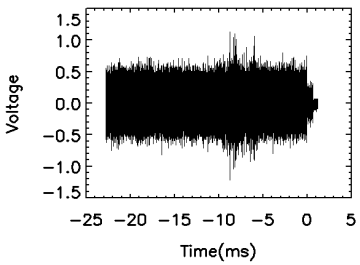


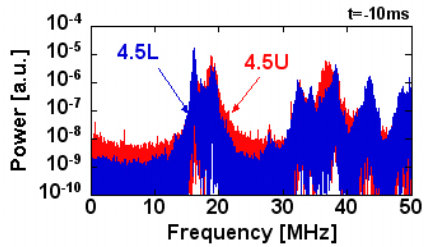
18/33 of particles are lost by loss canal.

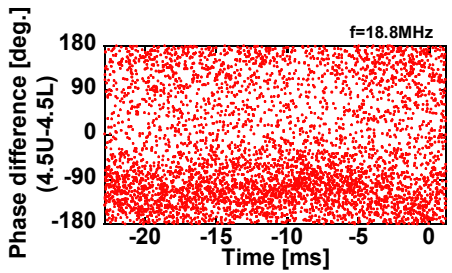
- **Life time of particles in loss canal is the same with the decay time of ICE. Short decay time and same timing of ICE decays of 3.5 and 4.5 antennas is possible.**
- **These particles may not be thermalized because of short life time and ICE was generated.**

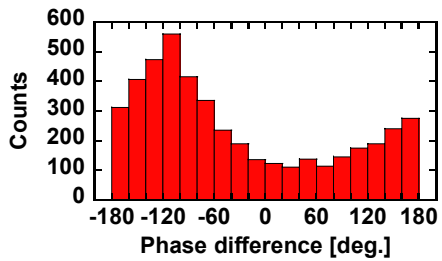
Phase measurement

4.5U & 4.5L antennas

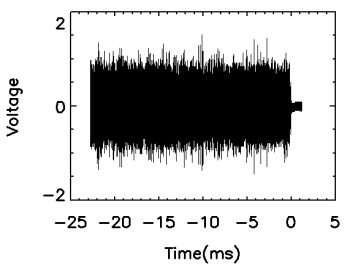




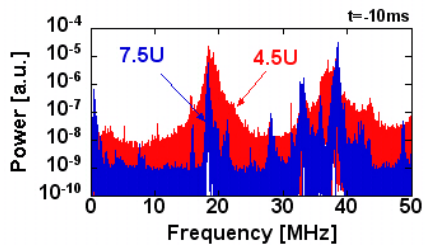




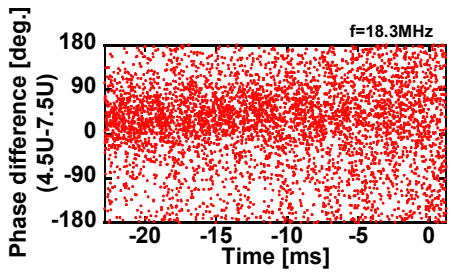
4.5U & 7.5U antennas



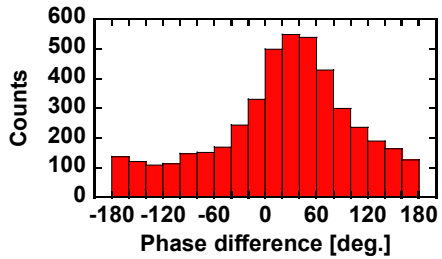
4.5U signal



Power spectrum
(time window = 1ms)



Phase difference
(time window=5μs)



Histogram of phase difference

Phase difference between toroidally separated antennas are scattered but determinable.

↓

Two antennas catch the same wave.

