POSTECH/ANU collaborations on MHD sawteeth and suprathermal electron modes in K-STAR plasmas

Chang-Mo Ryu
Dept. of Physics, POSTECH
Pohang, Korea

Outline

- 2009 KSTAR performance
- Search for electron-fishbone instability
- ECE/Mirnov coil data analysis
- Alfven wave/ MHD study for KSTAR
- 2010 and future plans

2009 KSTAR Experiment

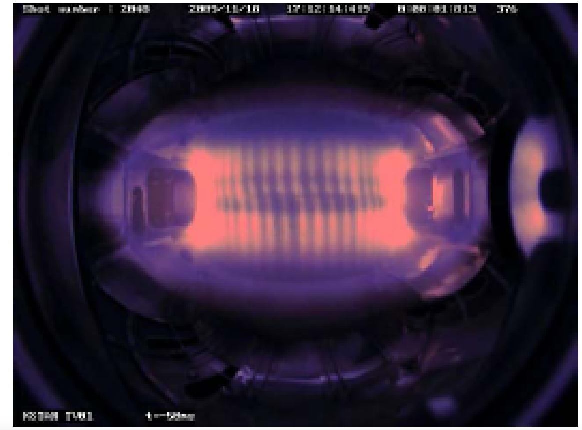
Operation Parameter (Max)	
B_T	~3 T
I_P	> 0.3 MA (0.34 MA)
t_p	> 3 s (4.06 s)
Te	> 0.3 keV
Shape	~Circular
Gas	H_2, D_2

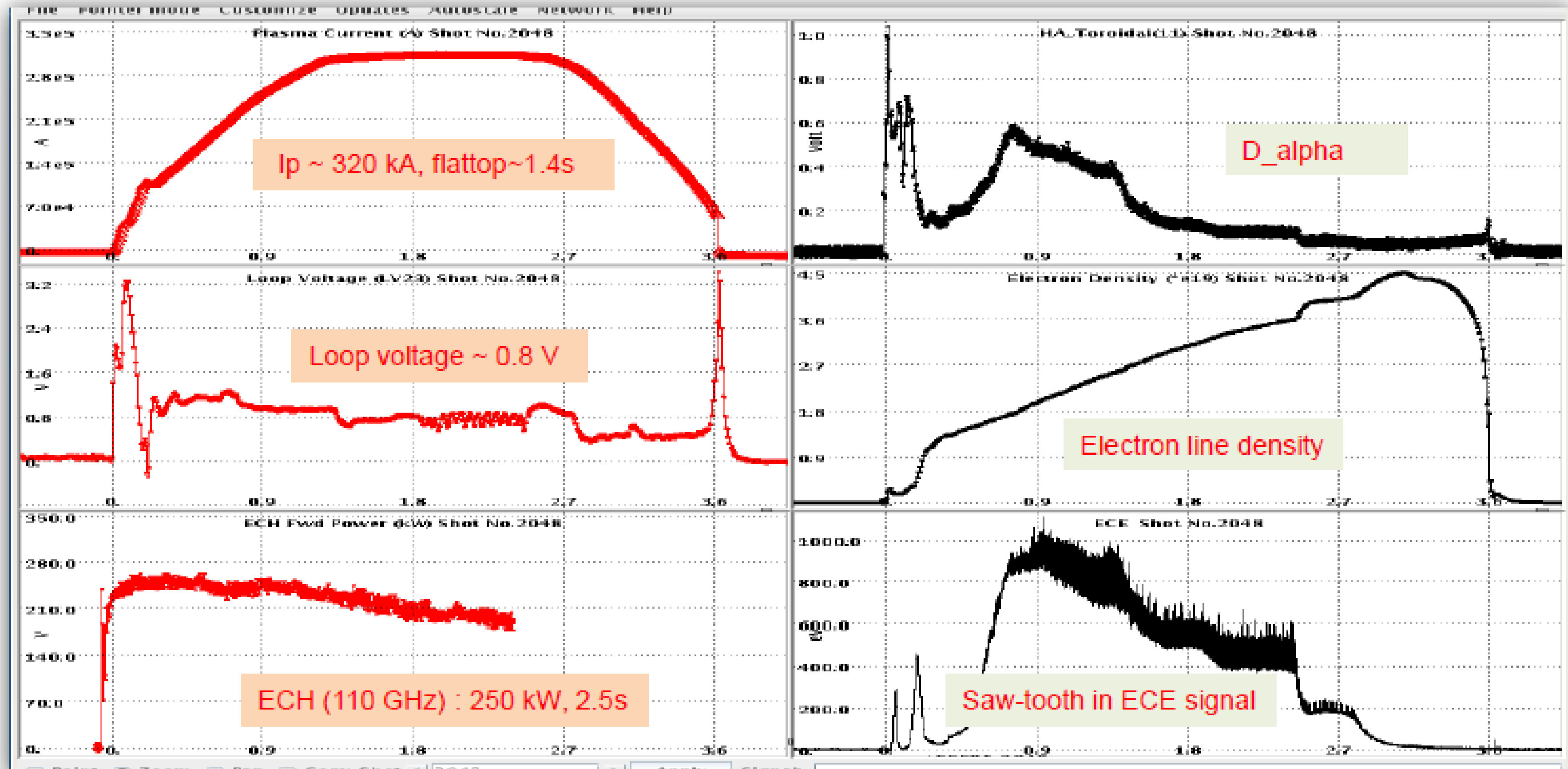
Magnetic control	TF : up to 3.5T PF : +4kA ~ - 10kA
Heating operation	ECH(84G) : 0.5MW, 2s ICRH(45M) : 0.2MW, 10s
Diagnostics	MD / mm-WI / ECE / Hα / filterscope / Vis.TV PD / XCS (1set) / Soft X-ray / Reflect. Bolometer (resistive) ECE (110 ~ 162GHz)

2009 KSTAR Target Plasma Achievement (2009. 11. 18)

Achieved parameters (target value)

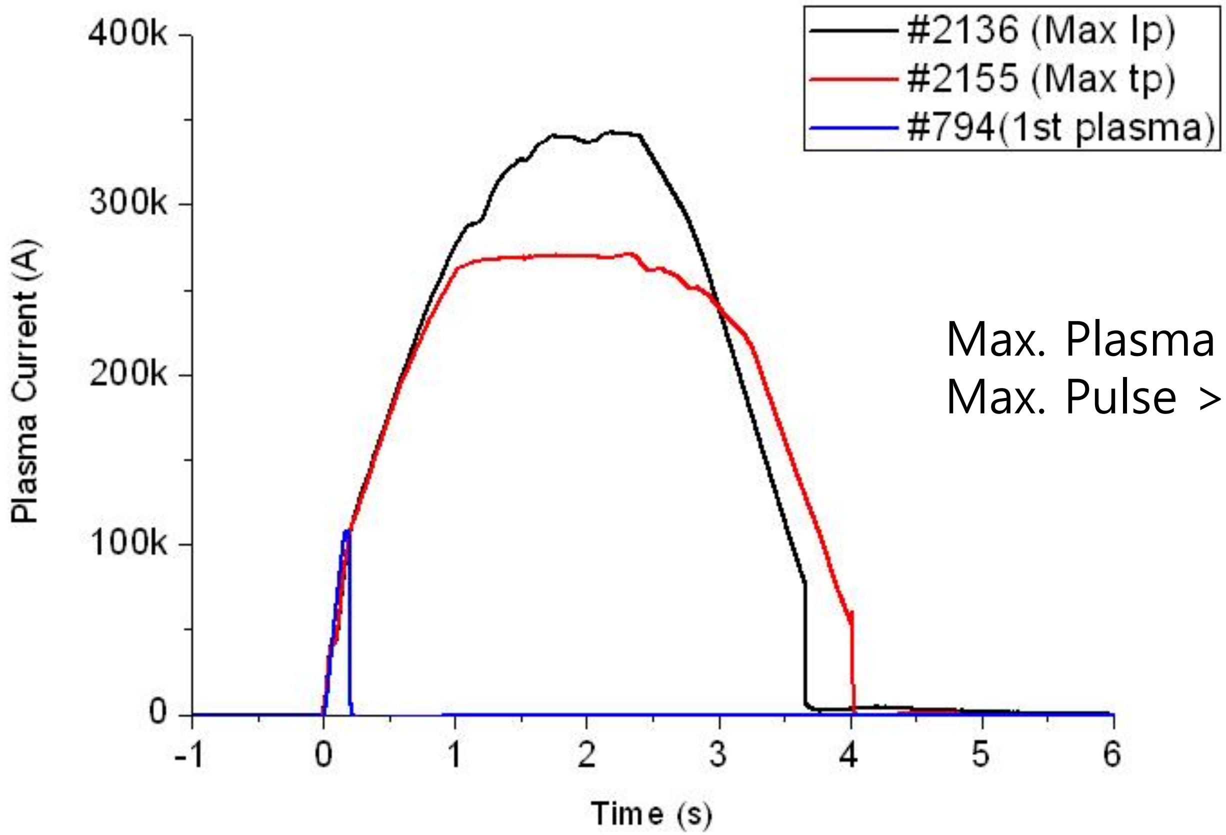
- Plasma current : 320 kA (>300 kA)
- Flattop : 1.4 s (> 1s)
- Pulse length : 3.6 s (> 2s)
- Shot # 2048
- Date : 2009. 11. 18
- ECH : 110 GHz, 250 kW, 2.5s





2009 KSTAR Experiment

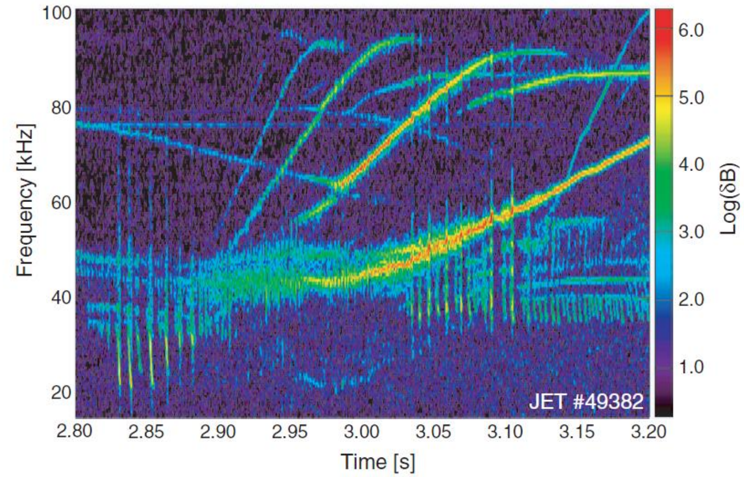
Current Profile measured by RC



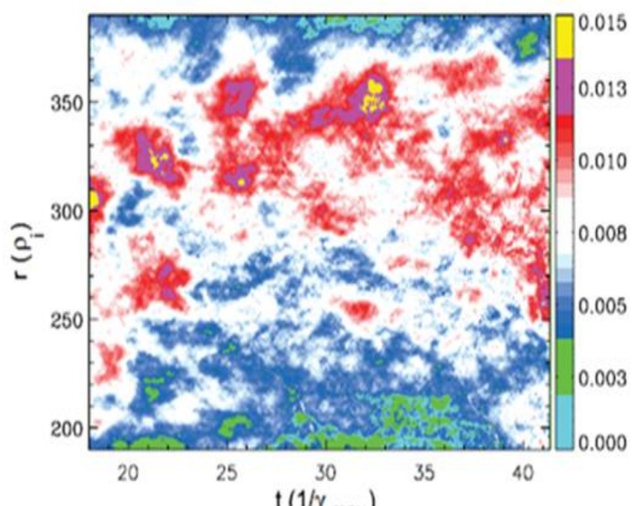
Max. Plasma Current 340.4 kA
Max. Pulse > 0.1kA 4056.9 ms

Why are we interested in energetic particle ?

- Enigmatic electron thermal transport channel is critical to confinement in all regimes
- Energetic particles excite high frequency Alfvenic eigenmodes, EGAMs, etc. (i.e. $\omega \sim k_{\|} v_{\|}$)
- Physics:
  - Phase space structure formation due highly coherent procession drift resonance → strongly nonlinear phenomena
  - Alfvenic turbulence including nonlinear wave-particle interactions → astrophysics, CR acceleration
  - Multi-scale interaction between high frequency modes and drift wave fluctuations
- Fusion:
  - α's slow down on electrons (ITER has $T_e = T_i$)
  - Good alpha confinement critical to achieve Q=10
  - EP modes may regulate bulk transport



S.D. Pinches et al., PPCF 2004



Y. Xiao et al., PRL 2009

Electron fishbone instability

Proposal No. 2009-06-21-001
Experiment done on 2009.11.25-26

Chang-Mo Ryu & Matthew Hole
POSTECH & ANU

Alfven wave excitation via minority heating

Proposal No. 2009-06-21-002
not approved

Chang-Mo Ryu & Matthew Hole

POSTECH & ANU

Motivation

- Fast electrons are characterized by small orbits, This is similar to alpha particles in reactor relevant conditions.[1]

- The bounce averaged dynamics of both trapped as well as barely circulating electrons depends on energy (not mass): thus, their effect on low-frequency MHD modes can be used to simulate/analyse the analogous effect of charged fusion products.

- K-STAR does not yet have neutral beams.

[1]F. Zonca et al, Electron fishbones: theory and experimental evidence Nuc. Fus. **47**, 1588-1597 , 2007

Purpose of Experiments

- Determine whether electron fishbones can be excited in K-STAR by ECRH injection
- Identify experimental parameters for maximum mode excitation

Background

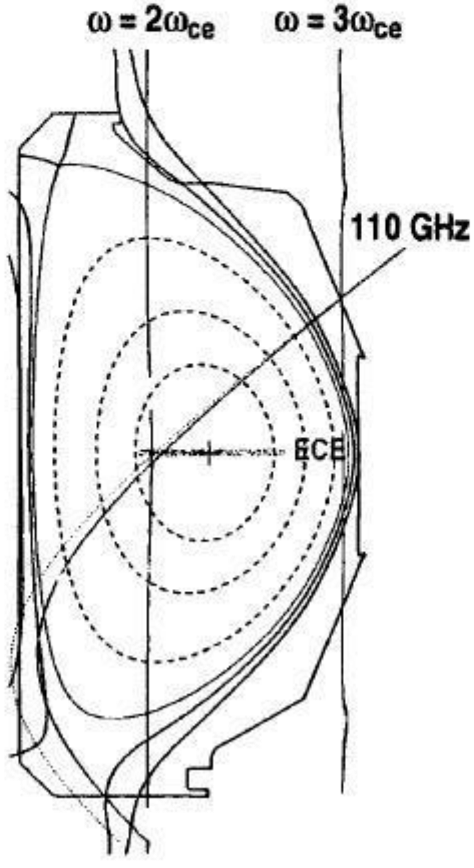
- In DIIID[1] when electron cyclotron current drive (ECCD) is applied on the high field side, an internal kink instability with bursting behavior (fishbones) has been observed.
  - fishbones exist even though thermal plasma is stable $\Rightarrow$ energetic particle origin.
  - Fokker Planck calculations show barely trapped suprathermal electron population.
  - Due to drift-reversal effects, barely trapped suprathermal electrons are in the same energy range as the fast ions from neutral beam injection, and can resonate with fishbones.

[1] Wong, K. L. et al. (2000). Physical Review Letters 85 (5), pp. 996-999

Experimental Plan

- Inspired by DIIID experiments by Wong et al [1]

DIII-D tokamak	Kstar
$B_T = -1.77T$	$B_T = 2T$
$I_p = 0.89MA$	$I_p = 0.25MA$
$R = 1.76m$	$R = 1.8m$
$a = 0.62m$	$a = 0.5m$
$q_{edge} = 6.06$	$q_{edge} = 3 \sim 6$
$q_{\min} \sim 1$	$q_{\min} \sim 1$



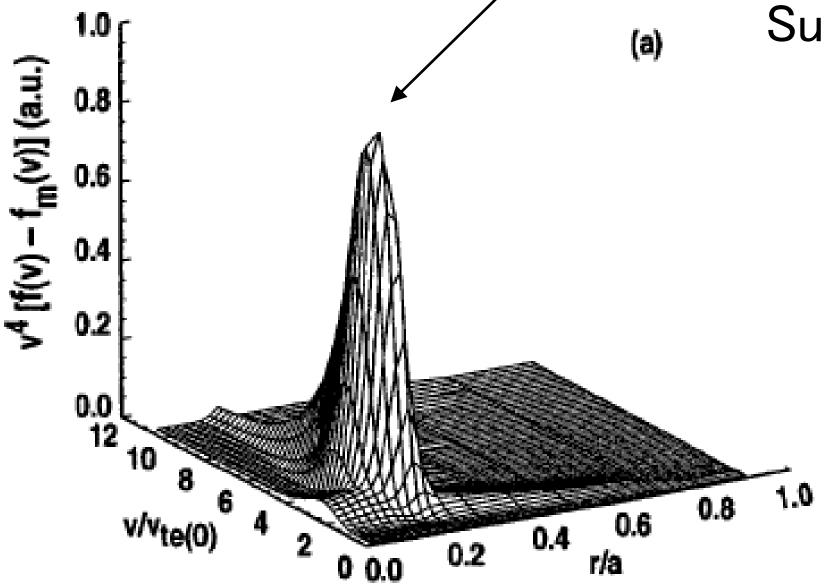
(ECCD)

[1]Wong, K. L. et al. (2000). Physical Review Letters 85 (5), pp. 996-999

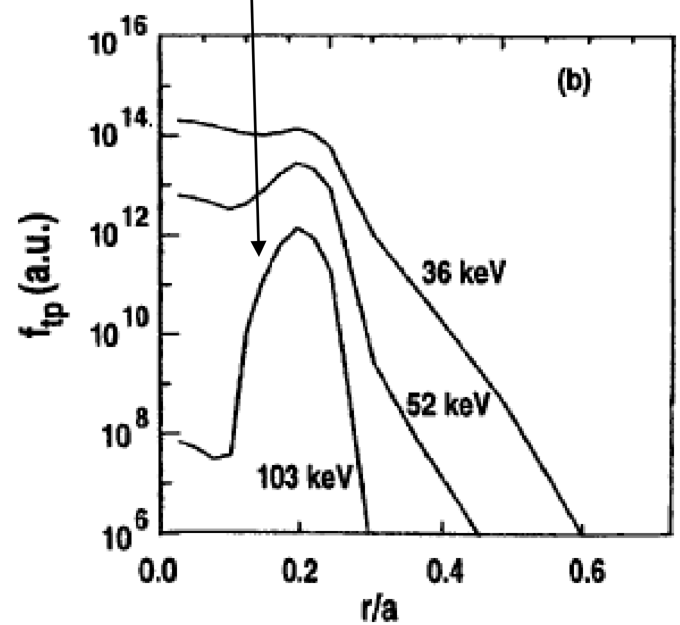
Off-axis ECCD ⇒ suprathermal electrons

・CQL3D Fokker-Planck code is used to calculate the electron distribution function

suprathermal distribution near core



Suprathermal population is hollow



[1]Wong, K. L. et al. (2000). Physical Review Letters 85 (5), pp. 996-999

q profile flattens during discharge

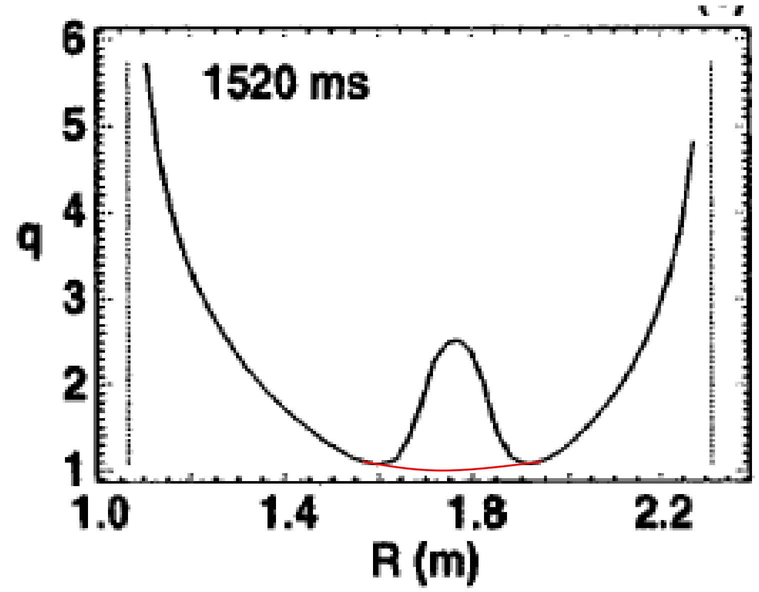
- q profile evolves from negative central shear (NCS) to positive shear throughout discharge.

⇒ The 2.5 MW of deuterium neutral beam is injected into DIII-D to produce the NCS plasma

q profile at onset of bursts (1520ms)

q profile flattens during discharge.

q_0 drops to qmin~1 after 1720ms

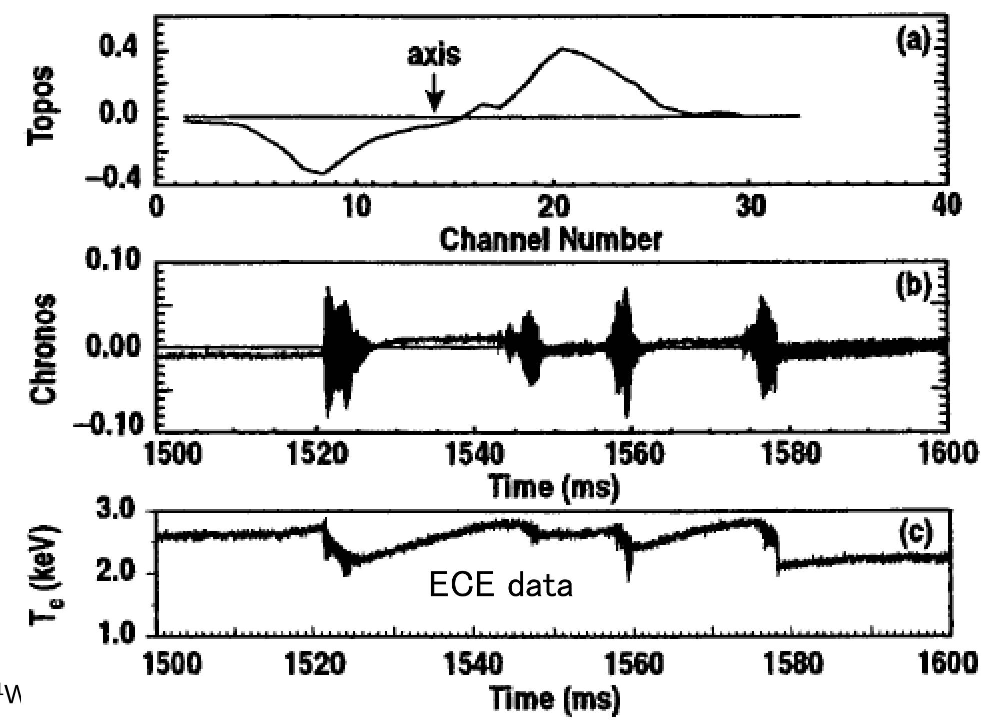


[1]Wong, K. L. et al. (2000). Physical Review Letters 85 (5), pp. 996-999

DIIID MHD observations

- (m,n) = (1,1) instability observed with a NCS plasma.
- ideal MHD stability analysis by GATO code (which does not treat energetic particles) shows the (m,n) = (1,1) mode is stable

$\Rightarrow$ suggests energetic particle drive

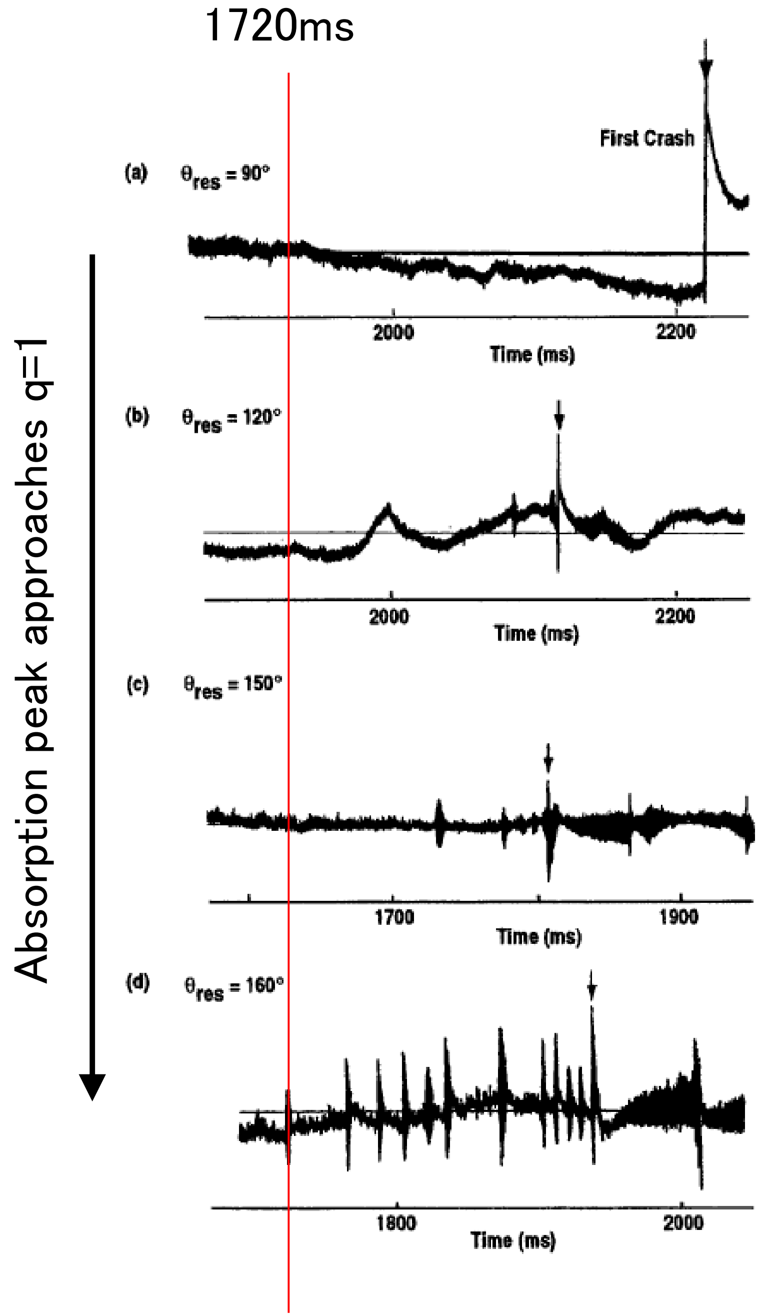


Spatial eigenfunction

Temporal eigenfunction

Central electron temperature

[1]W



- From 1720ms q profile is flat, and sawteeth crash clearly visible.

- GATO predicts (m,n) = (1,1) mode of thermal plasma is marginally unstable.

<u>However,</u> first crash advances in time, crash waiting times decreases, and mode amplitude grows as absorption peak approaches q=1 surface on high field midplane ($\theta_{res} = \pi$).

$\Rightarrow$ suggests drive from barely trapped suprathermal electrons,

[1]Wong, K. L. et al. (2000). Physical Review Letters 85 (5), pp. 996-999

Ding. et.al., Nuclear Fusion (2002)

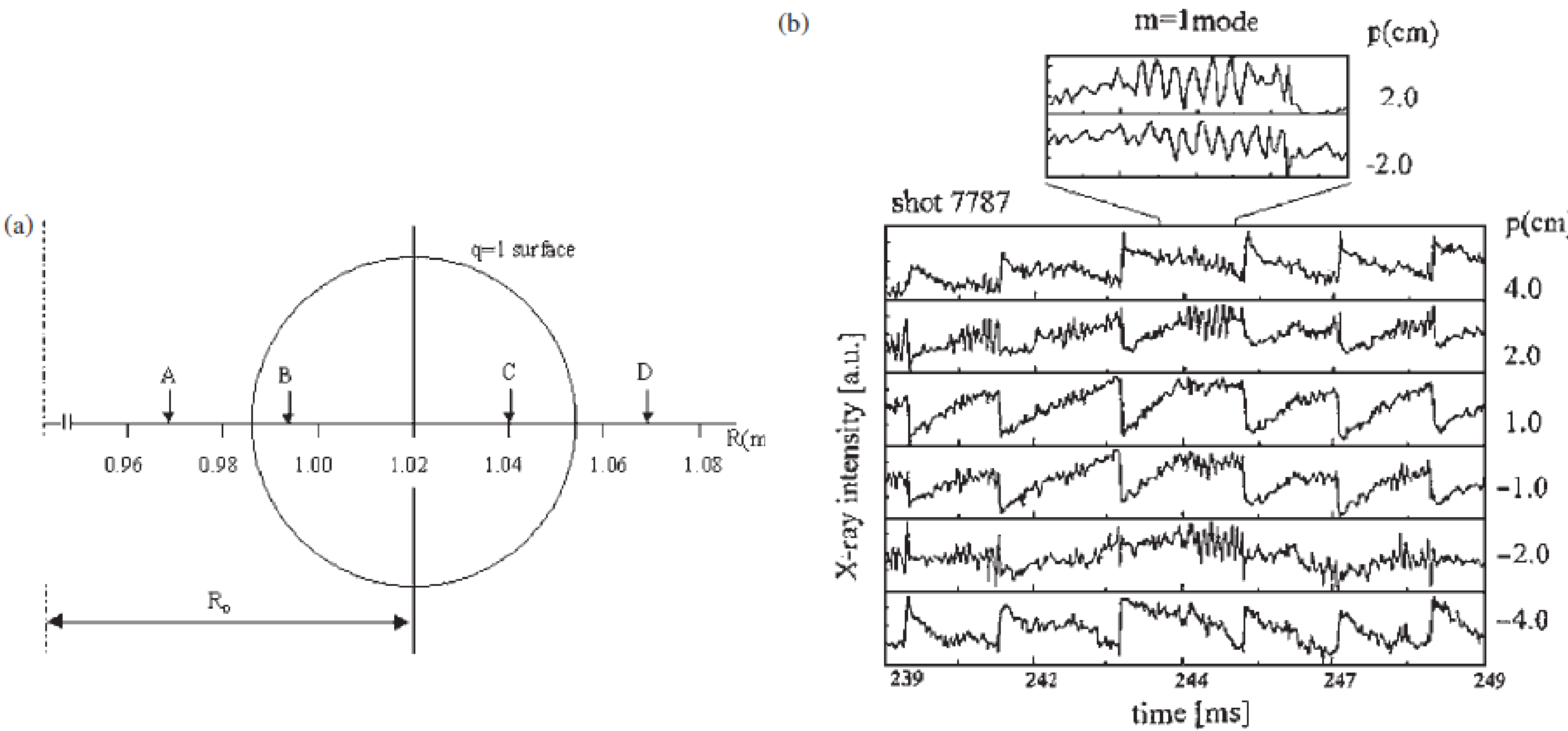


Figure 1. (*a*) Schematic diagram showing the $q = 1$ surface and the cyclotron resonance locations in the experiment. (*b*) Raw data from the soft x-ray imaging system showing the sawteeth and the $m = 1$ mode with 230 kW of ECH power. The ECR is located at point A in (*a*). The tangential radius of the sight line from the magnetic axis is denoted by p.

ECRH system

The original electron cyclotron heating (ECH) startup plan –using 84 GHz as fundamental freuqncy for the toroidal magnetic field of 3 T.
In 2009, the gyrotron had vacuum leak at the collector and sent to CPI for the repair– return was delayed due to baking– crack around the edge of the diamond disk.
110 GHz gyrotron loaned from General Atomics (GA) which was also loaned from TdeV in Canada.
But, the toroidal magnetic field was reduced to 2 T for the second harmonic 110 GHz ECH for the startup.
The second harmonic 110 GHz ECH–assisted startup was also very successful as it was in the first plasma campaign that used the second harmonic 84 GHz ECH–assisted startup

FIG 1. *Gycom 110 GHz gyrotron and collector coil which is loaned from GA DIII-*

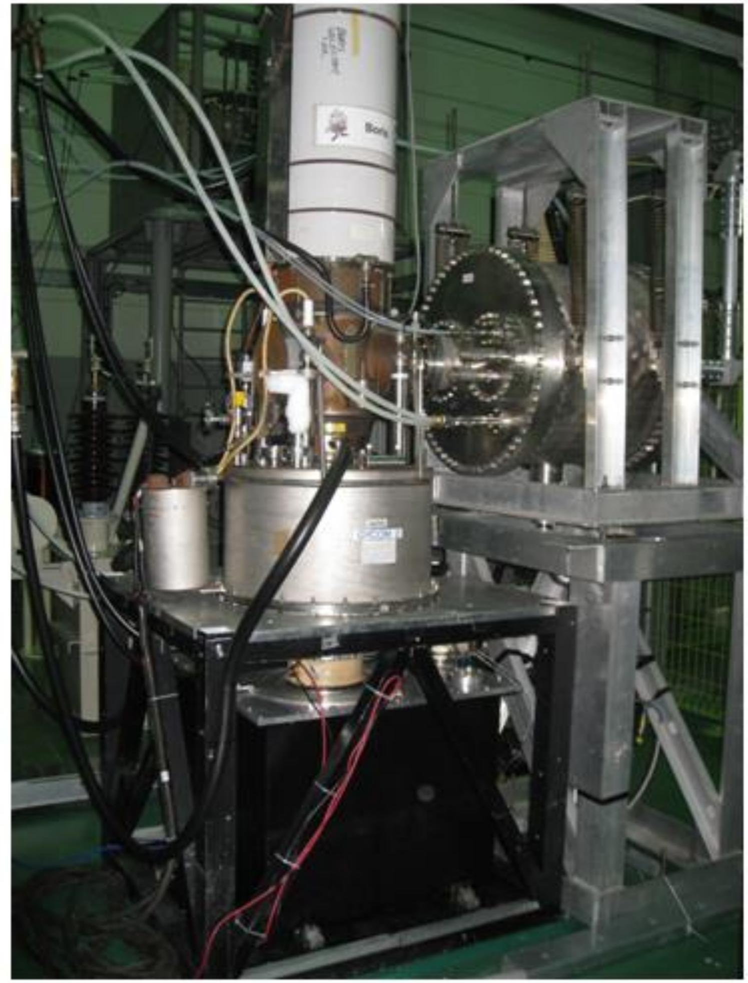


FIG 2. *Final installation of 110 GHz gyrotron and MOU.*

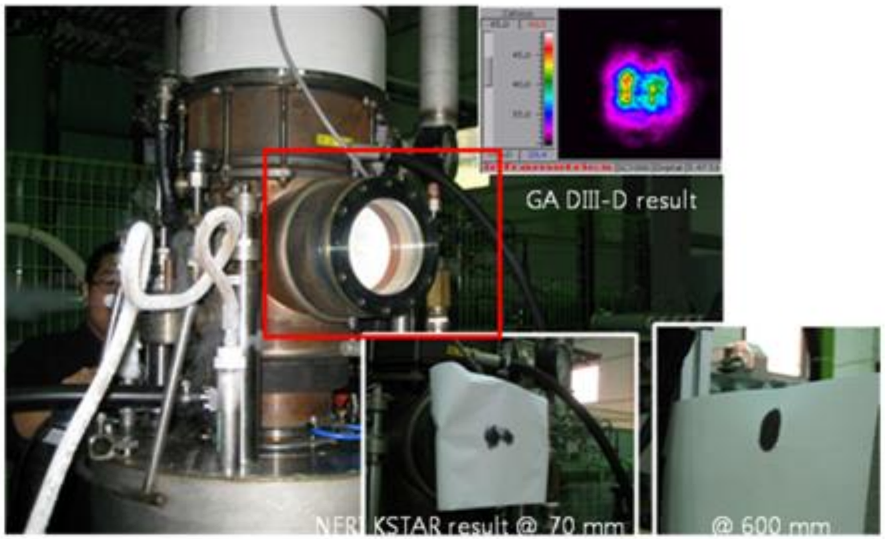


FIG 3. *Beam profiles using a thermally sensitive paper at 70 mm and 600 mm from the gyrotron window.*

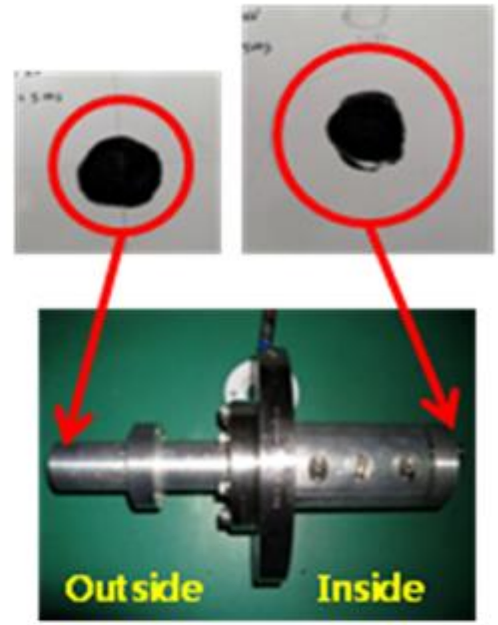


FIG 4. *Beam profiles at the input and the output of the MOU output waveguide.*

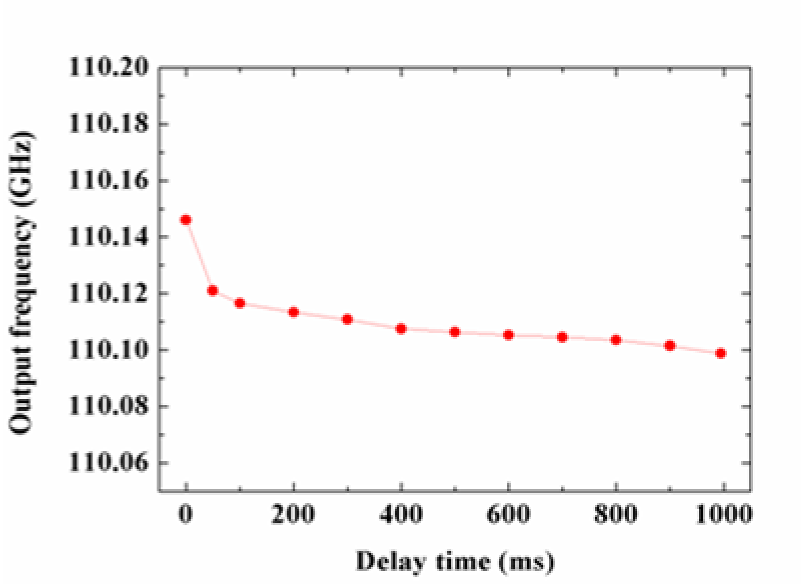


FIG 5. *Gyrotron output frequency as a function of time.*

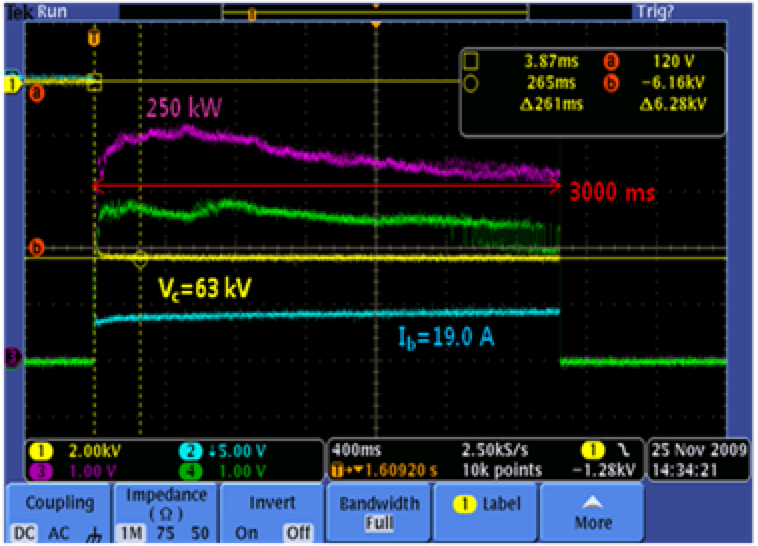
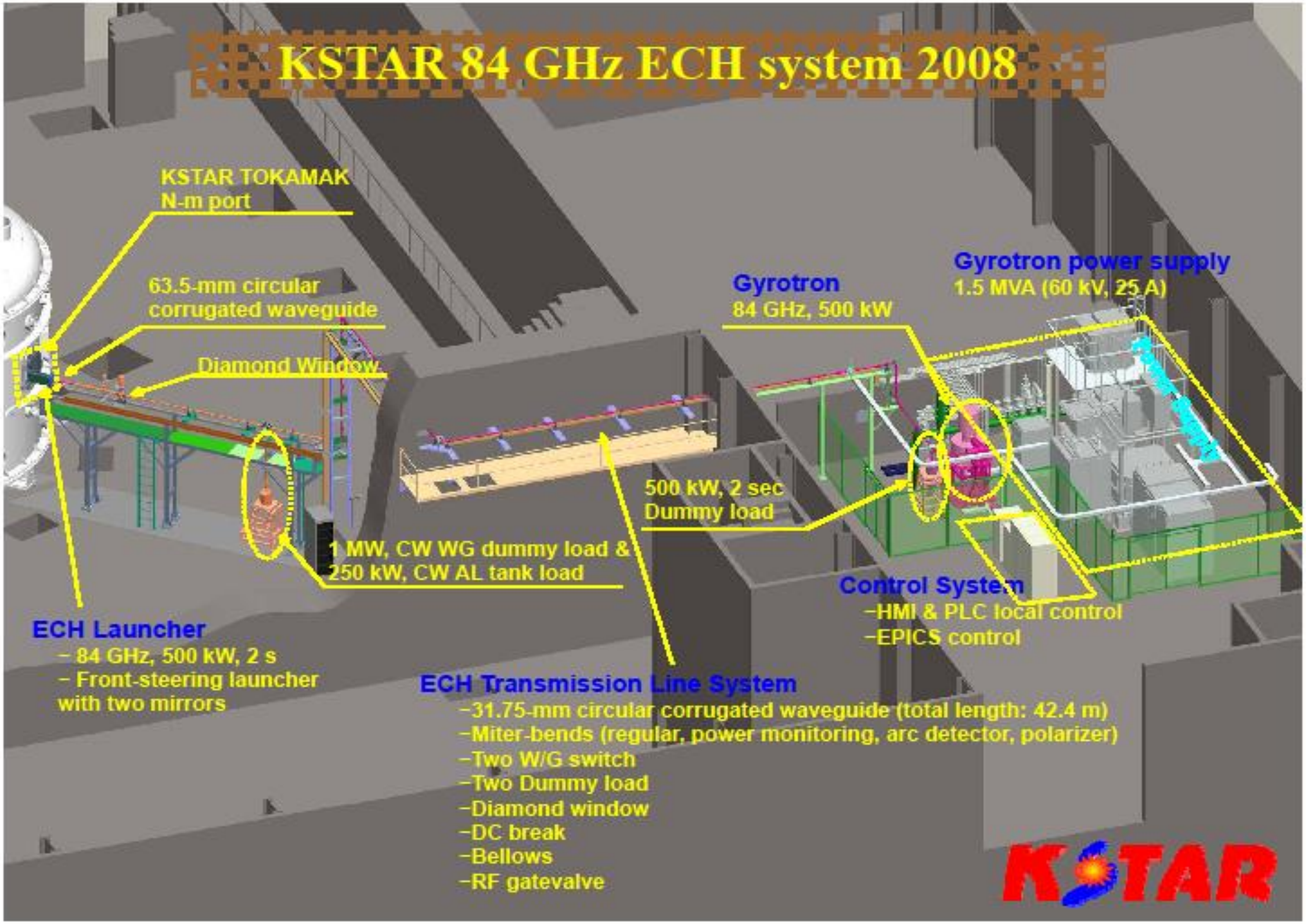
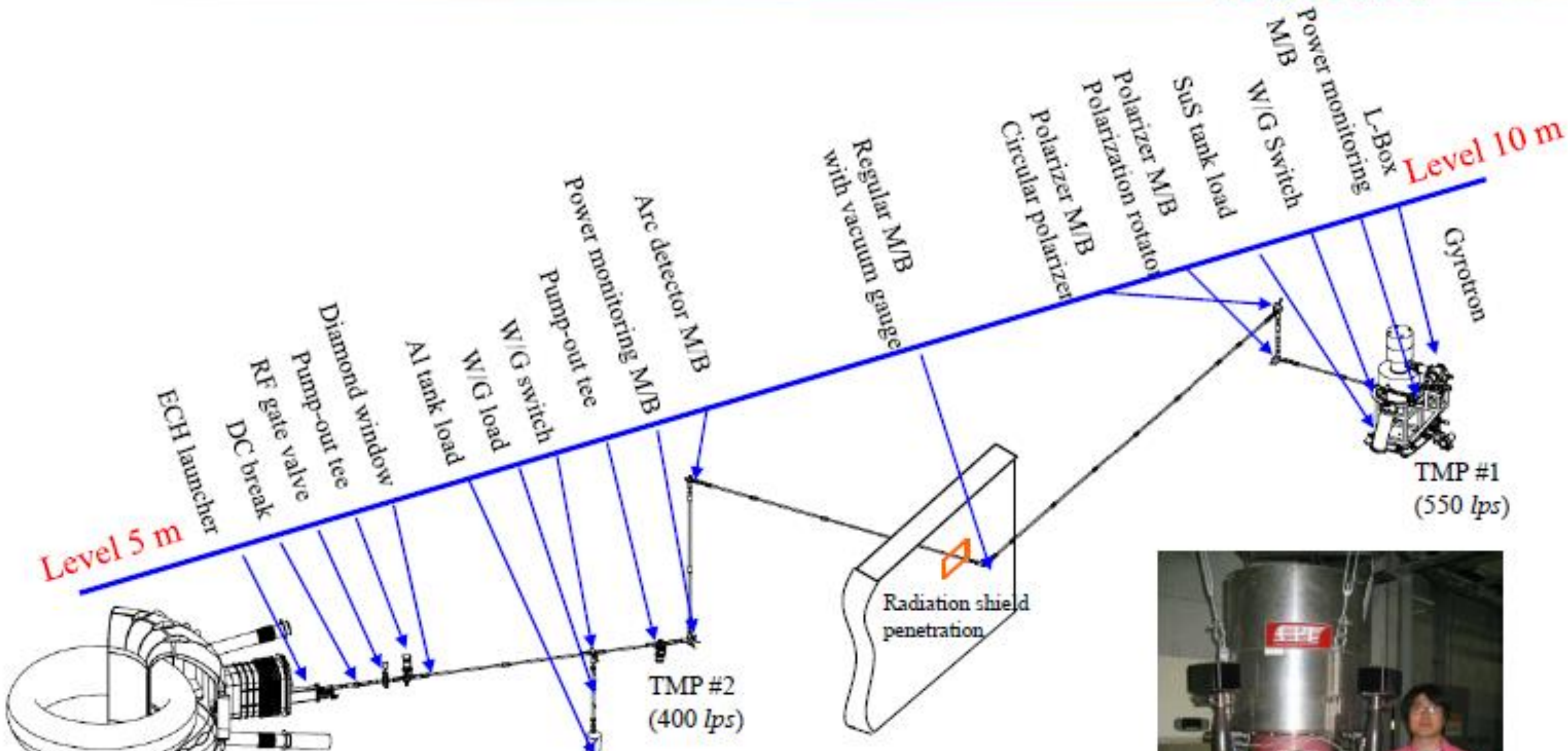


FIG 6. *Boris gyrotron operation waveforms; ch1 (yellow) is the cathode voltage, ch2(blue) the beam current, ch3(pink) and ch4(green) the forward power signals from the diode detector at the first and the second power monitoring miter bends. respectively.*