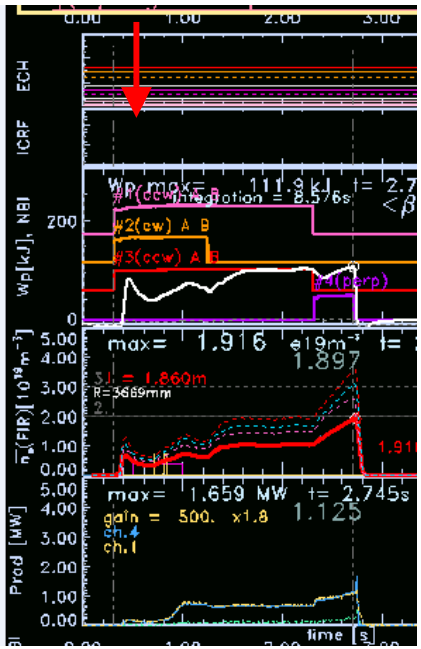
↓

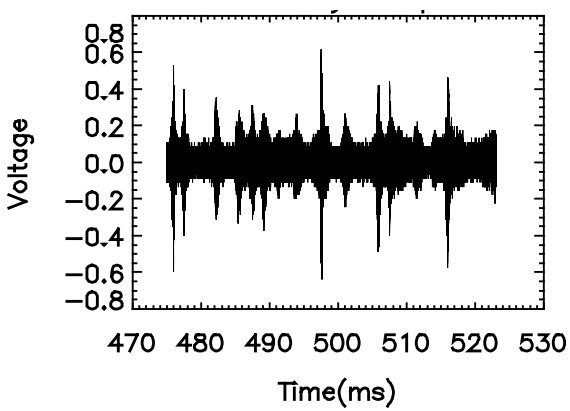
There is only one ICE source. (loss canal)