ECH–ECRH system



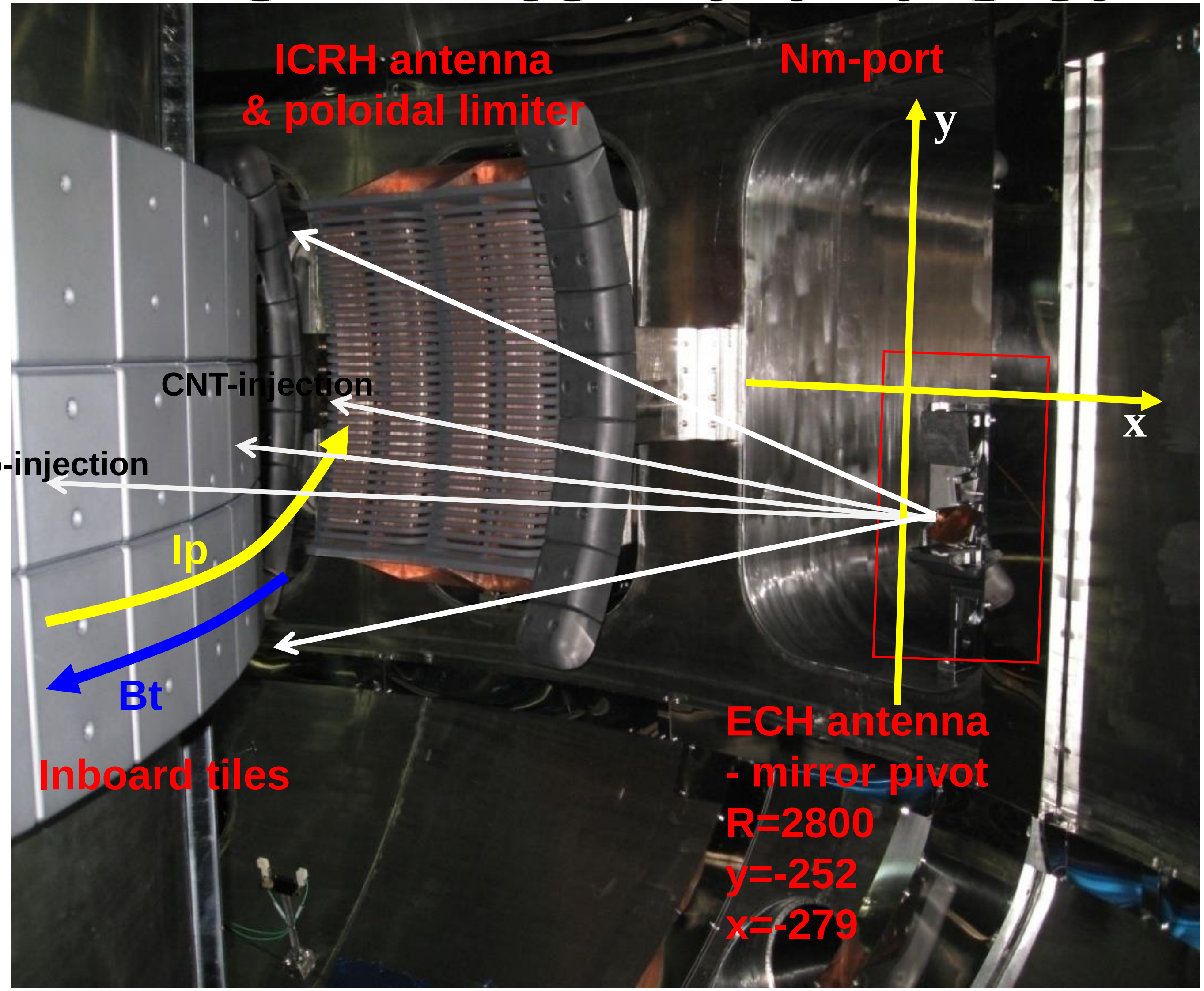
KSTAR 84 GHz ECH System



- 40-m long evacuated transmission line of low loss
- Waveguide diameter: 31.75-mm
- Propagating mode: Gaussian-like HE11

- Propagation constant for HE11 mode, $\beta = 0.996k_0$
- Corrugation parameters
  - period=1.3 mm, width=1.0 mm, depth=0.76 mm

ECH Antenna and Beam Size



- Beam diameter at the resonance positions
  - R_{X2} = 1.6 m
    (I_{TF}= I3.3 kA)
    d = 8.2 cm
  - R_{X2} = 1.68 m
    (I_{TF}= 14 kA)
    d = 7.8 cm
  - R_{X2} = 1.8 m
    (I_{TF}= 15 kA)
    d = 7.2 cm

12009.11.25 Shot Plan

Operation Objective

Using ECCD at q=1 surface high field side, off-axis heating, try to see sawtooth oscillation & electron fishbone instability.

Detailed Experiments

1. Plasma current 250kA , plasma is mainained for 3.6s.
2. Toroidal magnetic field Bt= 2.03T, TF coil current = 20.3kA
2.250kW ECH second harmonics heating from −160ms
pre-ionization, plasma is maintained till 2.6s.
3.ECH position Rp=1.8m , toroidal angel −10° (counter clockwise) .
(ECH heating position was 1.86m .)
4.ICRF was used in pre-ionization process.
5. Using PF coil 6 &7, move plasma from Rp=1.8m to1.9m linearly.
6. Secondary gas puffing opened at 1.0V to adjust the gas flow.
in the blipping phase. Plasma density and its increase rate are adjusted
in ramping up plasmas.

Brief Summary of our Experiment

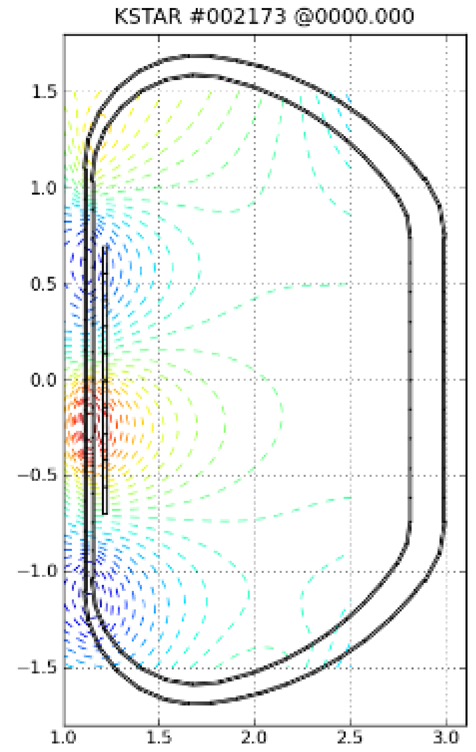
1. 2009. 11.25, shot #2170~#2180 atempted, 4 shot successful
   #shot 2181 (ECCD) fishbone-like indication.
2. Total Plsama current: 250kA, Density:1.5*10^19/m^3 ,
   Temperature: 2.5 keV
2. Clear Sawtooth oscillation was observed
3. Sawtooth inversion occurred at channel ece02 and ece16
   when plasma position Rp was near 1.9m from 2.25s to 2.6s
4. As plasma moves outward, sawtooth inversion was found in single
   channel ece16
5. Small fish-bone like pre-cursor oscillation was observed near 2.45s
   before sawtooth oscillation

Future works

1. Analysis of EFIT data
2. Minrov coil data should be investigated
3. ECE data calibration is not finished. Detected temperatures from
   ECE channel does not have correct corresponding position.
4. Soft X-ray data were erroneous,so could not be compared with ECE signals

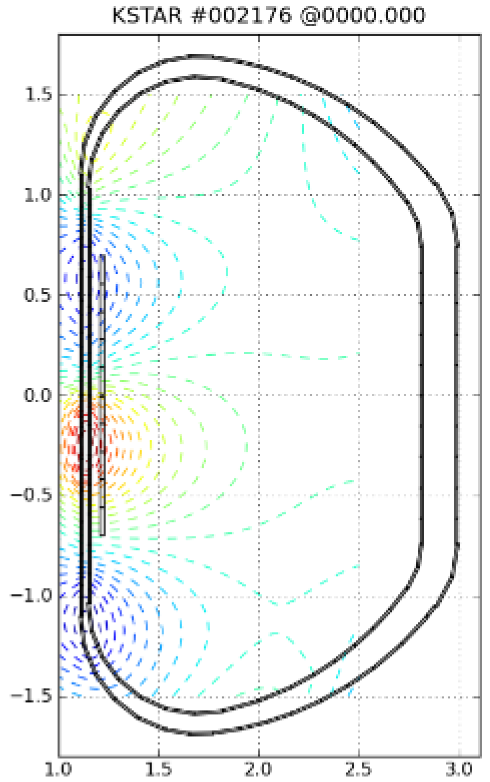
Shot #2173

I_tf(kA)	20.4
Ip(kA)	239.6
Pulse > 0.1kA(msec)	3455.4
Ne(e19/m^2)	2.1
Te(eV)	0.0
Pressure(mbar)	1.8E-5
ECH_P(kW)	270.8



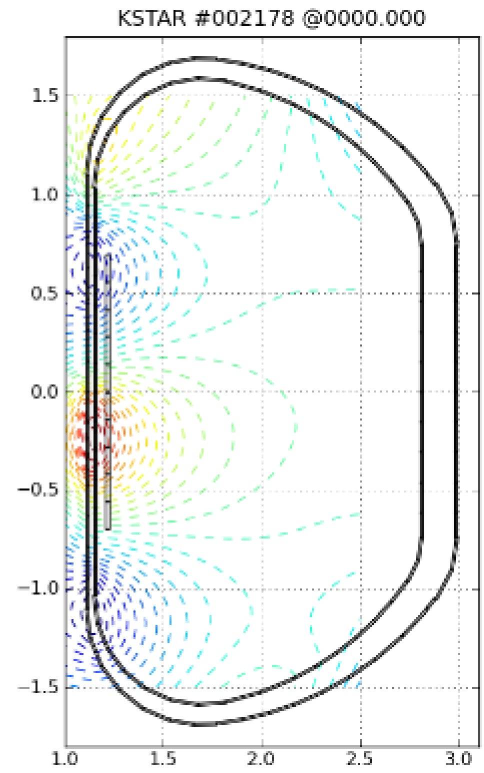
Shot #2176

I_tf(kA)	20.4
Ip(kA)	249.8
Pulse > 0.1kA(msec)	3816.5
Ne(e19/m^2)	1.8
Te(eV)	0.0
Pressure(mbar)	1.7E-5
ECH_P(kW)	257.1



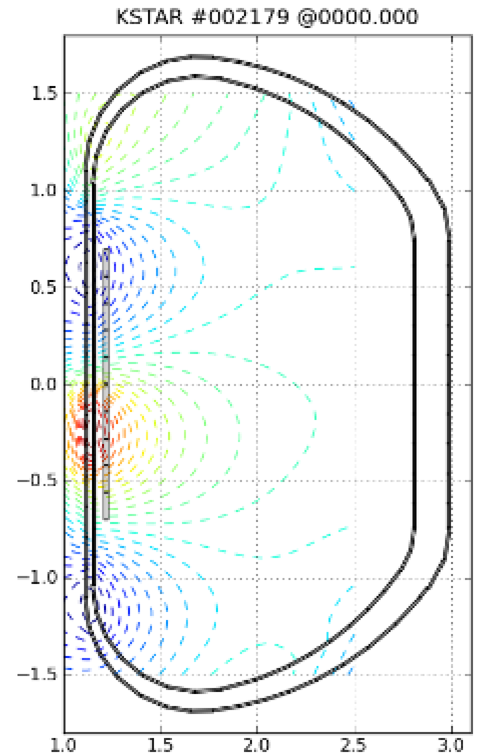
Shot #2178

I_tf(kA)	20.4
Ip(kA)	250.2
Pulse > 0.1kA(msec)	3569.1
Ne(e19/m^2)	2.1
Te(eV)	0.0
Pressure(mbar)	1.6E-5
ECH_P(kW)	257.3



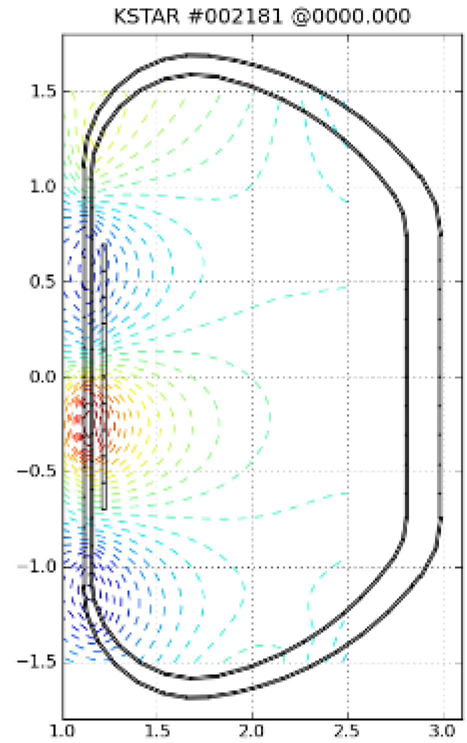
Shot #2179

I_tf(kA)	20.4
Ip(kA)	258.8
Pulse > 0.1kA(msec)	3296.0
Ne(e19/m^2)	4.1
Te(eV)	0.0
Pressure(mbar)	1.6E-5
ECH_P(kW)	256.9



Shot #2181

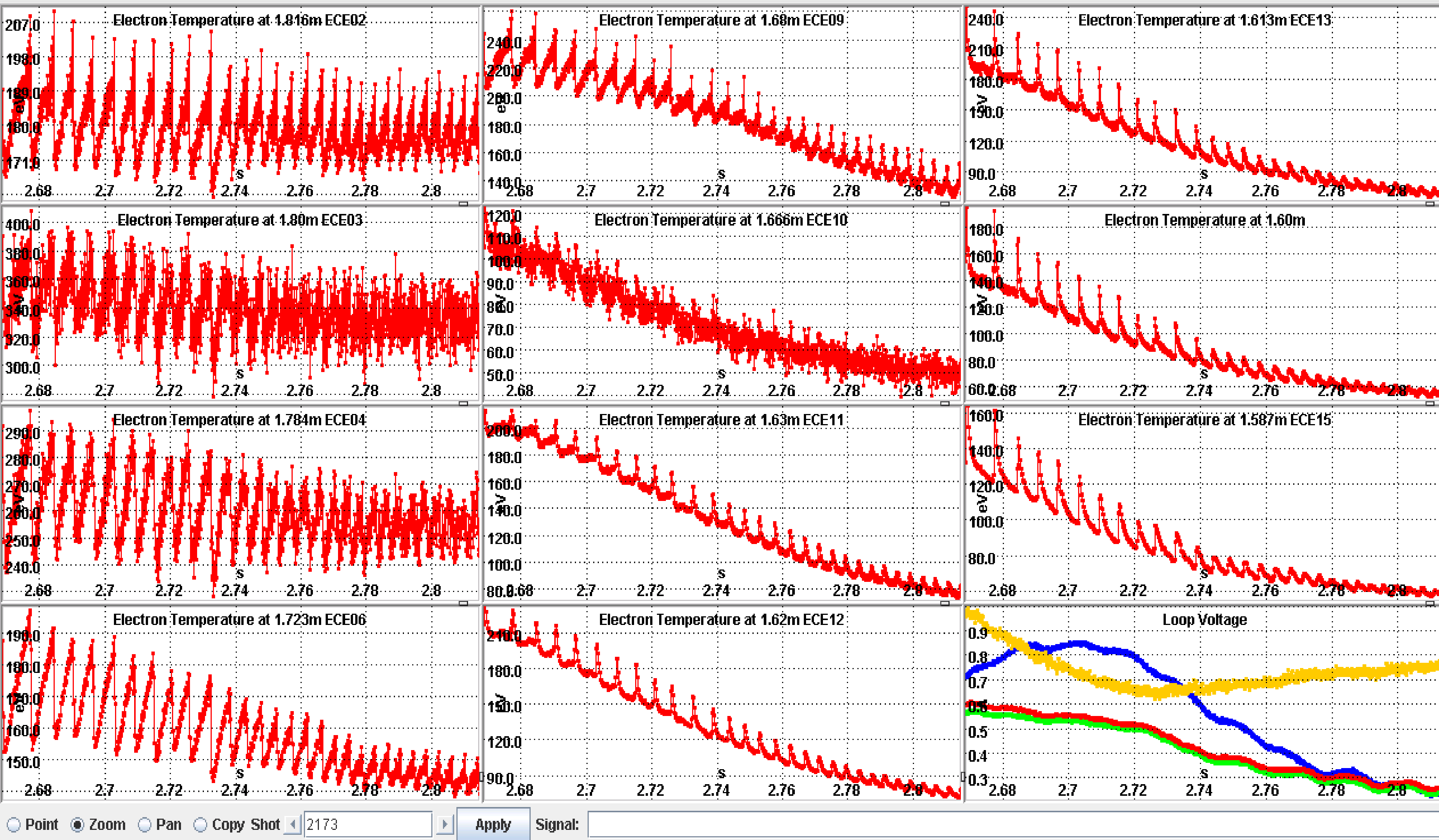
I_tf(kA)	20.4
Ip(kA)	250.1
Pulse > 0.1kA(msec)	3761.1
Ne(e19/m^2)	1.8
Te(eV)	0.0
Pressure(mbar)	1.7E-5
ECH_P(kW)	256.6



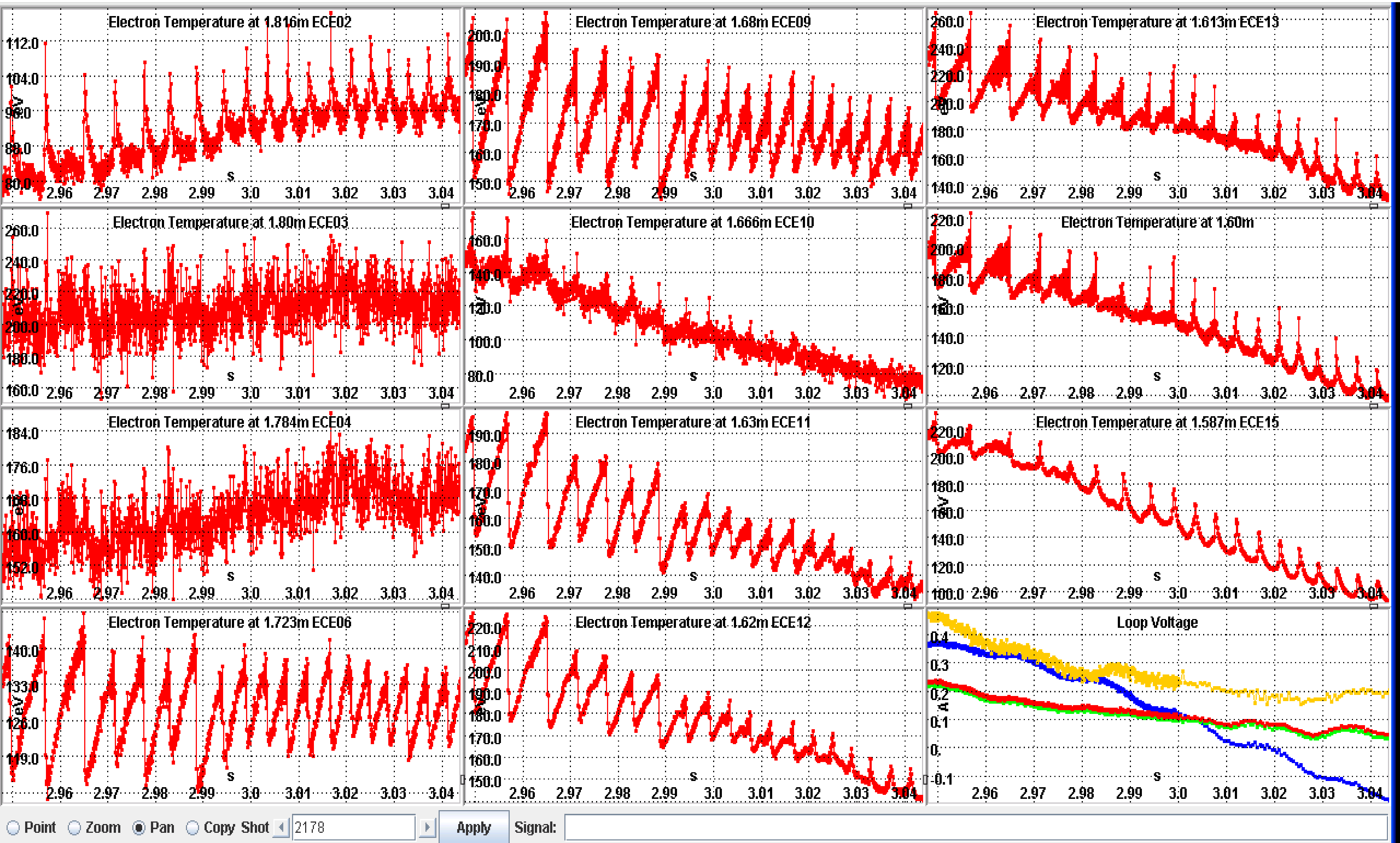
ECE channels with corresponding frequencies and spatial positions

ECE ch	f (GHz)		B=3T R (cm)	B=3T r (cm)		B=2T R (cm)	B=2T r (cm)	
ECE01	110		274.9	94.9		183.3	3.3	
ECE02	111		272.4	92.4		181.6	1.6	
ECE03	112		270.0	90.0		180.0	0.0	← Magnetic Axis
ECE04	113		267.6	87.6		178.4	-1.6	
ECE05	115		263.0	83.0		175.3	-4.7	
ECE06	117		258.5	78.5		172.3	-7.7	
ECE07	118		256.3	76.3		170.8	-9.2	
ECE08	119		254.1	74.1		169.4	-10.6	
ECE09	120		252.0	72.0		168.0	-12.0	
ECE10	121		249.9	69.9		166.6	-13.4	
ECE11	123		245.9	65.9		163.9	-16.1	
ECE12	124		243.9	63.9		162.6	-17.4	
ECE13	125		241.9	61.9		161.3	-18.7	
ECE14	126		240.0	60.0		160.0	-20.0	
ECE15	127		238.1	58.1		158.7	-21.3	
ECE16	128		236.3	56.3		157.5	-22.5	
ECE17	129		234.4	54.4		156.3	-23.7	
ECE18	130		232.6	52.6		155.1	-24.9	
ECE19	131		230.8	50.8		153.9	-26.1	
ECE20	132		229.1	49.1		152.7	-27.3	

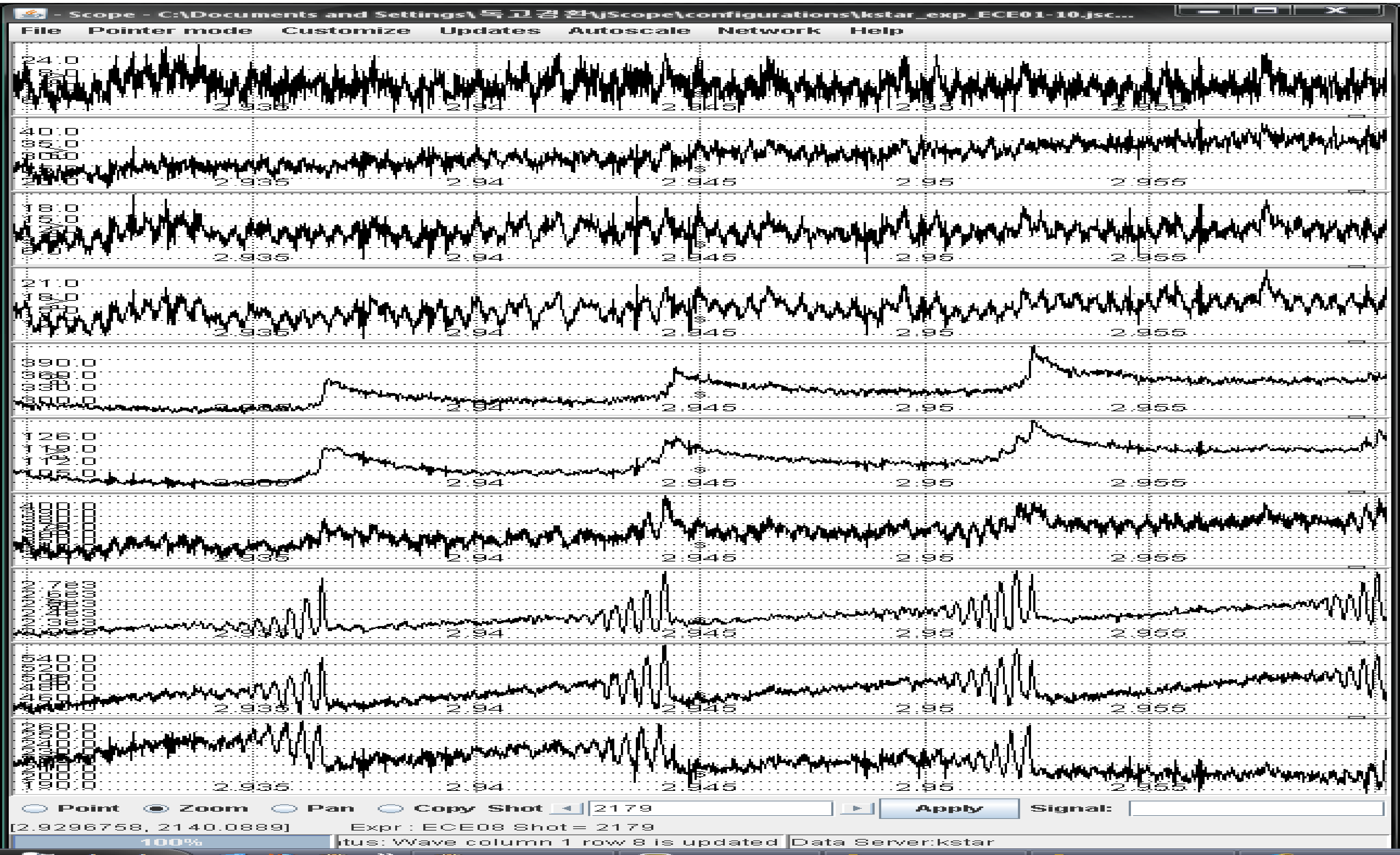
Shot #2173 ECE data



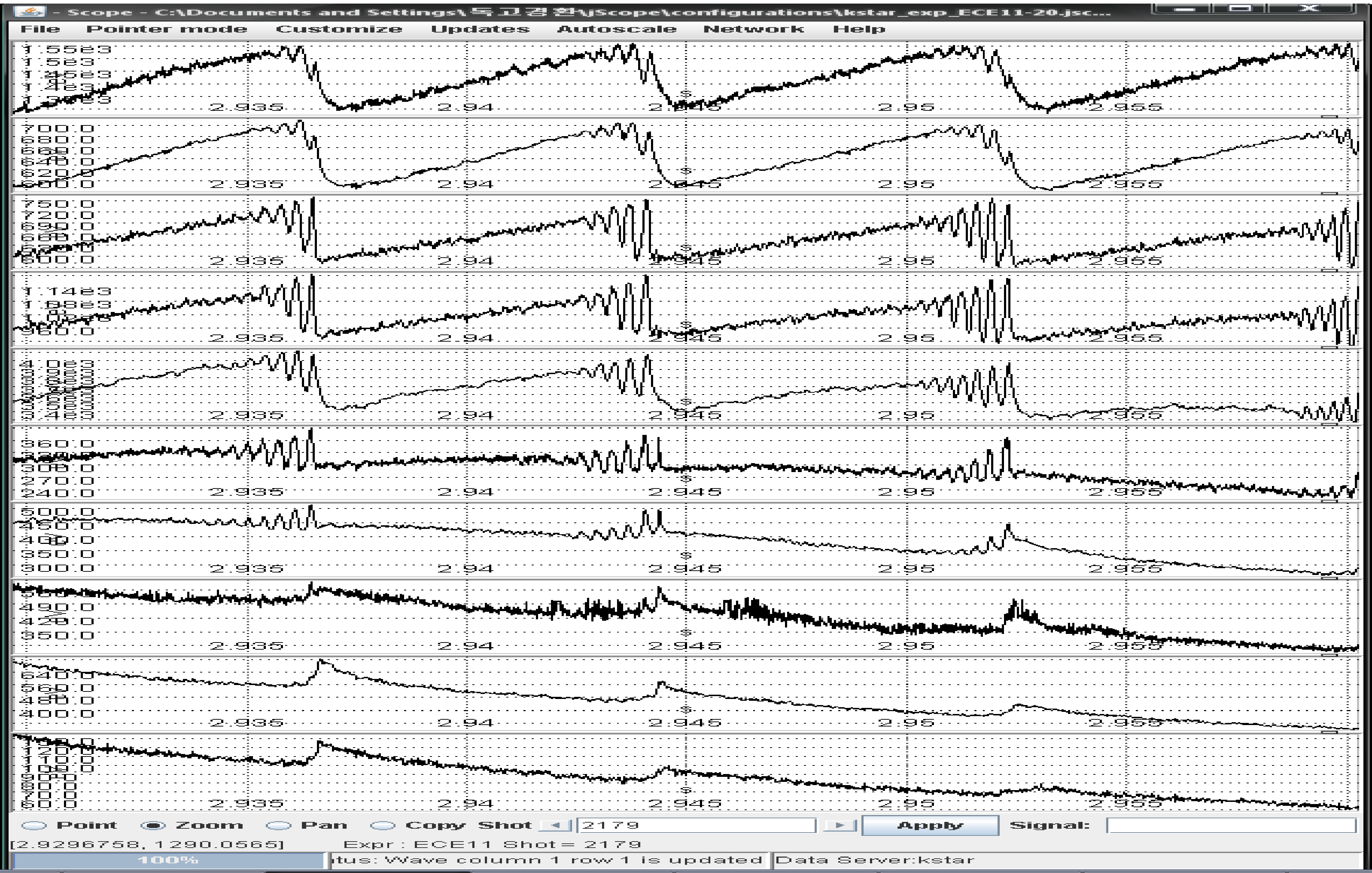
Shot #2178 ECE data



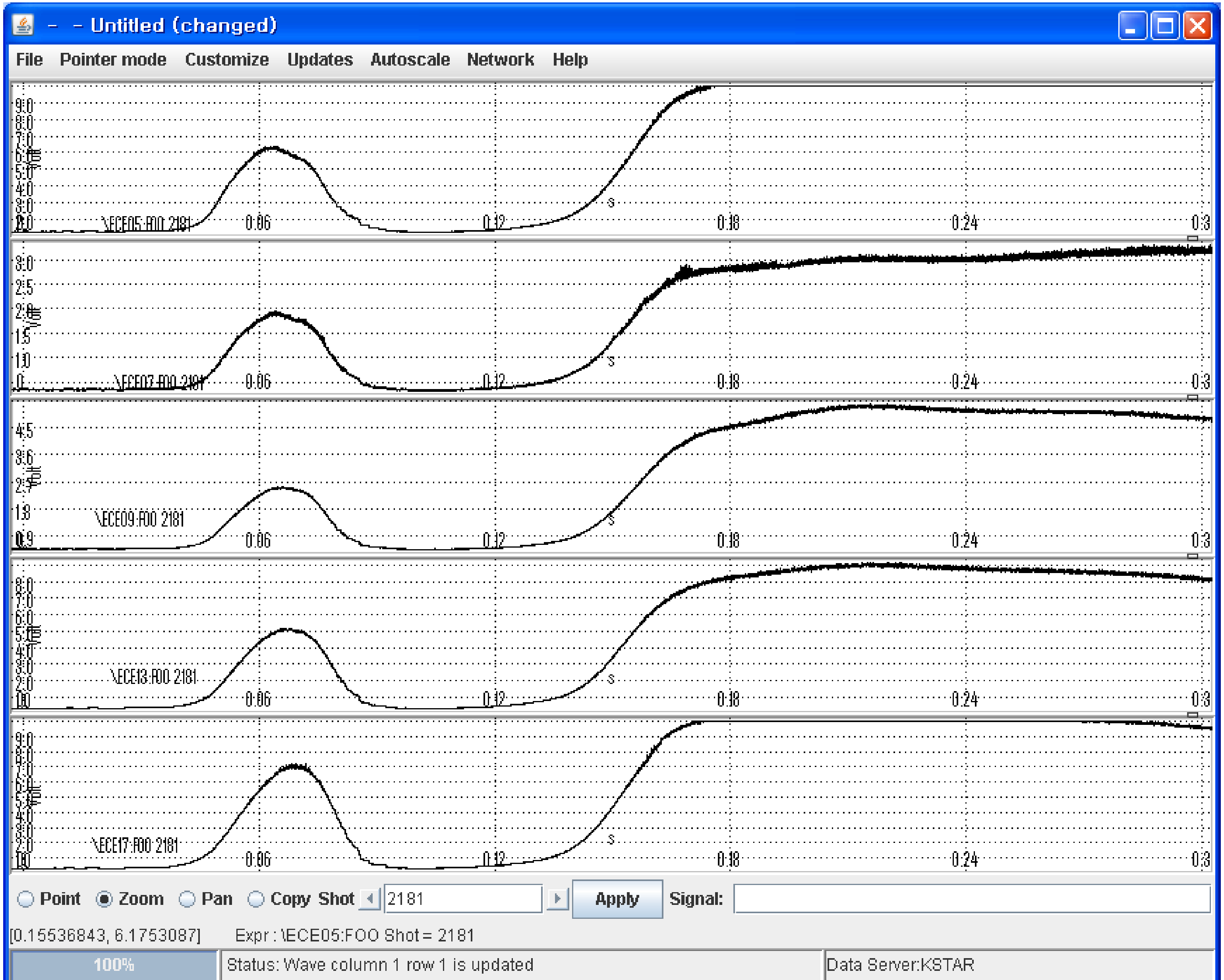
Shot # 2179 ECE channel 1~10



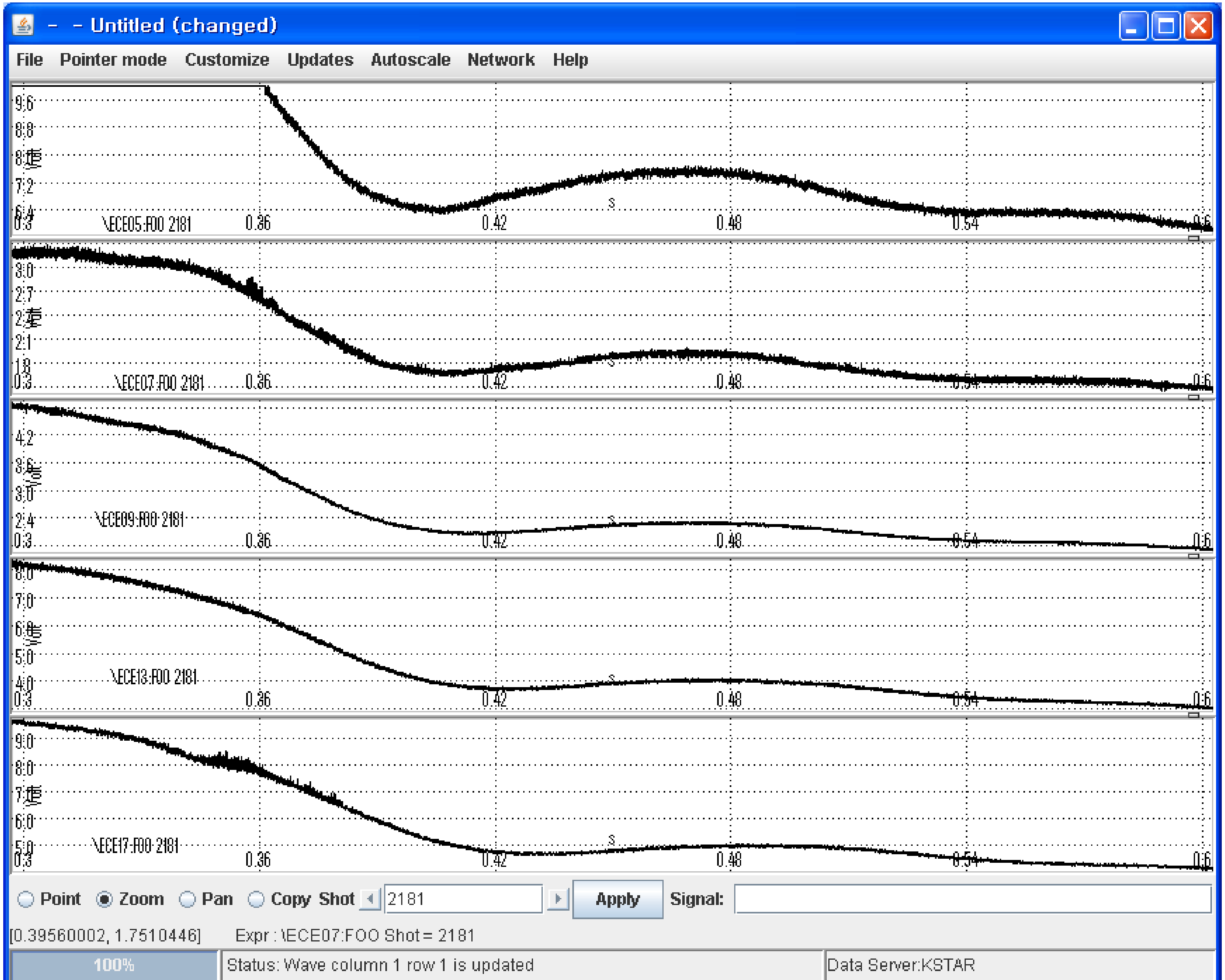
Shot # 2179 ECE channel 10~20



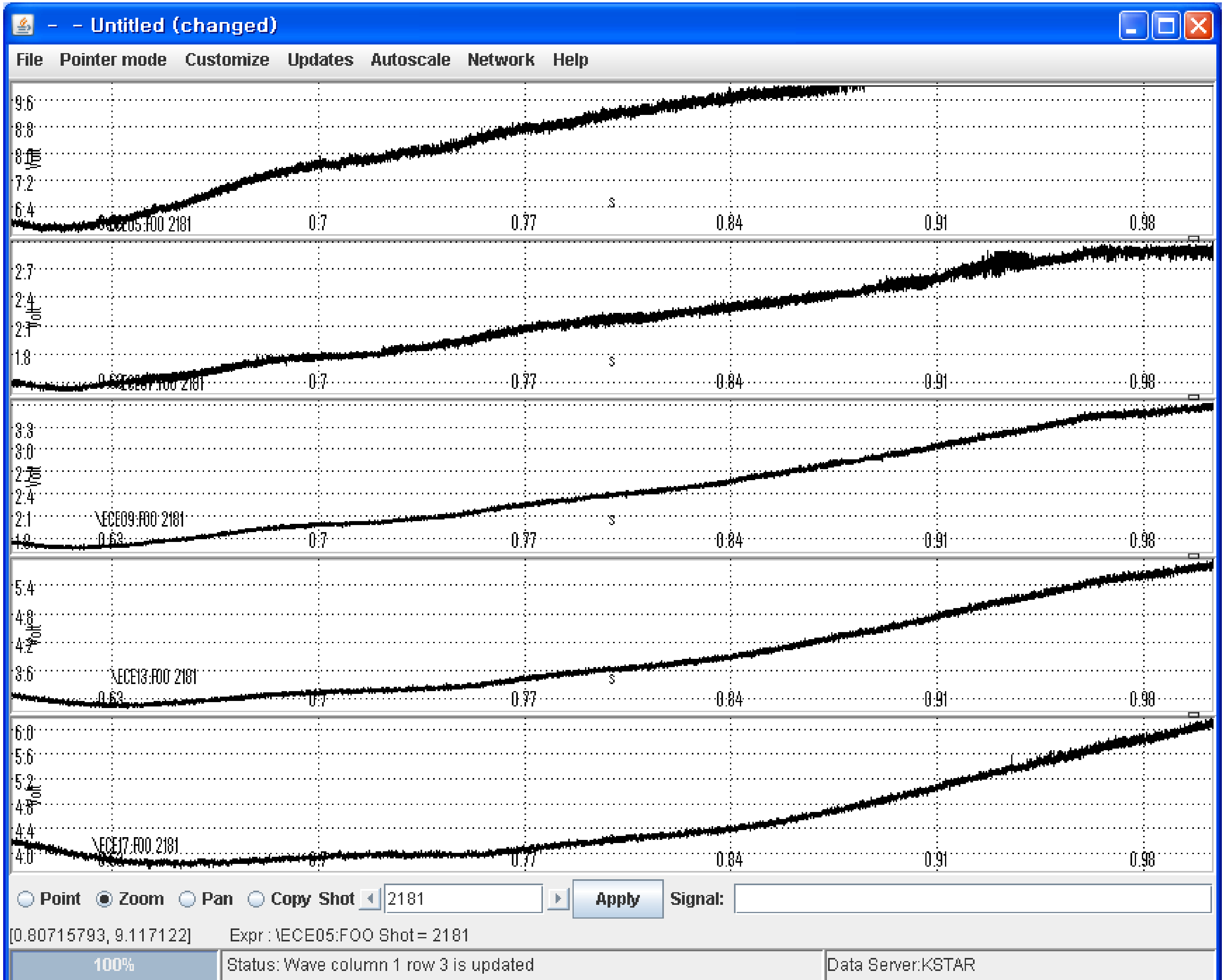
Shot#2181 EC time : 0.0 ~ 0.3s



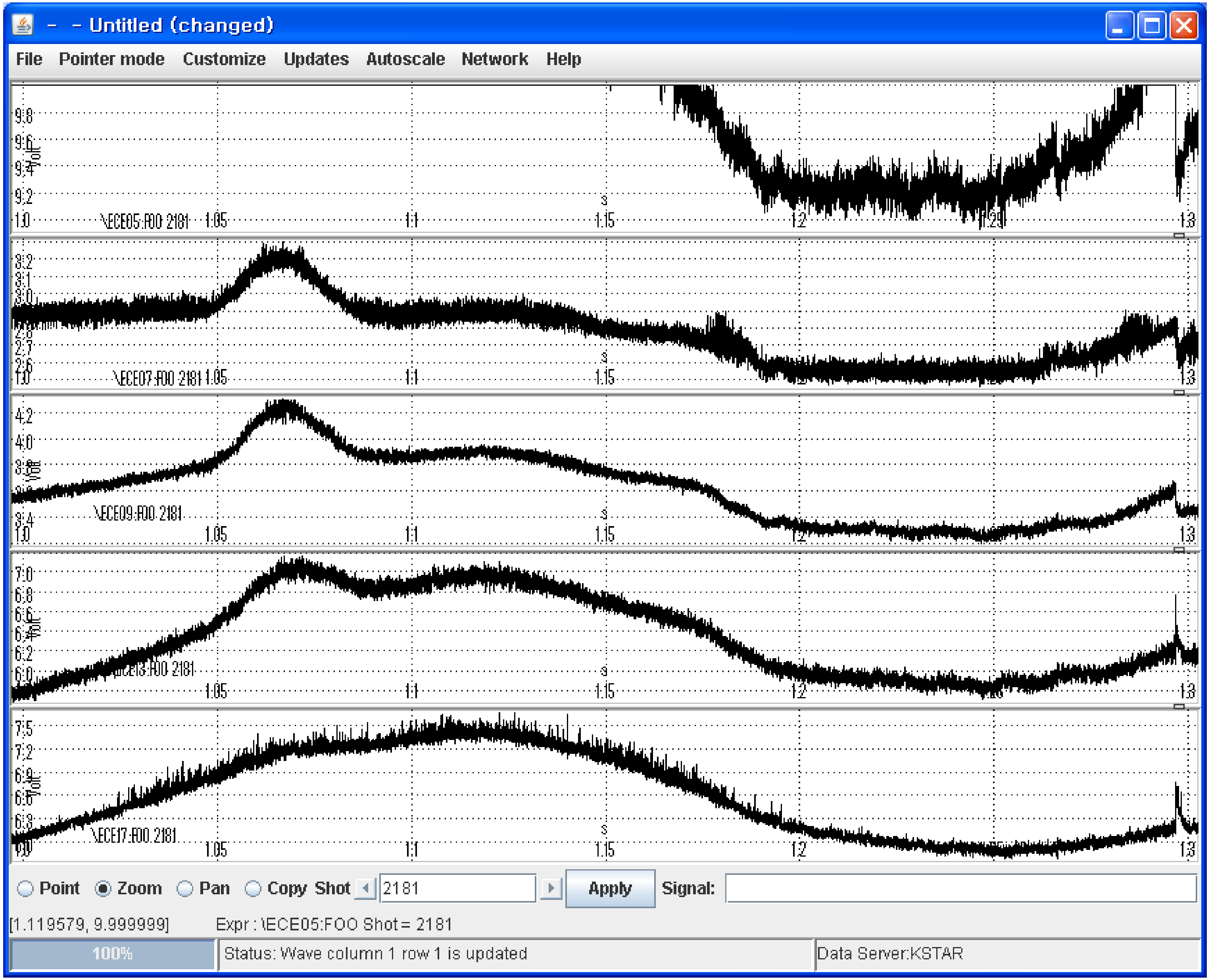
Shot#2181 time : 0.3 ~ 0.6s



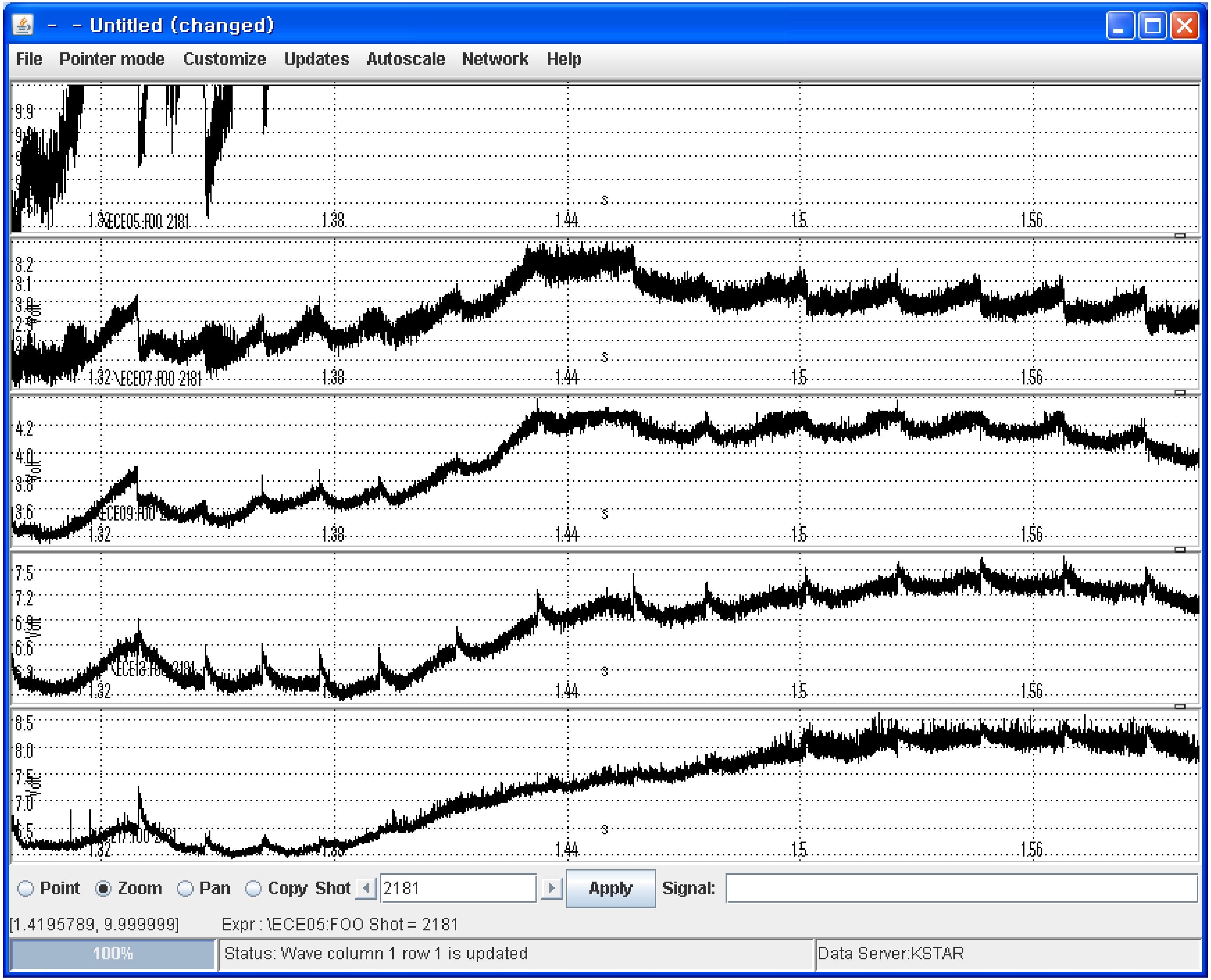
Shot#2181 time : 0.6 ~ 1.0s



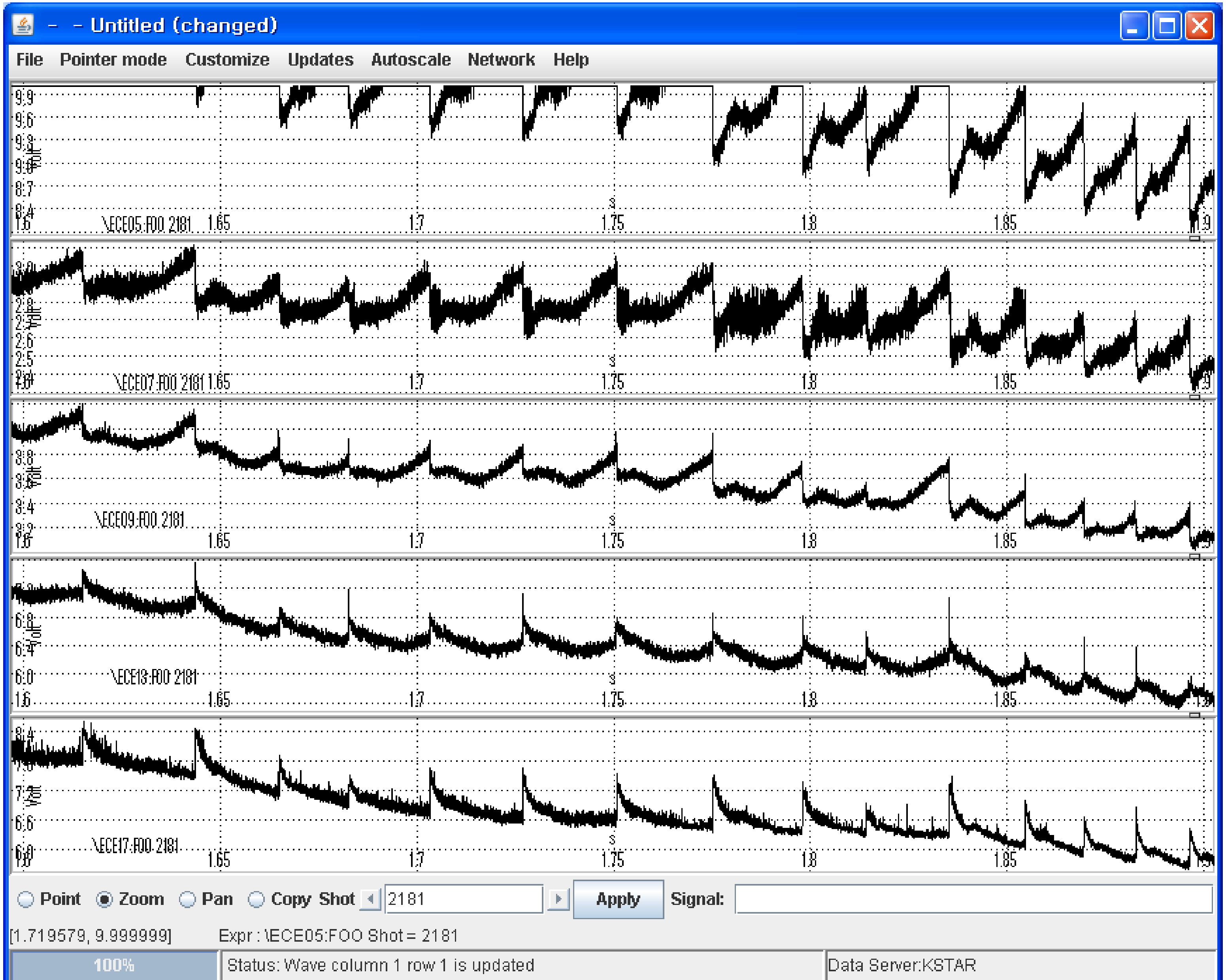
Shot#2181 time : 1.0 ~ 1.3s



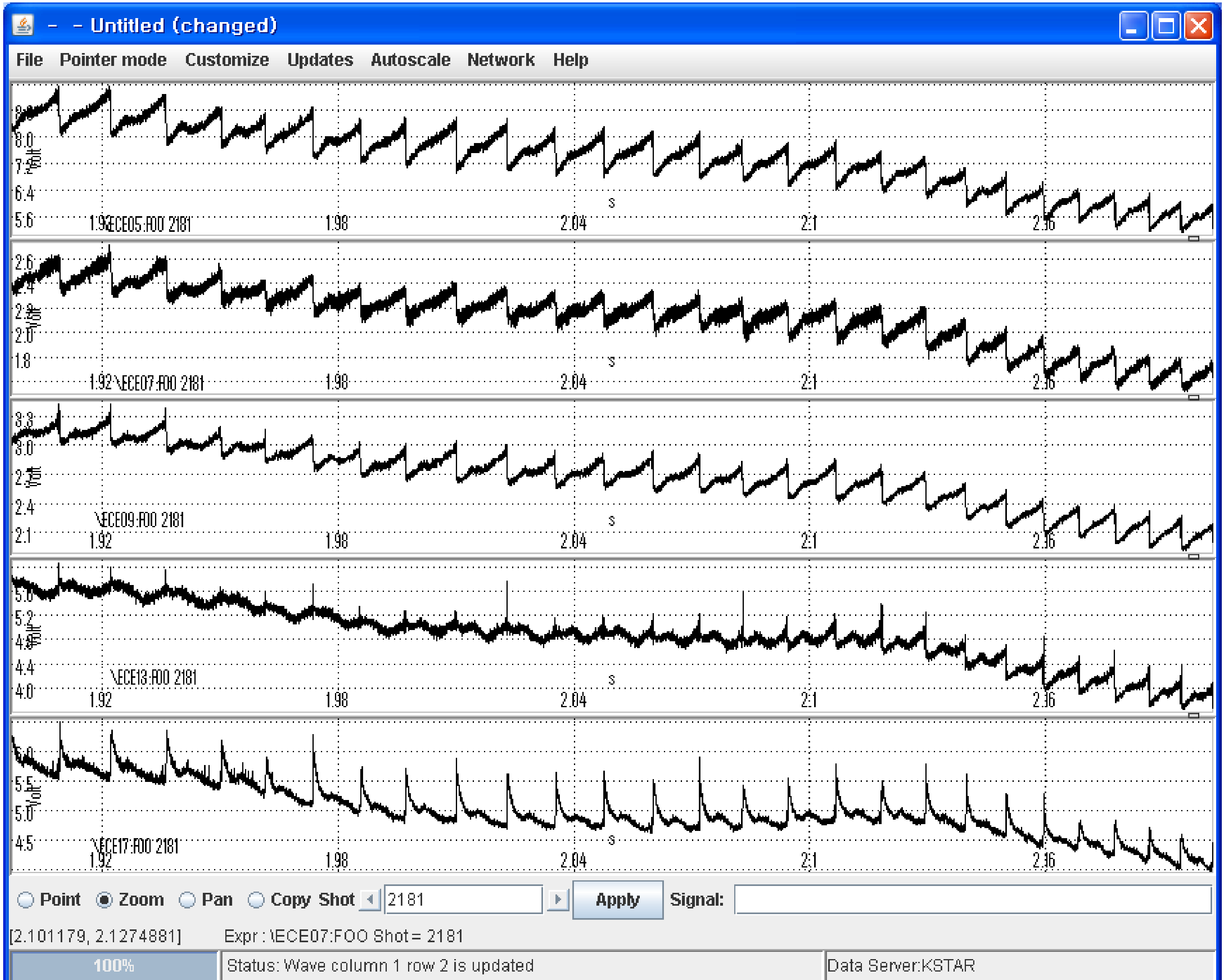
Shot#2181 time : 1.3 ~ 1.6s



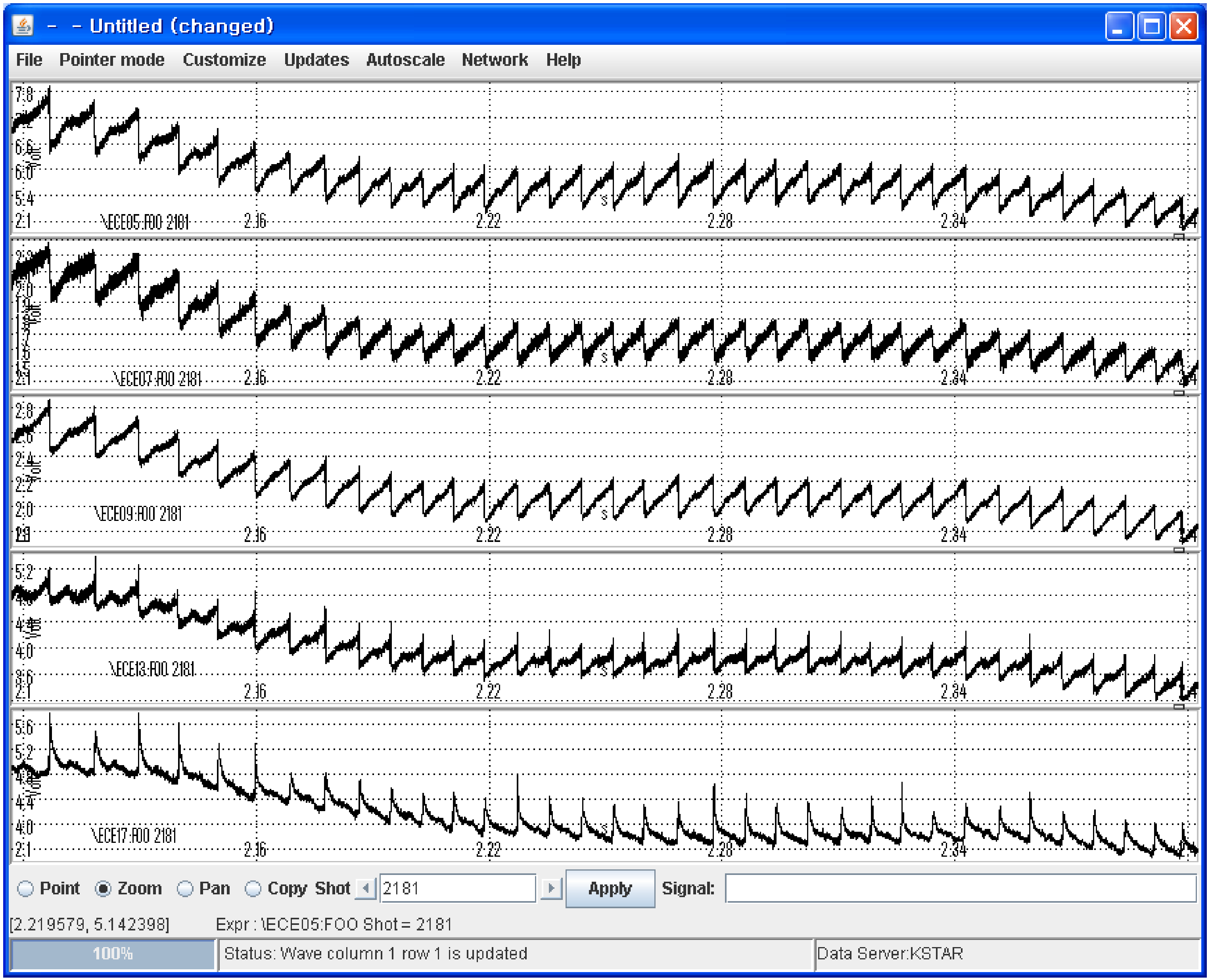
Shot#2181 time : 1.6 ~ 1.9s



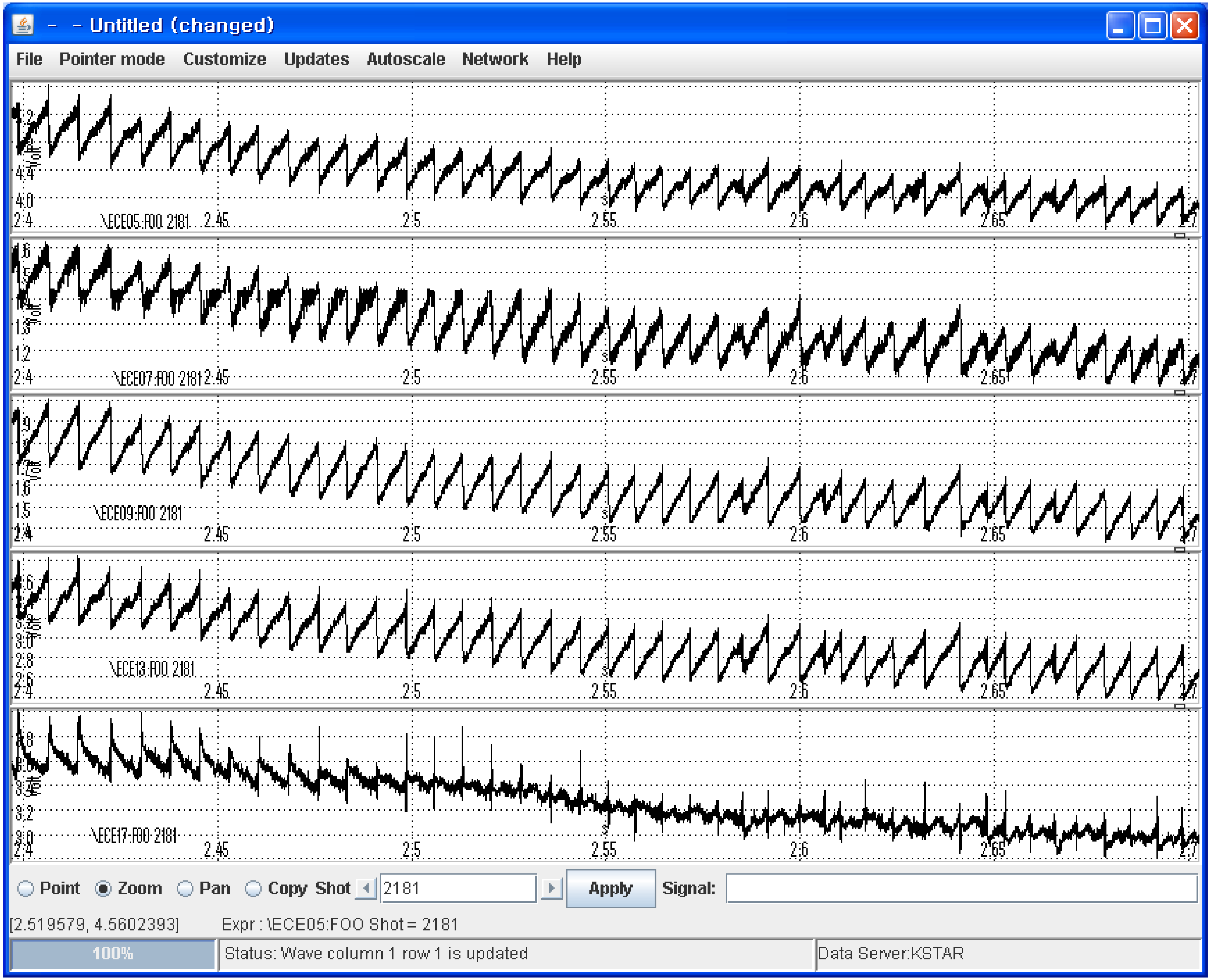
Shot#2181 time : 1.9 ~ 2.1s



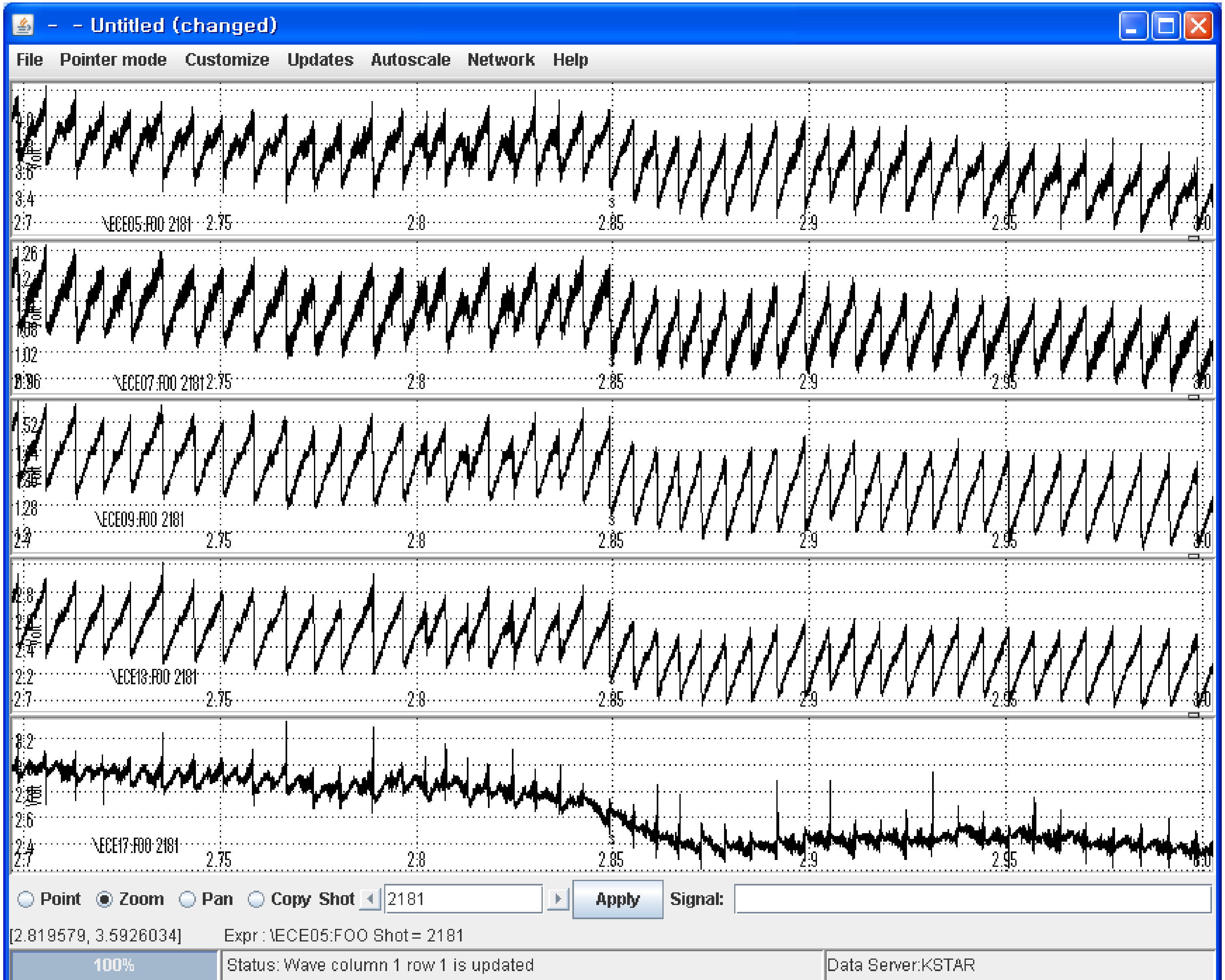
Shot#2181 time : 2.1 ~ 2.4s



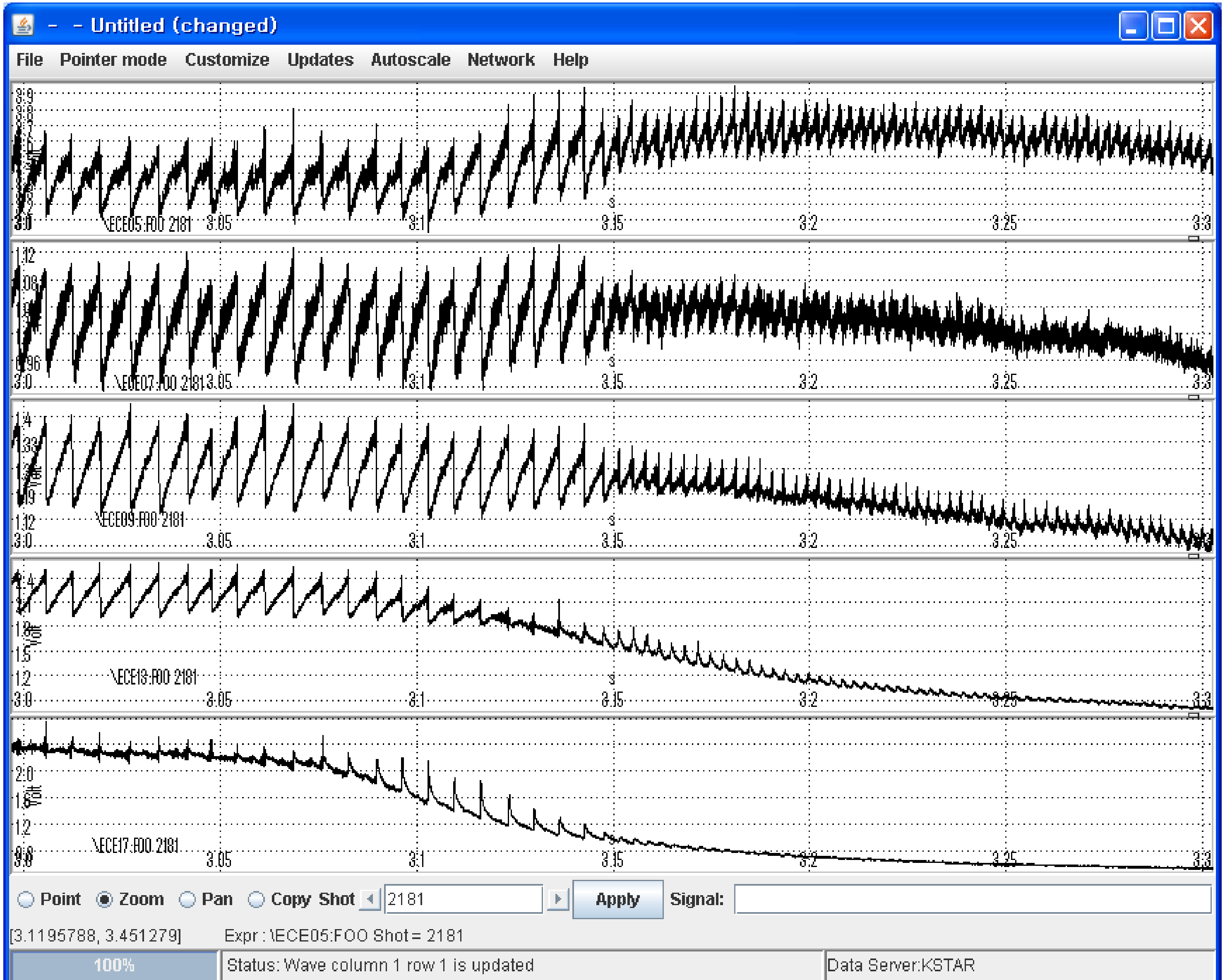