Other type of ICE-1

ICE synchronized with AE burst

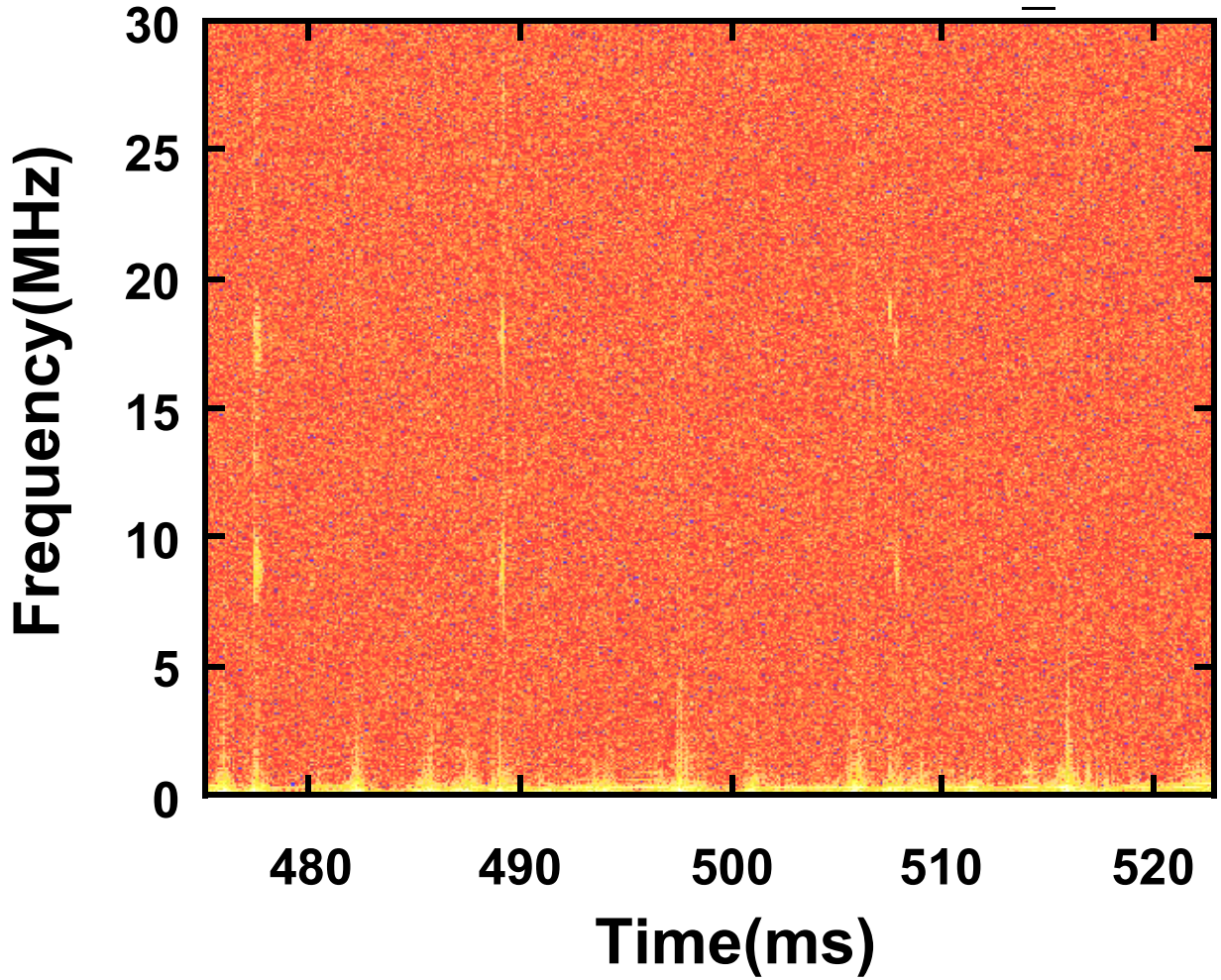
B=0.75T





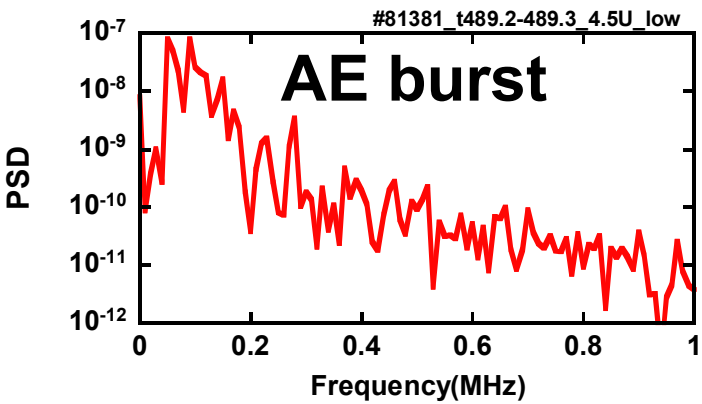
Raw signal of 4.5L antenna