Shot#2181 time : 2.4 ~ 2.7s



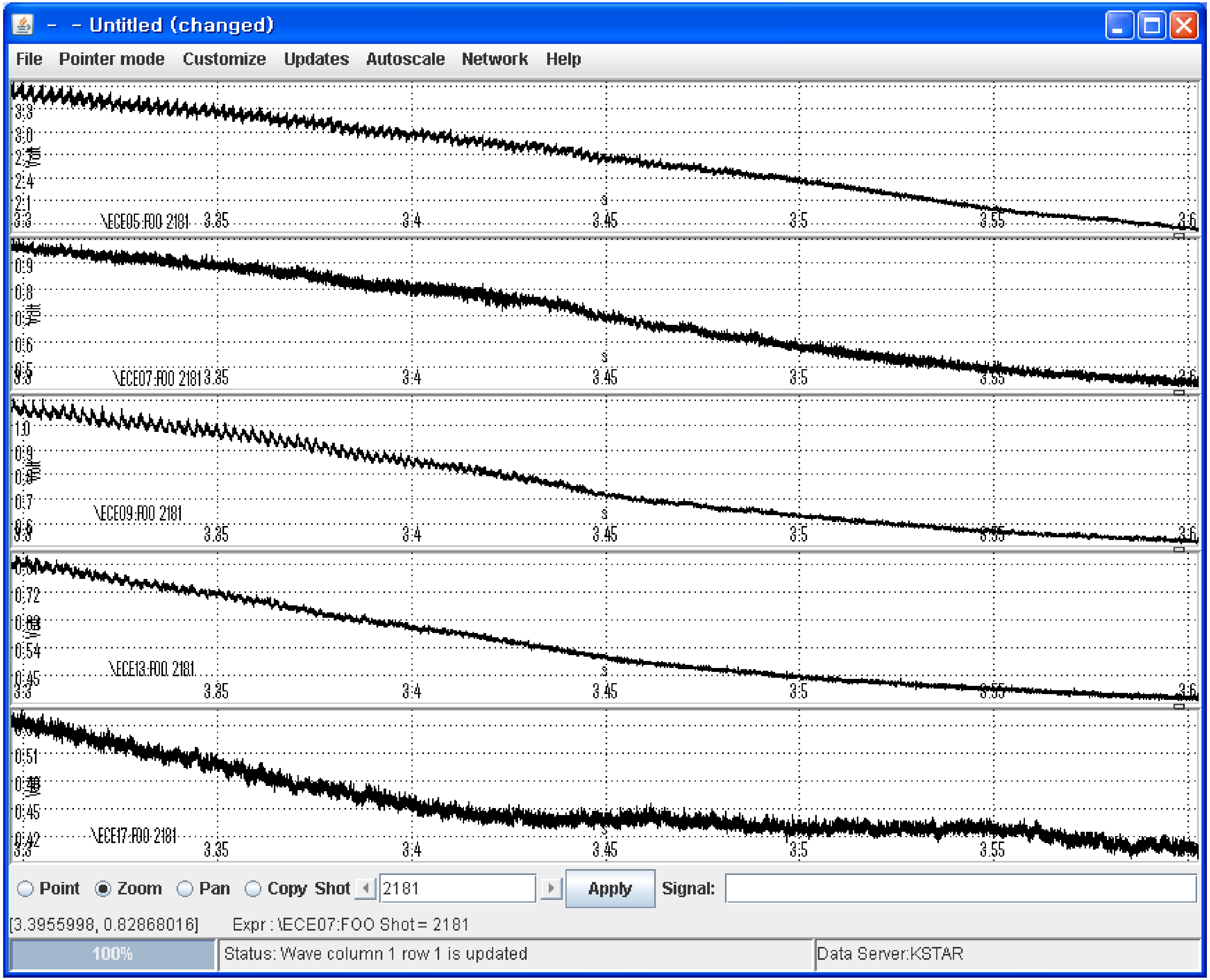
Shot#2181 time : 2.7 ~ 3.0s



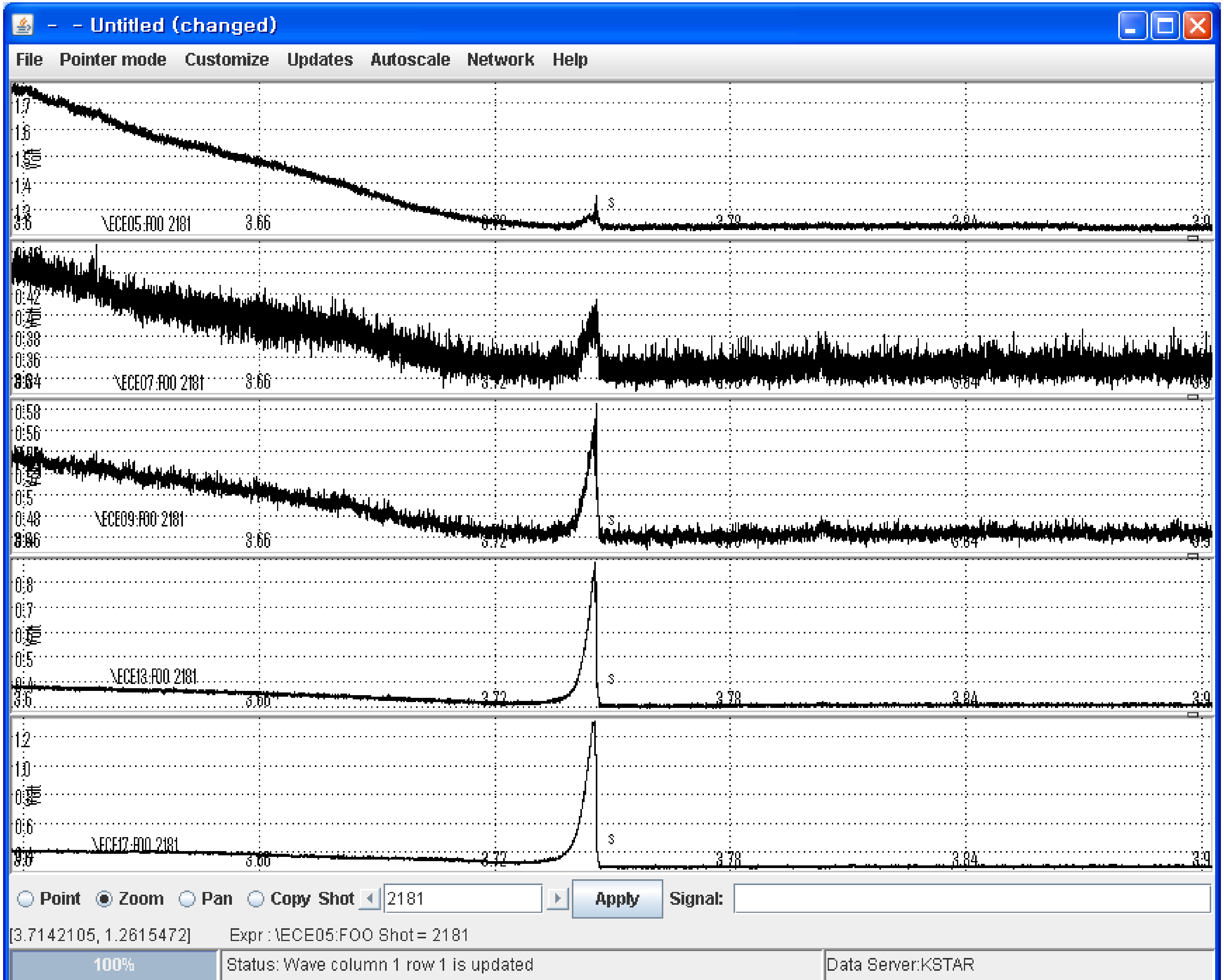
Shot#2181 time : 3.0 ~ 3.3s



Shot#2181 time : 3.3 ~ 3.6s



Shot#2181 time : 3.6 ~ 3.9s



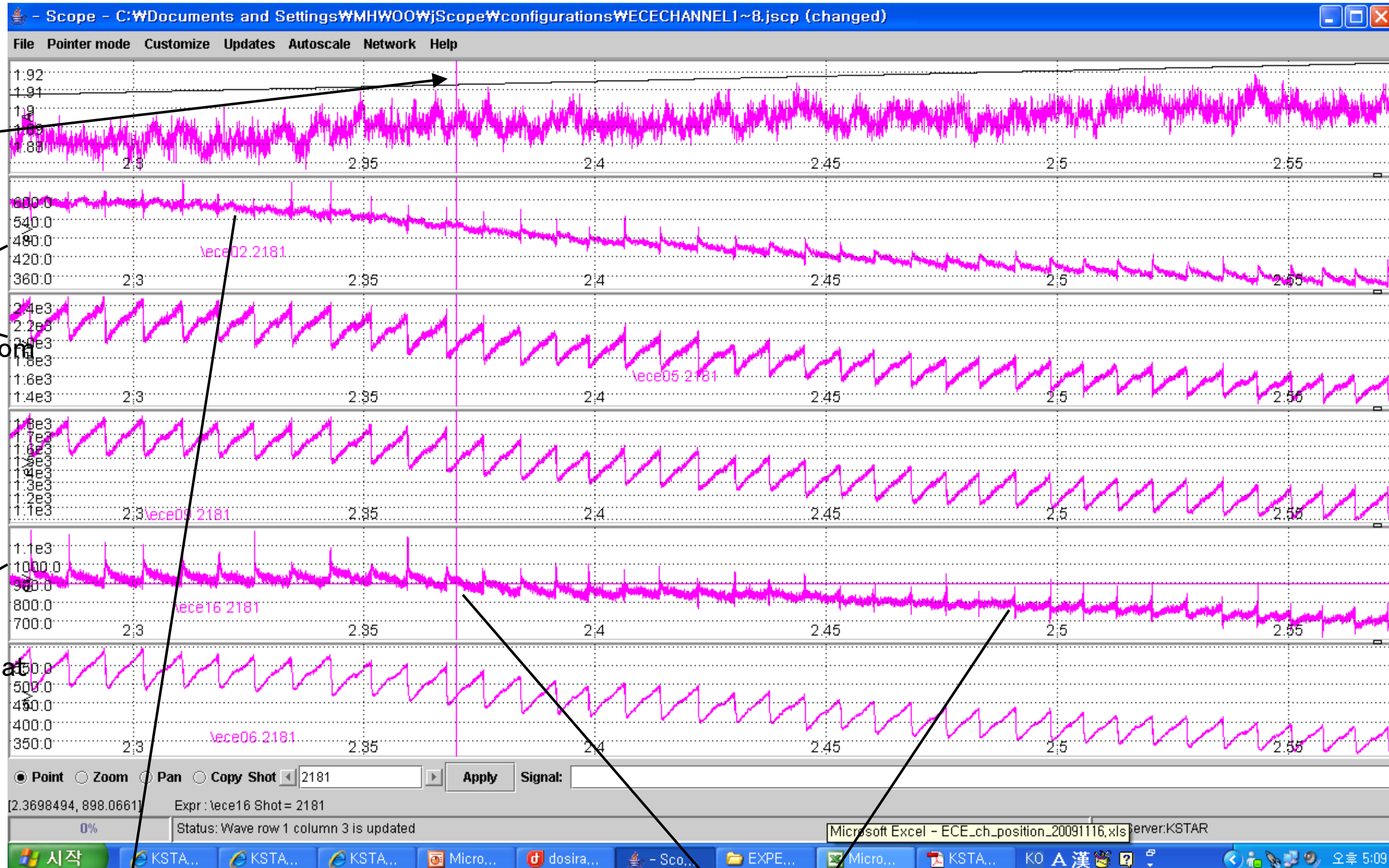
Experimental Result: shot #2181

ECE Data

Radial position at R=1.9m

Chanel phase inversion from ¥ece02 to ¥ece05

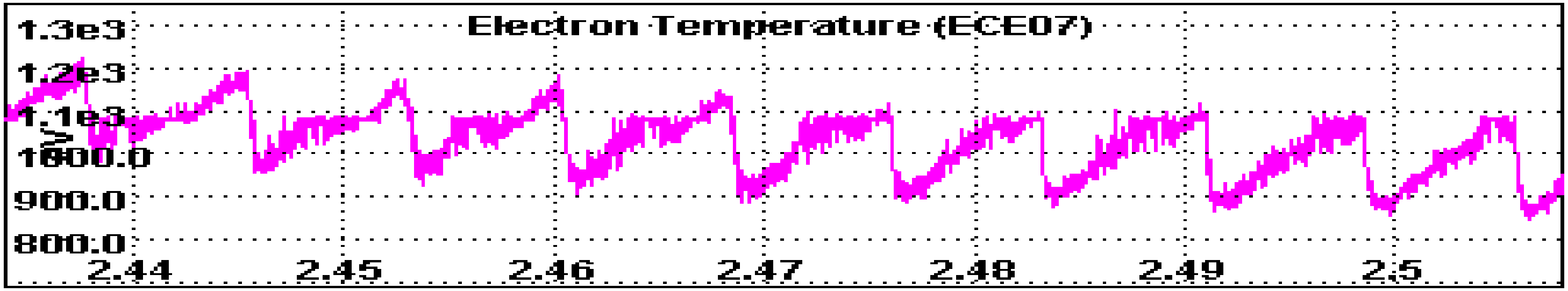
An other phase inversion at ¥ece16



Phase inversion at same chanel they at Exactly at q=1 surface, plasma is moving From outer to inner side here.

Same phase inversion at this ¥ece02 chanel happened, but not that clear Like ¥ece16 chanel

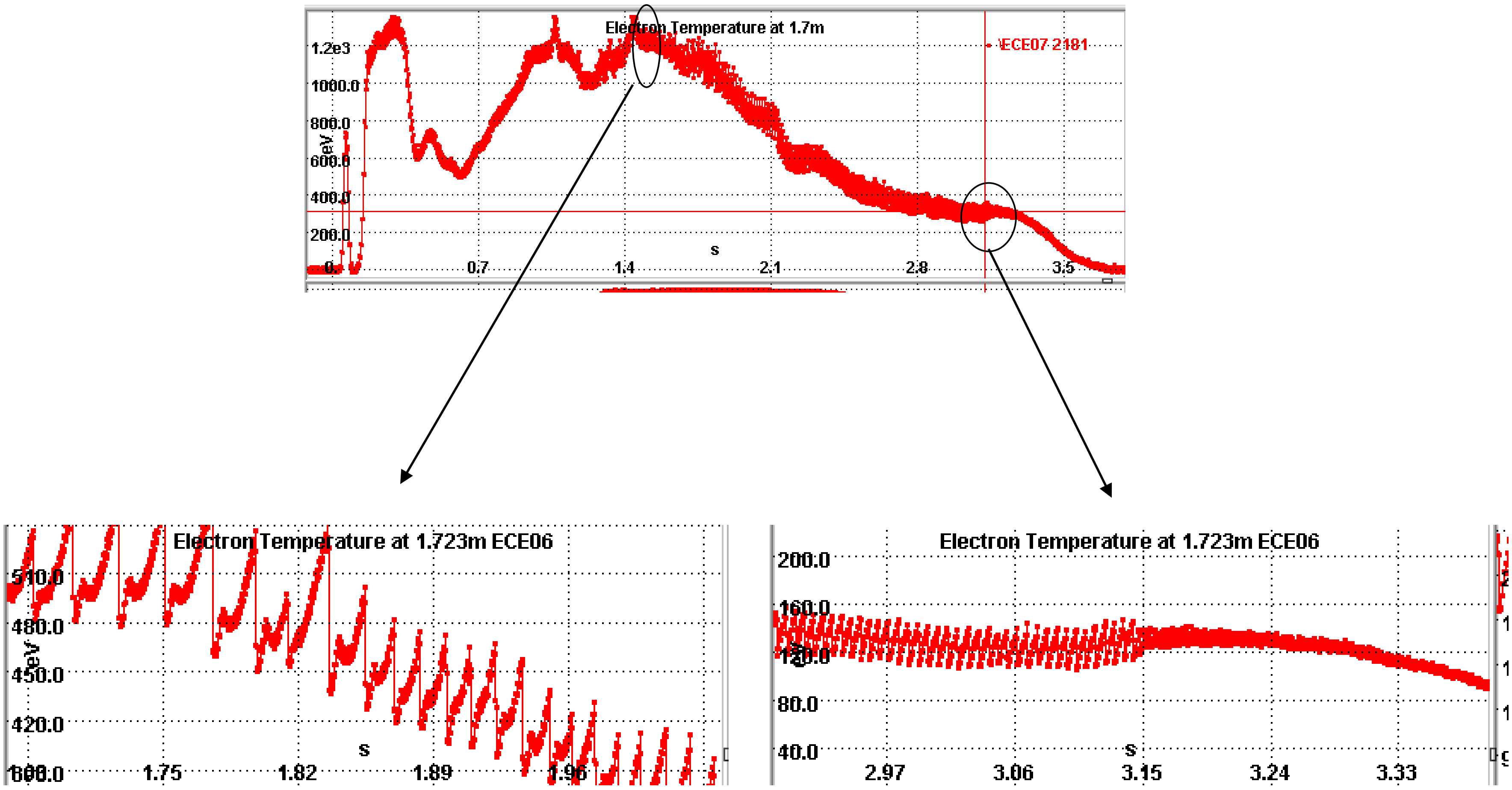
ECE signal at



After 2.45s before sawtooth oscillation there are small fish-bone like
Oscillations occur before sawtooth crash