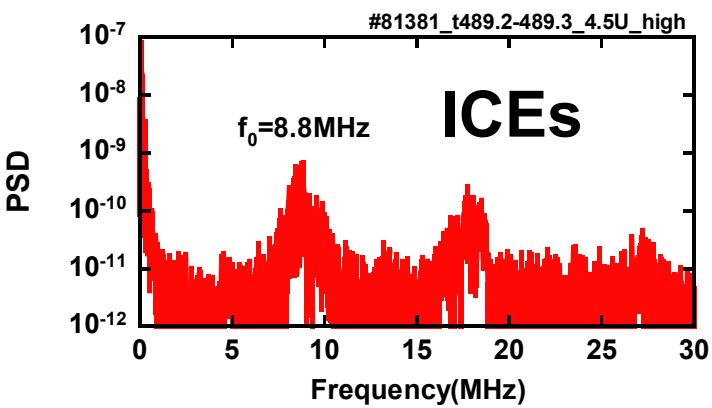
#81381_4.5U

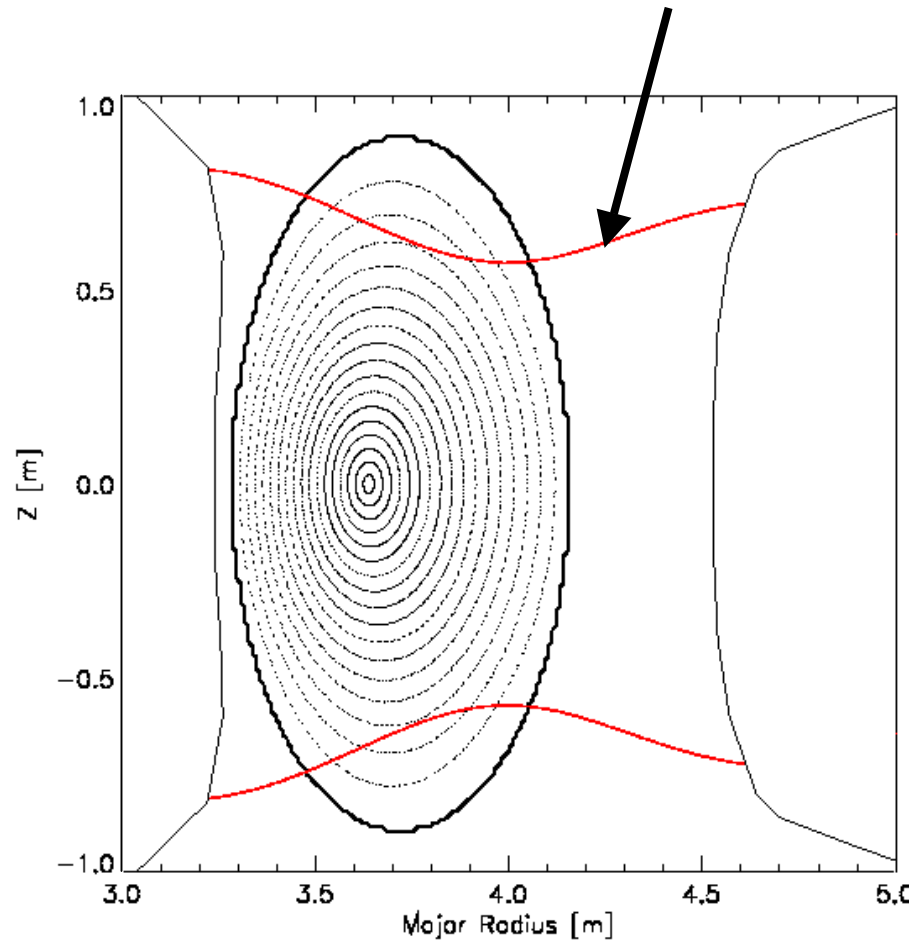


・ICE was detected at the same timing of burst of low frequency.

Cyclotron Resonance (B=0.75T,f=8.8MHz)



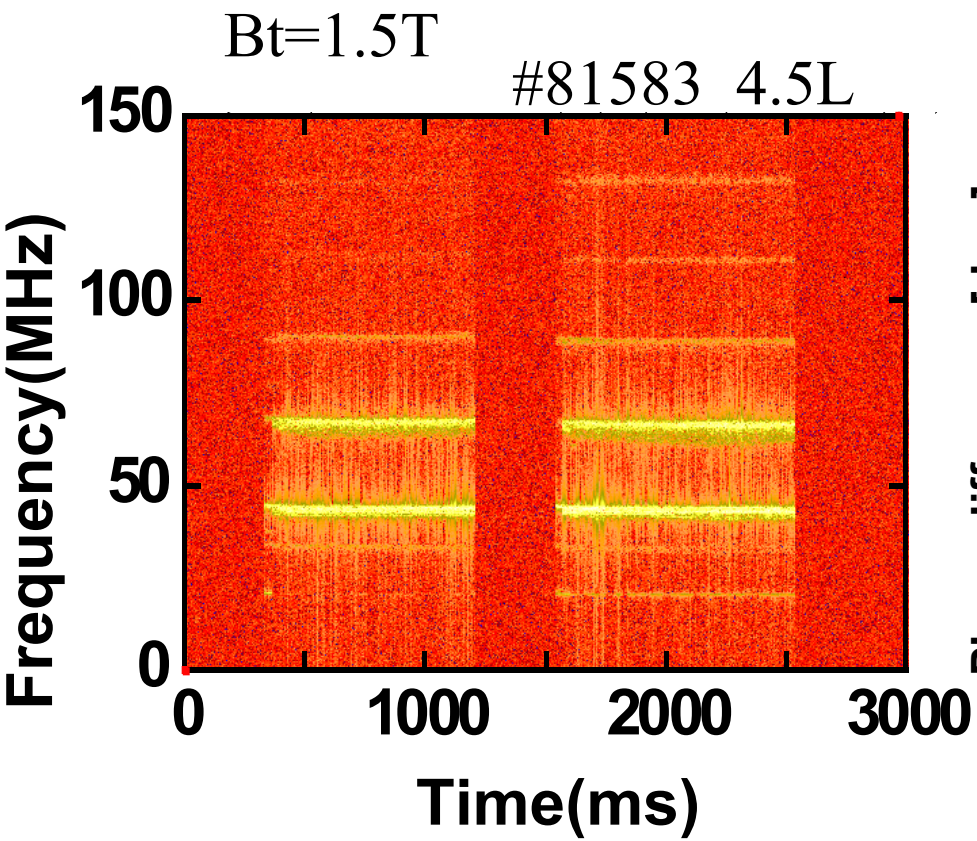


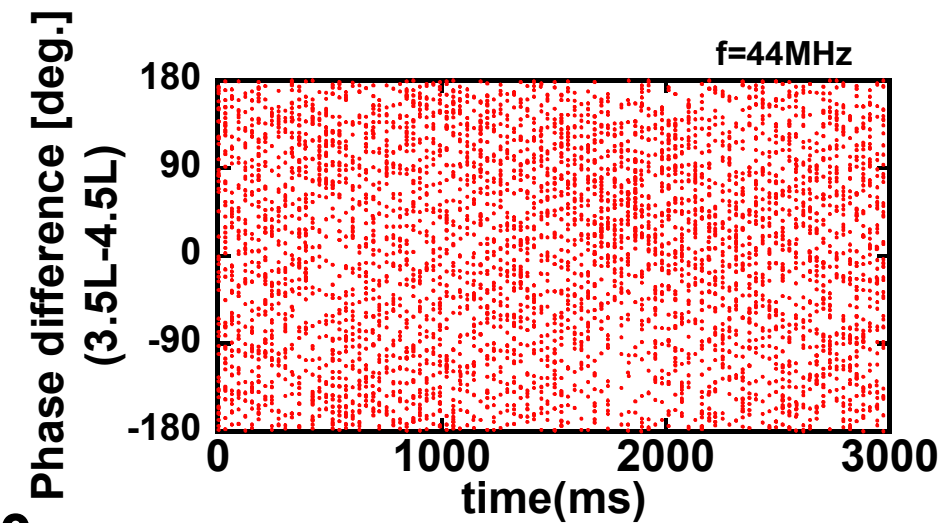


- Passing of high-energy lost particles produced by the burst through peripheral resonant region may be the cause of ICE.