Different behaviors of sawteeth at diffeentent times

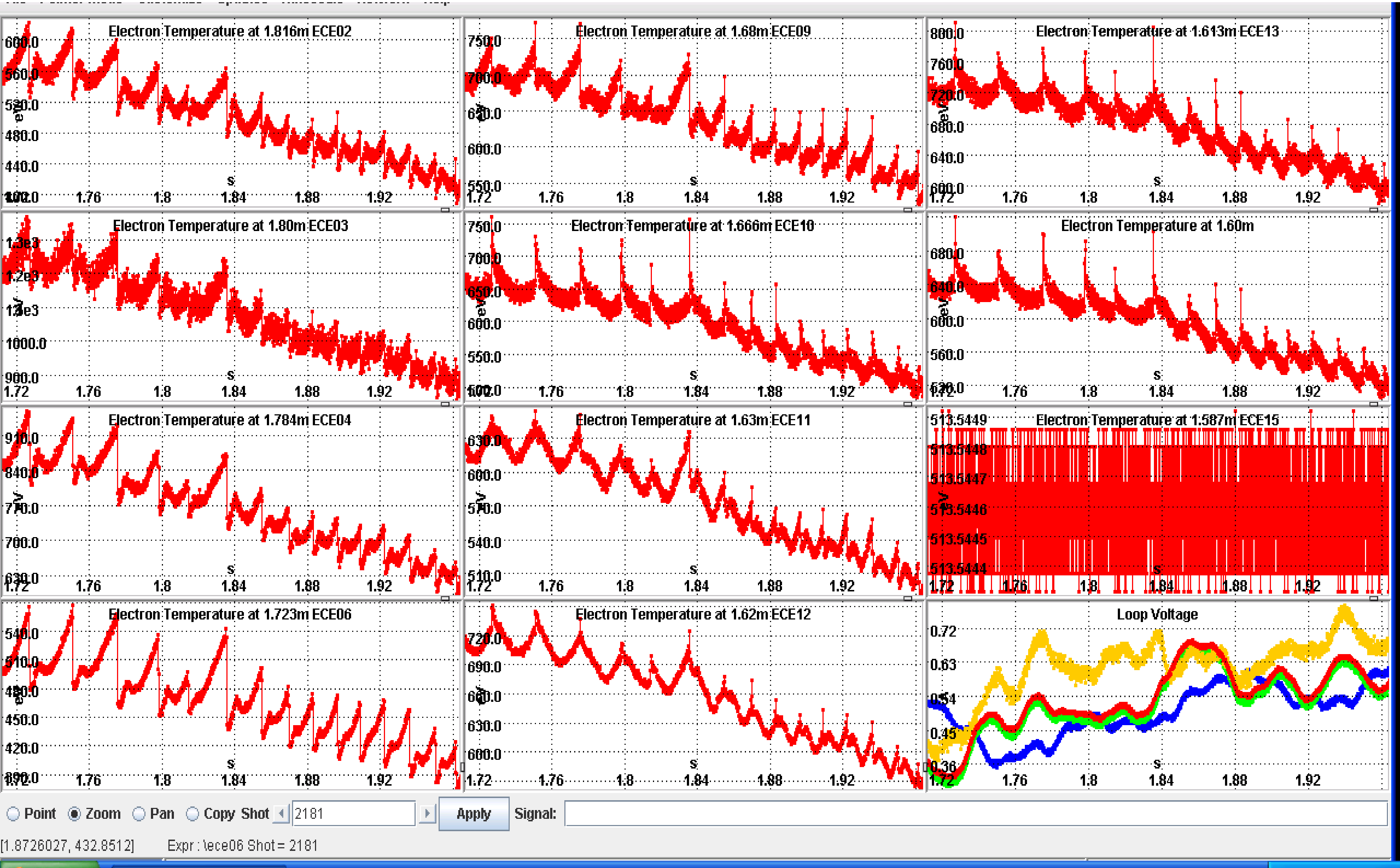
Twice or more than that of period changing in sawtooth occurred in ECE



CASE1

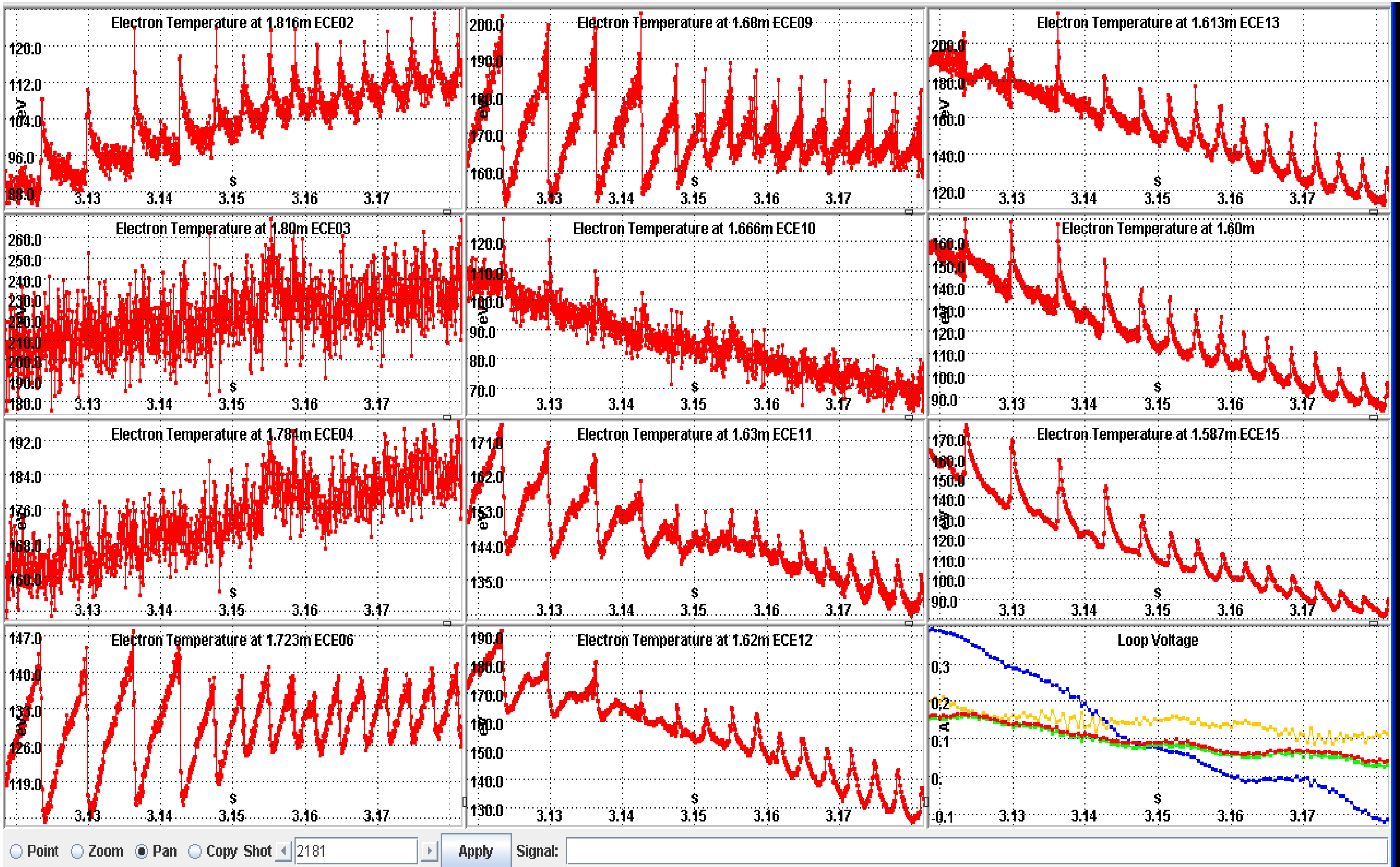
CASE2

CASE1



Electron Temperature at 1.816m ECE02
Electron Temperature at 1.68m ECE09
Electron Temperature at 1.613m ECE13
Electron Temperature at 1.80m ECE03
Electron Temperature at 1.666m ECE10
Electron Temperature at 1.60m
Electron Temperature at 1.784m ECE04
Electron Temperature at 1.63m ECE11
Electron Temperature at 1.587m ECE15
Electron Temperature at 1.723m ECE06
Electron Temperature at 1.62m ECE12
Loop Voltage
1.72 1.76 1.8 1.84 1.88 1.92
s
Point Zoom Pan Copy Shot 2181 Apply Signal:
[1.8726027, 432.8512] Expr : \ece06 Shot = 2181

CASE2 Shot#2181

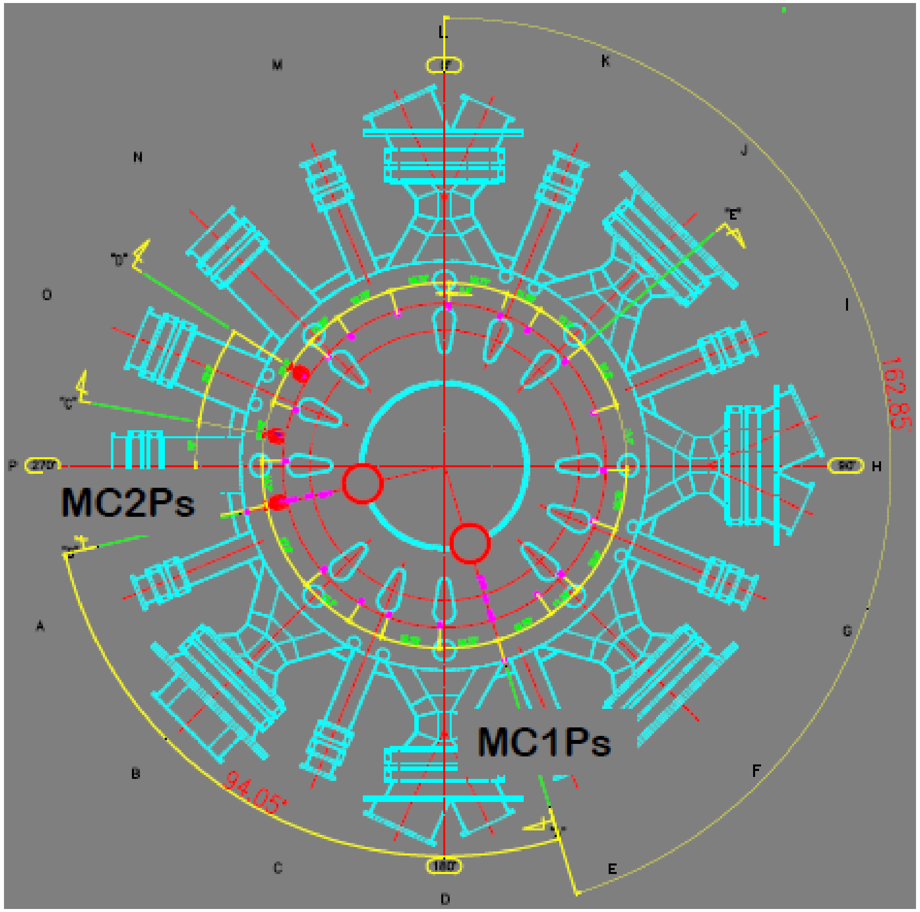


Sensors to measure magnetic fluctuations

Table 1. MD sensors in the KSTAR machine.

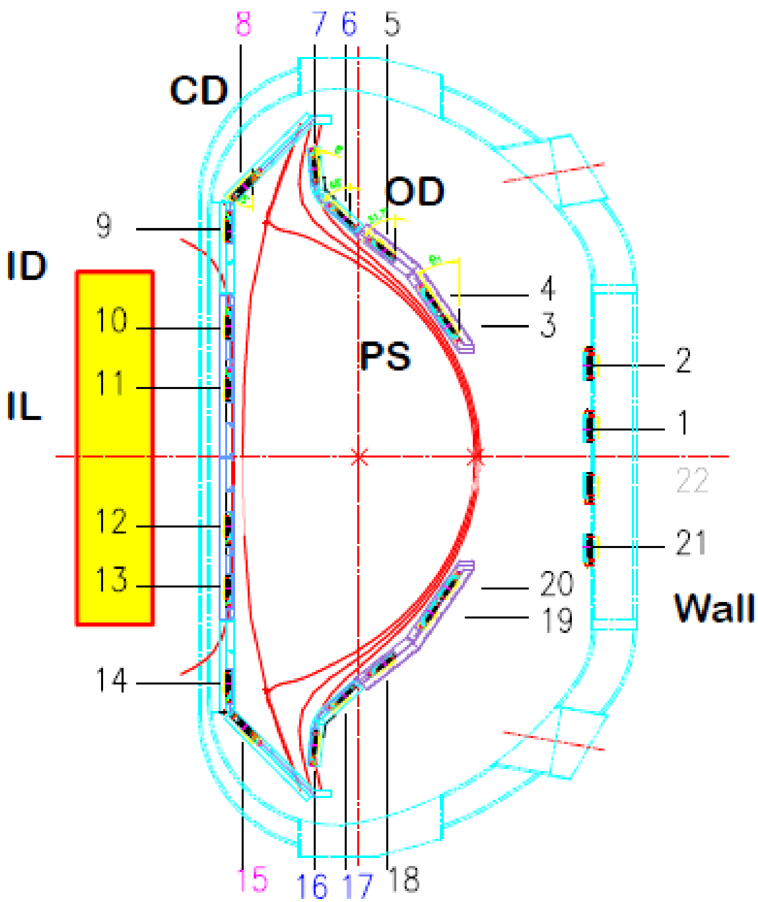
Magnetic sensors	Number	Magnetic sensors	Number
Rogowski coils (RCs)	3ea	Mirnov coils (MCs)	8ea (+ 37ea)
Flux loops (FLs)	45ea	Diamagnetic loops (DLs)	8ea
Magnetic field probes (MPs)	244ea	Vessel current monitors (VCMs)	3ea
Lock mode coils (LMs)	4ea	Halo current monitors (HCMs)	16ea (+32ea)
Saddle loops (SLs)	40ea		

Layout of Mirnov coils– toroial view



IL : inboard limiter
ID : inboard divertor
CD : central divertor
OD : outboard divertor
PS : passive stabilizer
PL : poloidal limiter

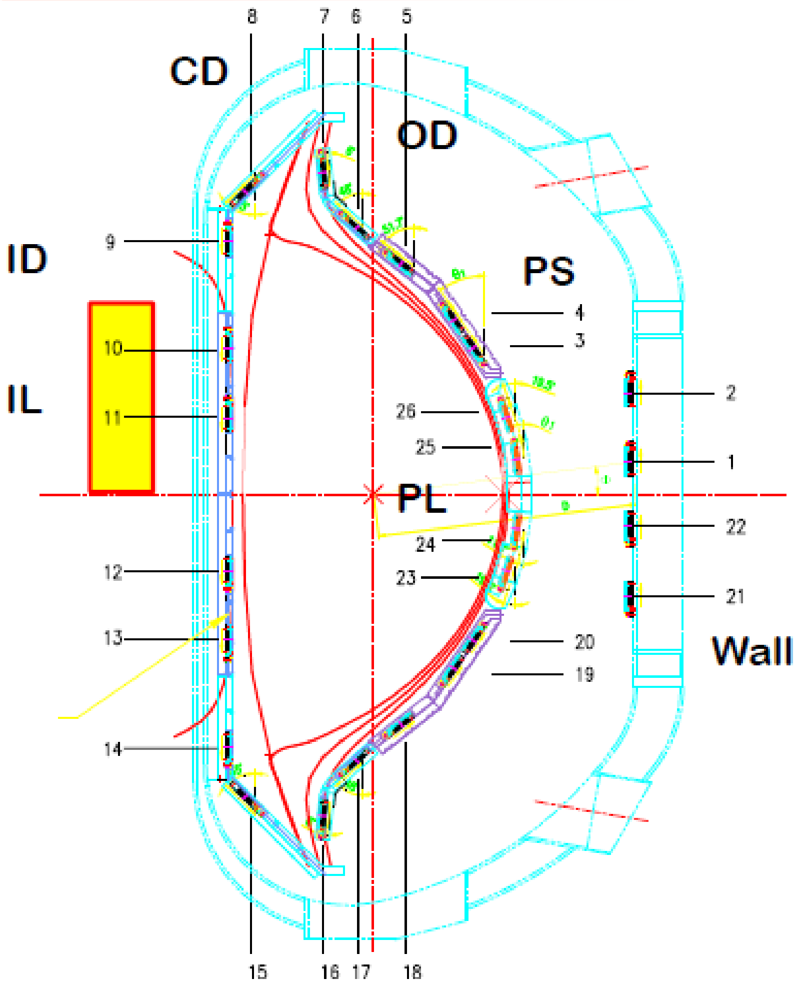
Four channels poloidally located at MC1P



MC1P10 – MC1P13

	No.	Z(mm)	R(mm)	ϕ (deg)
WALL	1(22)	121.4(–)	2780.5	162.8°
	2(21)	389.3(–)	2780.5	
P.S	3(20)	560.4(–)	2182.9	162.8°
	4(19)	680.1(–)	2099.9	
	5(18)	883.6(–)	1905.6	
O.D	6(17)	1023.1(–)	1731.9	163.2°
	7(16)	1235.5(–)	1605.3	
C.D	8(15)	1160.2(–)	1308.3	162°
I.D	9(14)	970.8(–)	1240.5	163.1°
I.L	10(13)	561.5(–)	1240.5	163.2°
	11(12)	294.5(–)	1240.5	

Two channels poloidally located at MC2P



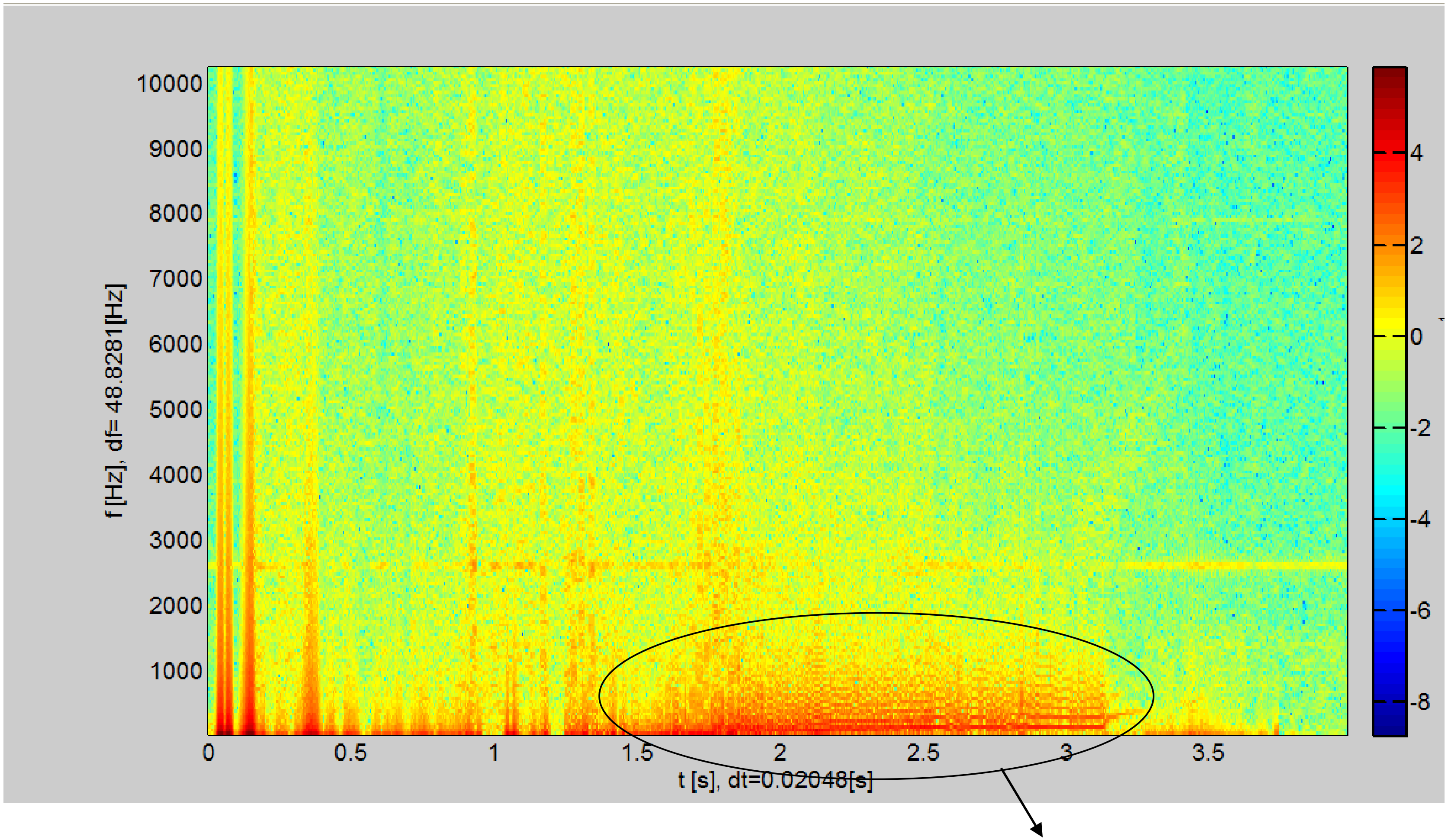
MC2P10 – MC2P11

	No.	Z(mm)	R(mm)	ϕ (deg)
WALL	1(22)	121.4(−)	2780.5.	253.9°
	2(21)	389.3(−)	2780.5.	
P.S	3(20)	560.4(−)	2182.9	257.3°
	4(19)	680.1(−)	2099.9	
	5(18)	883.6(−)	1905.6	
O.D	6(17)	1041.8(−)	1711.1	253.2°
	7(16)	1227.2(−)	1606.2	
C.D	8(15)	1183.5(−)	1331.7	256.6°
I.D	9(14)	970.8(−)	1240.5	258.7°
I.L	10(13)	561.5(−)	1240.5	258.8°
	11(12)	294.5(−)	1240.5	
P.L_1	23(26)	180.1(−)	2341.2	257.5°
	24(25)	316.3(−)	2304.1	

Spectogram Analysis
of ECE and Mirnov coil data of KSTAR

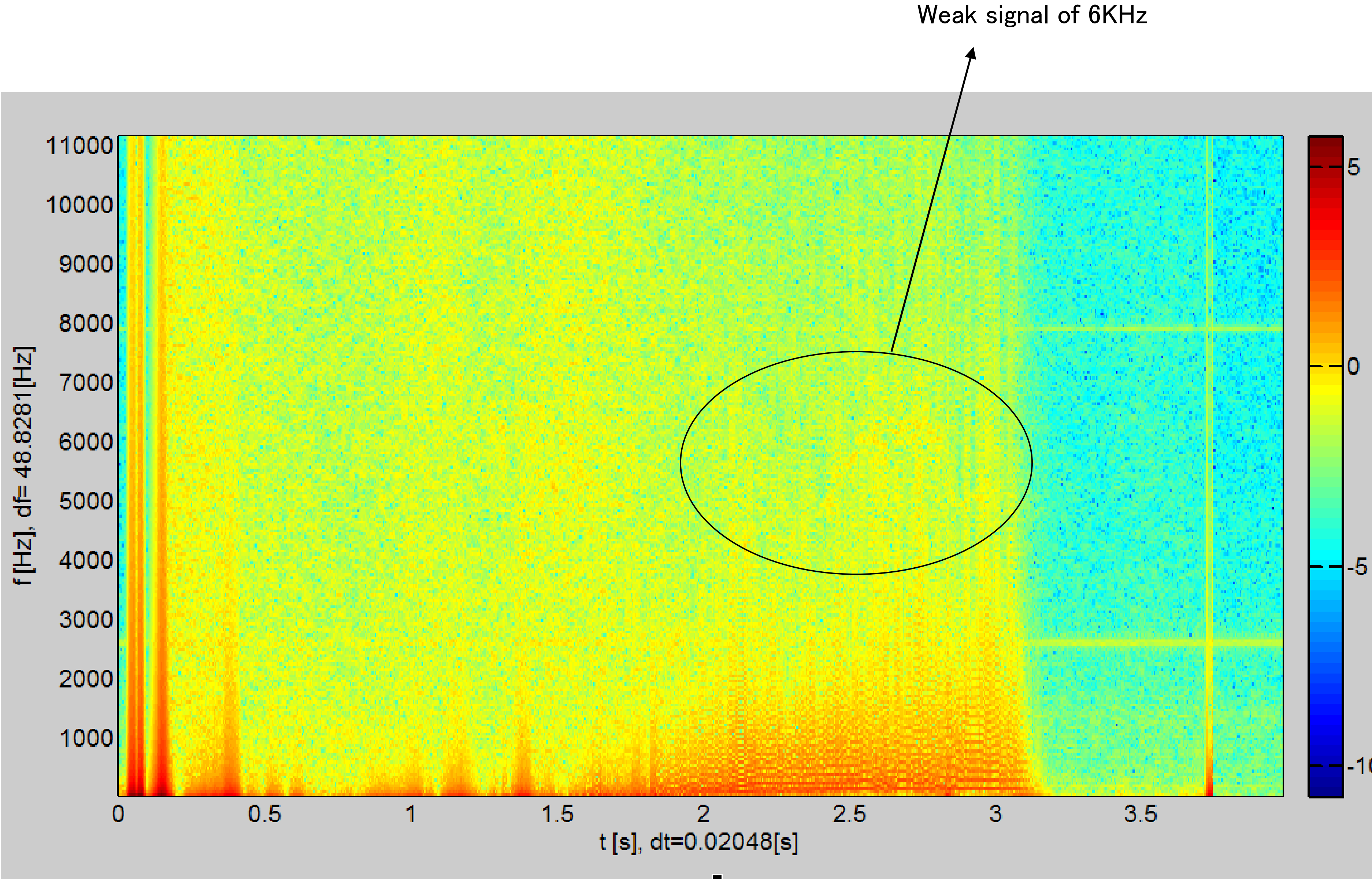
ECE spectrum for Shot#2181 time : 1.6 ~ 1.9s

ECE chanel 07, no high frequencies are found, low frequency sawtooth is exists only



Evidence of sawtooth

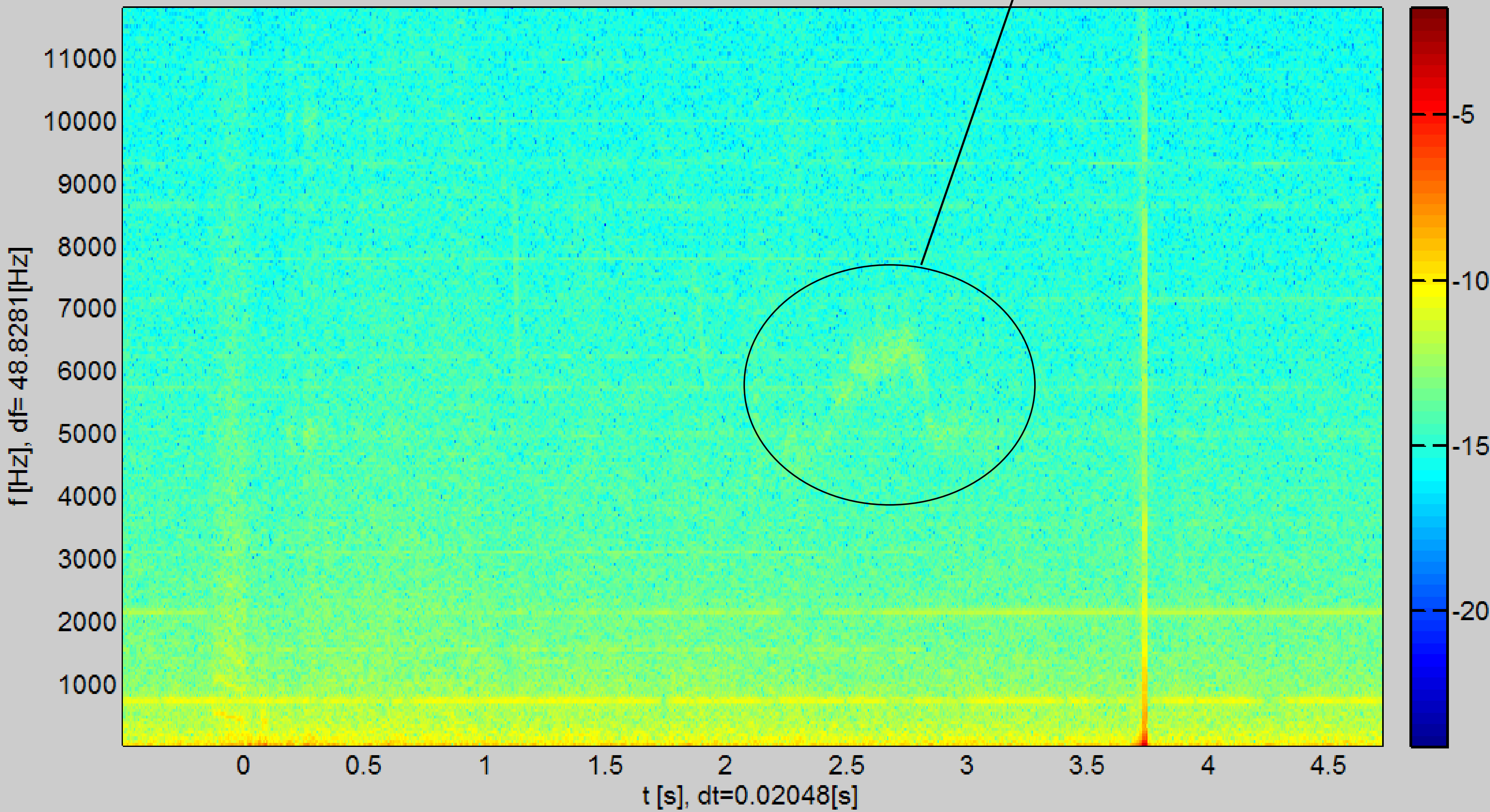
ECE channel 20 (close to the position of Mirnov coil) shows a 6kHz mode which is also shown in the MC data.