Other type of ICE-2

ICE from low density plasma



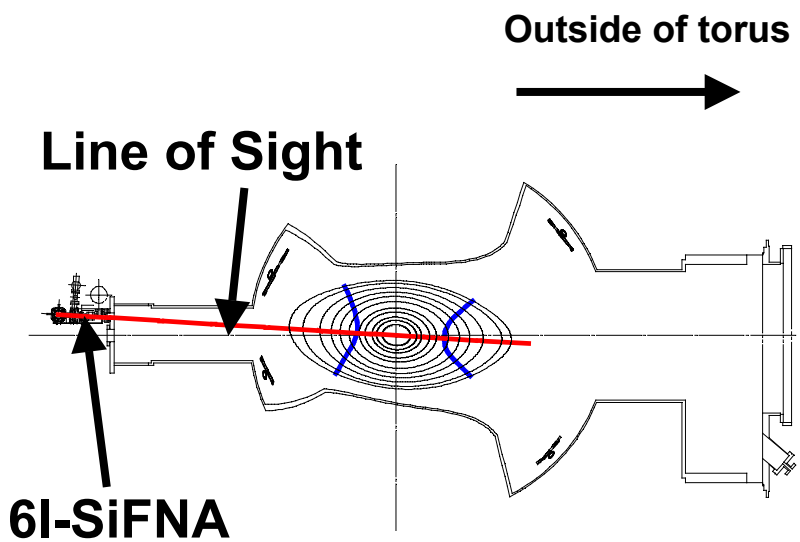


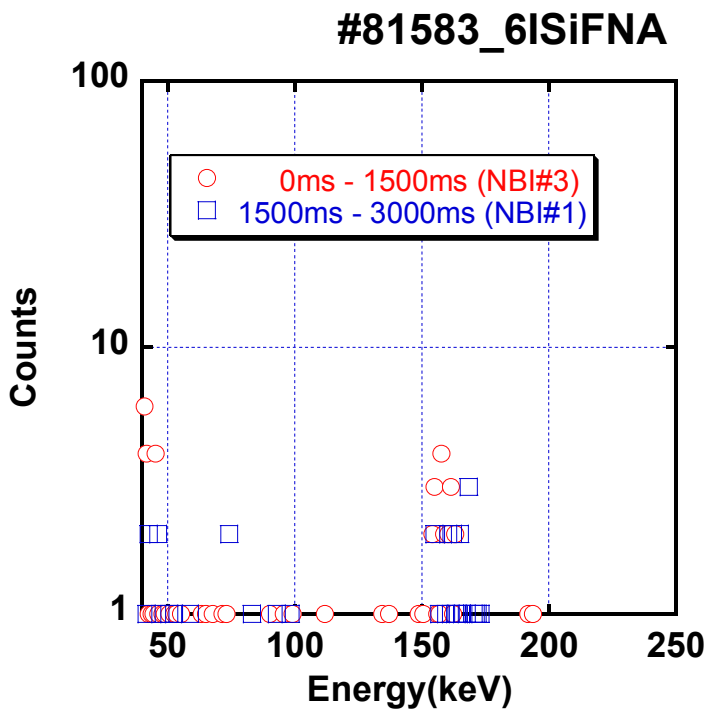
・Tangential NBI (NBI#3→ NBI#1) was injected without gas puffing for NBI power calibration. At this timing ICE was observed. (n_e<0.01×$10^{19}m^{-3}$)

・f_0=22MHz → ICE source is near center of plasma.

・Phase difference between toroidaly separated antennas was not determinable.→there are a lot of ICE sources in plasma.

Detection of source particles





The reversed distribution of high-energy particles causing ICE was directly measured with Silicon-diode-based Fast Neutral Analyzer (SiFNA@6I).

Summary 1 (long pulse operation)

- Plasma duration time with more than 1MW reached 525sec (1.1MW).
- But, plasma often collapsed by the outgassing and sudden influx of iron impurity.
- Application of mode conversion heating to long-pulse discharge enabled the scattering of toroidally localized heat load.
- High heat-removal performance of improved divertor plates was proved.

Summary 2 (ICE)

- In helical device, ICE was observed precisely with ICRF heating antennas.

- ICE is observed mainly during perpendicular NBI.

- These ICE frequencies are proportional to magnetic field strength, and ICE source locates at peripheral region of plasma.

- Short decay time (within 100μs) of ICE agrees with life time of particles in loss canal which exists in helical device.
→ICE source is particles in loss canal.

- Lost particles or beam in low density plasma are also the cause of ICE.