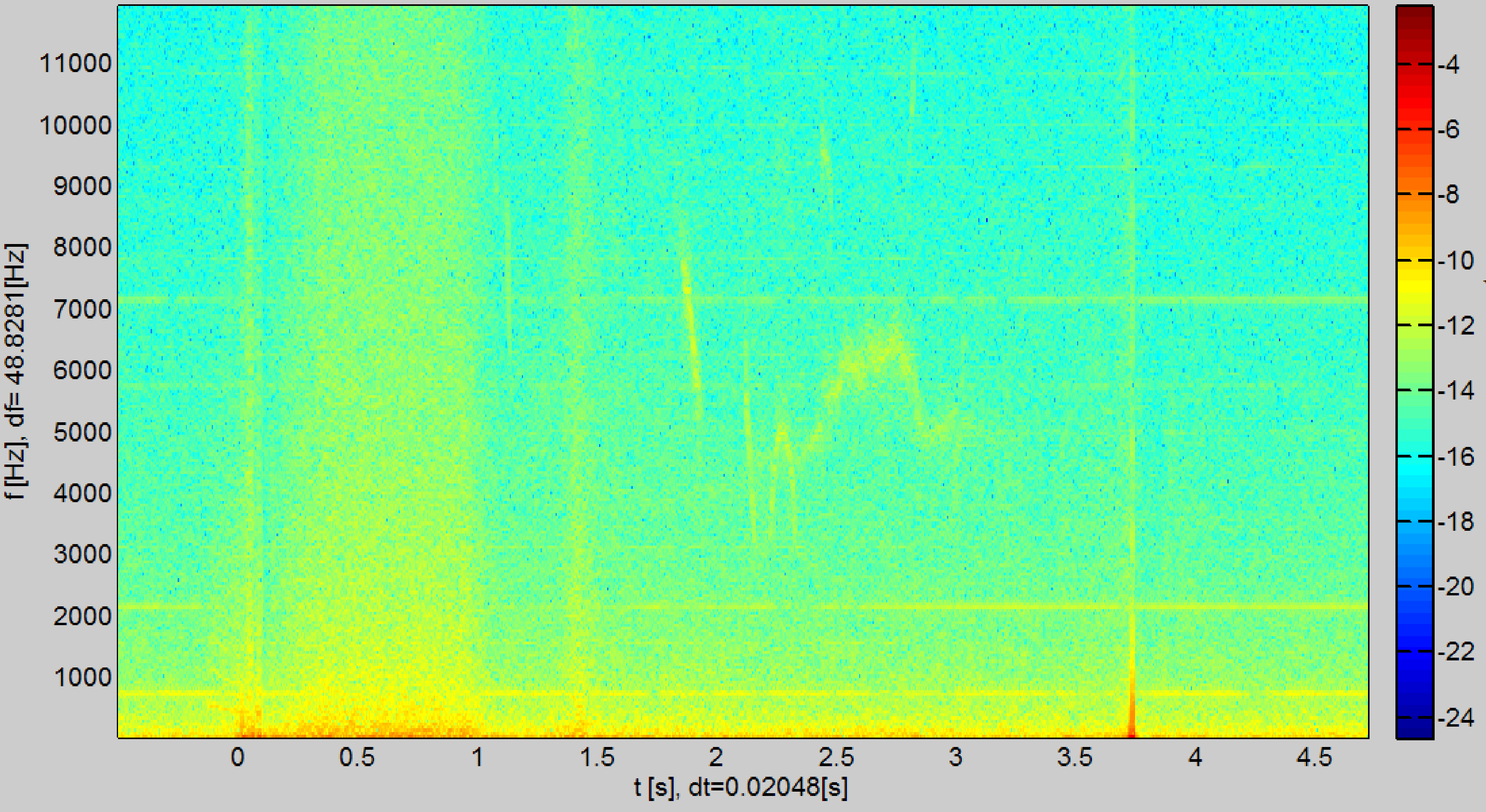
Spectrogram of Mirnov Coil data at # 2181

Chanel: 2181MC1P10

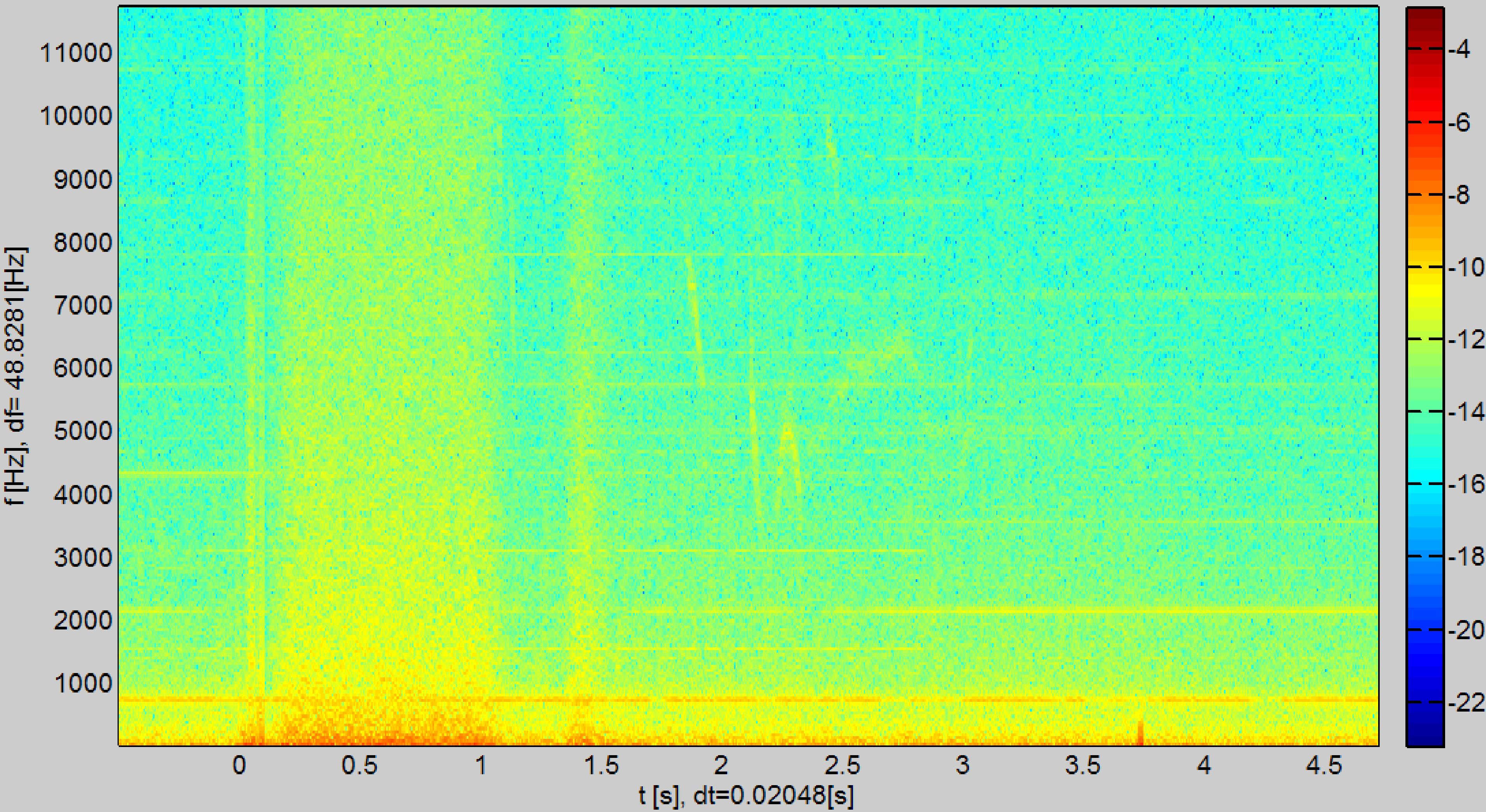
Similar mode is found in Mirnov coil data



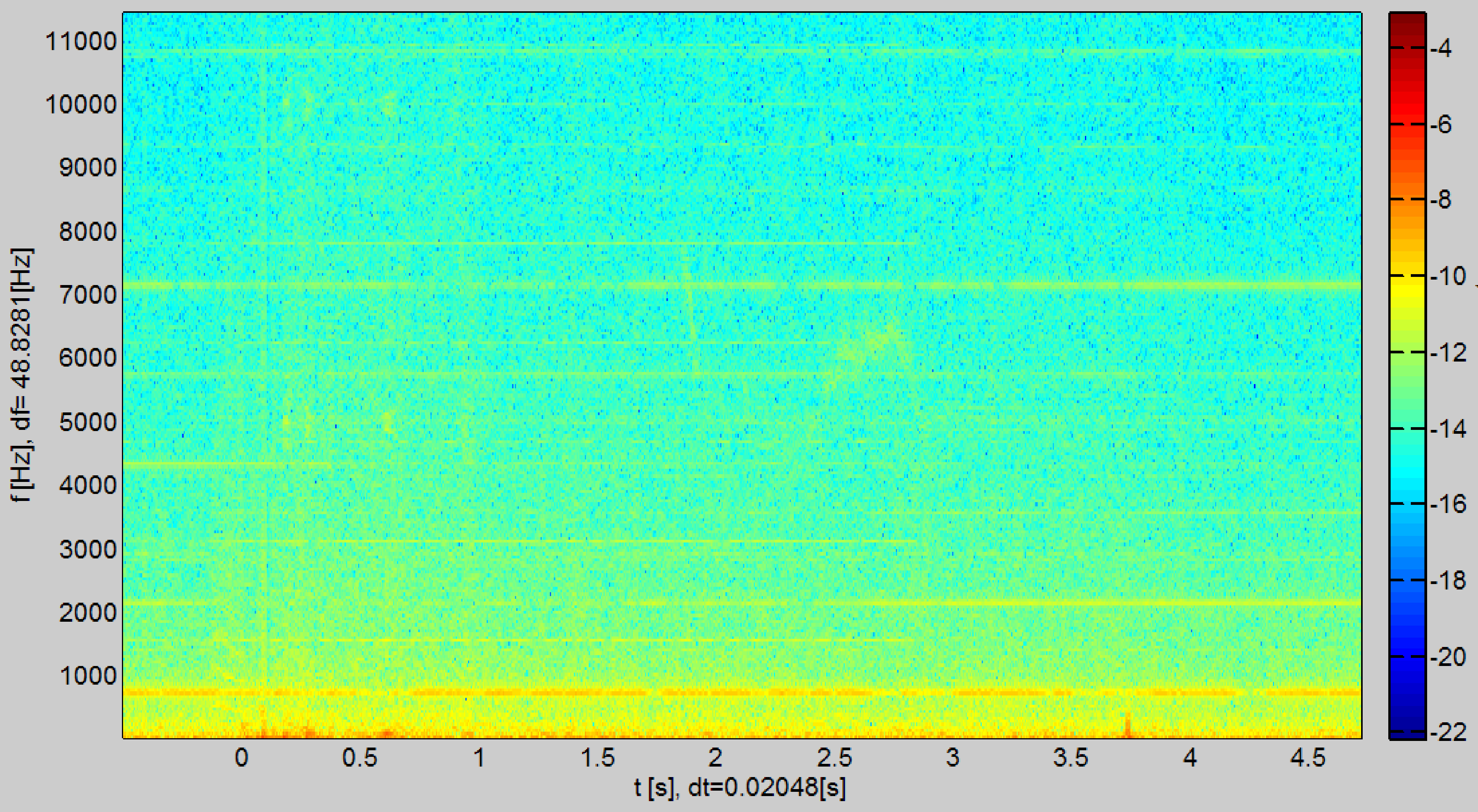
Chanel: 2181MC1P11



Chanel: 2181MC1P12



Chanel: 2181MC1P13



Disruption Study

Disruption Phenomena in KSTAR (2009. 11. 29)

Four disruption scenarios were studied.

- Natural elongation
- Q-limit
- Radial elongation
- Density limit

Ratio (3xPthr)/Ptot^2 (2009. 11. 28)

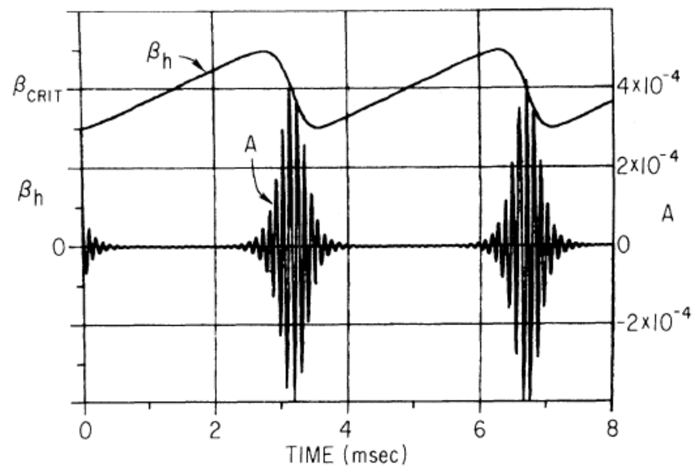
Target : achieve the ratio of (3xPthr)/Ptot^2 to try rapid Ip rampdown for magnetic shear change to trigger H-mode transition.

2010 and future plans

Study on the instabilities by energetic particles

Internal Kink

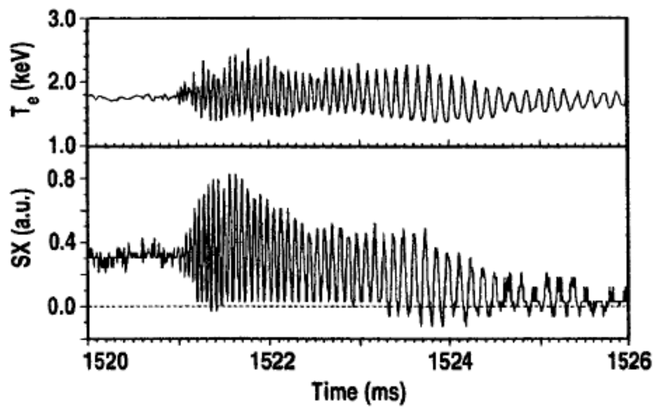
- Low frequency low n, m mode.
- m=1, n=1, Fishbone.
- Severe loss of beam-ion in relatively small machines like DIII-D and PDX.
- Wave particle resonance of trapped energetic ions and magnetic precession frequency.
- Electron fishbone destabilized by trapped superthermal tail heated by ECRH or LHCD.



Chen et al, 1984

Alfven waves

- Frequency range of Alfven frequency
- Toroidicity causes breakup of continuous frequency spectrum and makes a gap.
- Toroidal Alfven Eigenmode (TAE) exist in this gap as discrete frequency mode.
- Energetic particles interact with this TAE mode.
- Beam-ion loss is induced by excited TAE.



Wong et al, 2000

Fasoli et al., Nucl. Fusion, 2007

Equilibrium/Instability

Tokamak equilibrium : CHEASE

- CHEASE solves the Grad-Shafranov equation

$$\nabla \cdot \frac{1}{R^2}\nabla\Psi = \frac{j_\phi}{R} = -p'(\Psi) - \frac{1}{R^2}TT'(\Psi) \longleftarrow \nabla p = \vec{j}\times\vec{B}$$

- Equilibrium is determined by pressure p and current flux function T.
- Analytic profile of EFIT result can be used for equilibrium

Linear ideal MHD growth rates and eigenvectors : KINX

- KINX solves the energy principles of plasma
- Eigenvalue and eigenvector of most unstable mode
- Perturbed plasma quantities are obtained

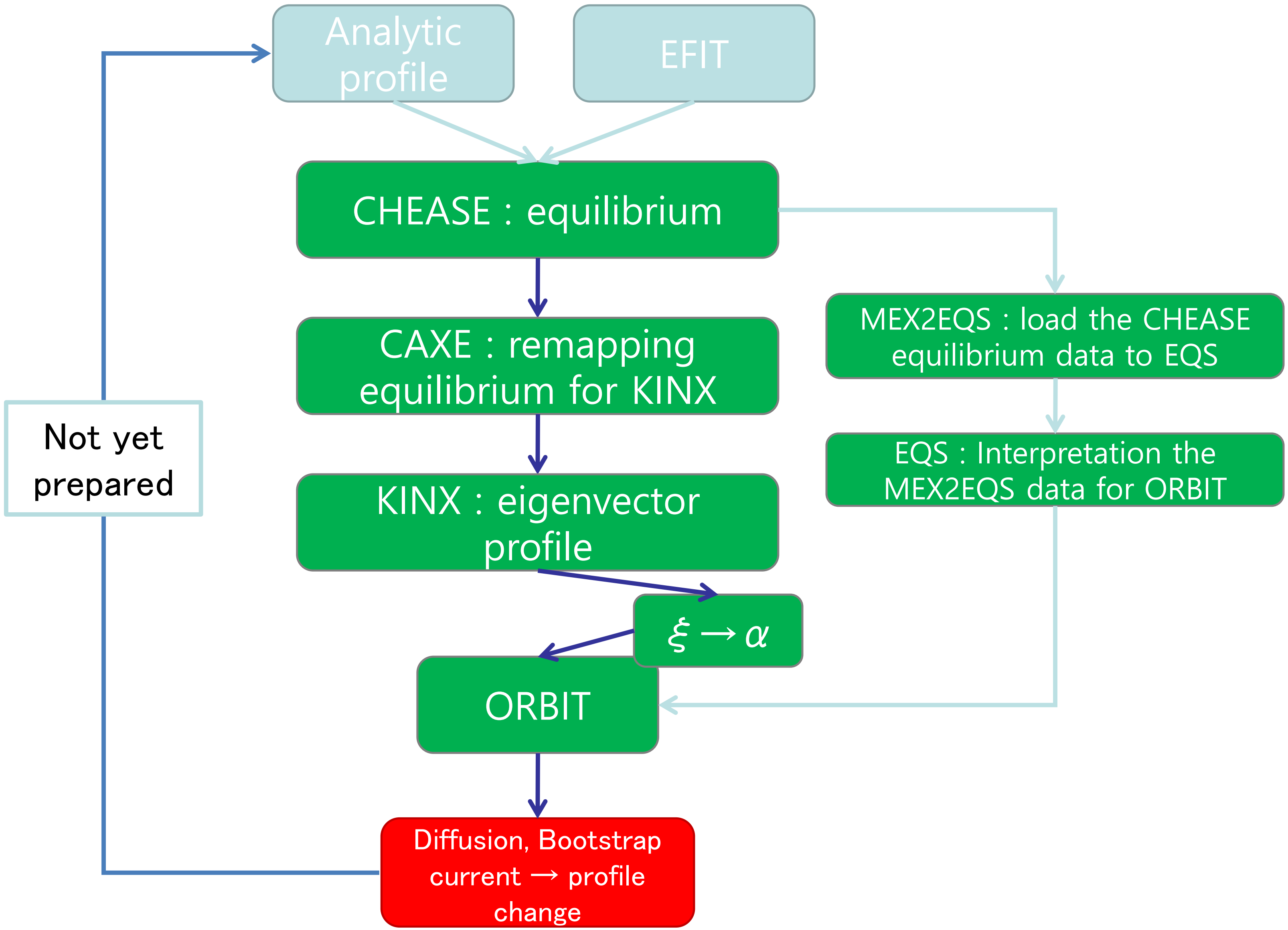
$$\delta\vec{B} = \nabla\times(\vec{\xi}\times\vec{B})$$

Particle orbit

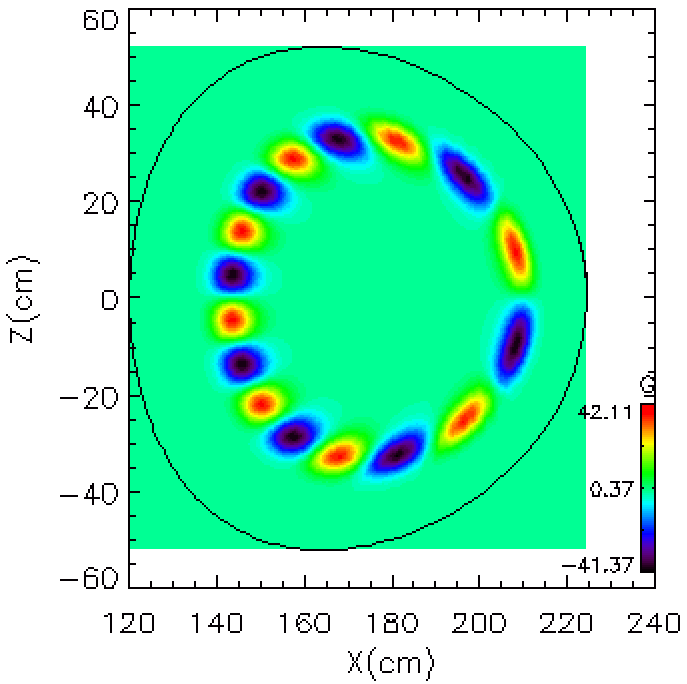
Particle orbit on the flux coordinate : ORBIT

- Guiding center orbit on the flux surface (ψ, θ, ϕ)
- Particle orbit during particle transit time
- Perturbed B field can be considered, $\delta\vec{B} = \nabla \times (\alpha\vec{B})$
- Particle diffusion coefficient, transport, local boot strap current.

Simulation scheme



Solovev Equilibrium and assumed perturbation



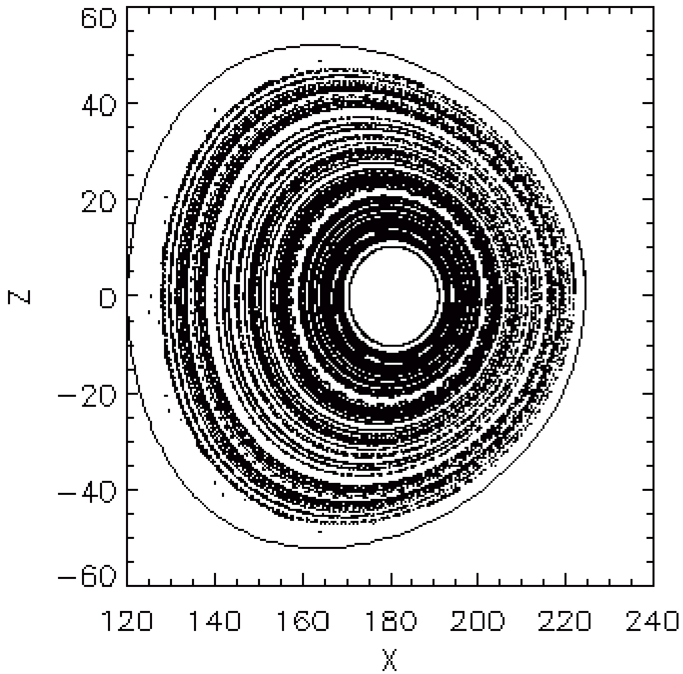
$$\delta \mathbf{B}_{\perp} = \nabla \times \alpha \mathbf{B}$$
$$\alpha = \alpha_{mn} \cos(n\phi - m\theta - \omega t)$$

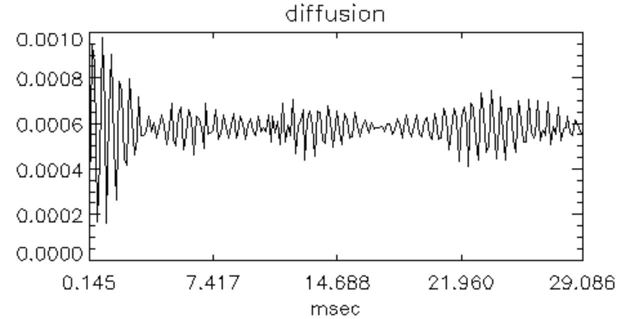
Perturbation is given by following method. $\boldsymbol{\alpha}$ is modeled by following method

$$\alpha_{mn}(\psi) = \exp\left[-\beta\left(1 - nq(\psi)/m\right)^2\right]$$

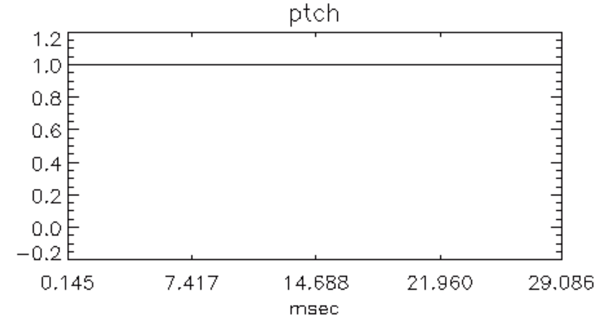
where n=1, m=8, $\boldsymbol{\beta}=10^4$.

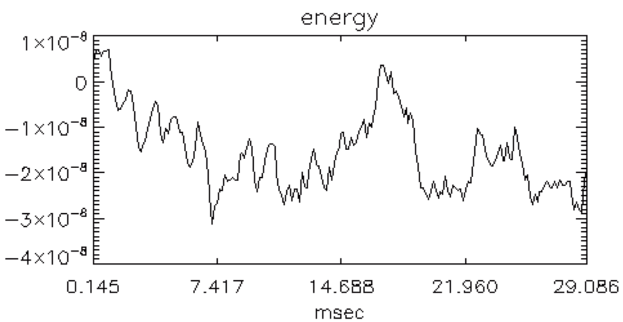
Poincare section and Diffusion coefficient – Equilibrium case





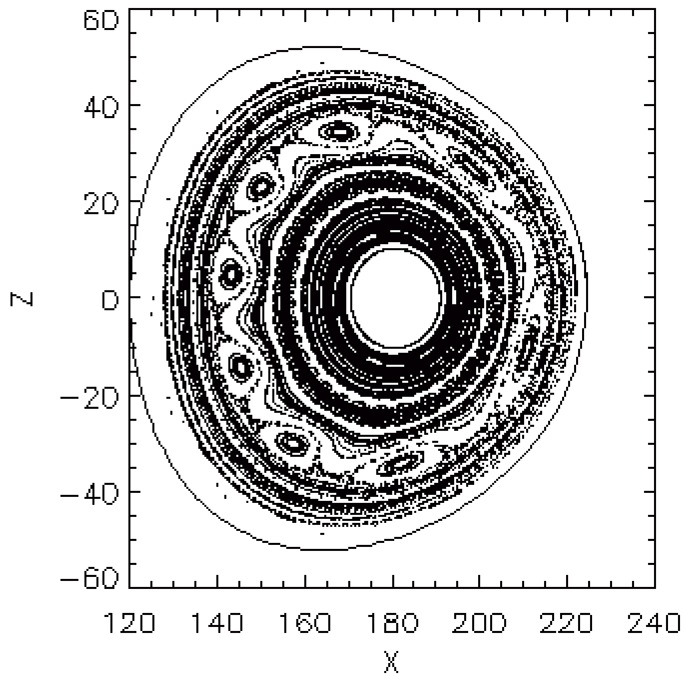
$$\left\langle \left(\psi_t - \psi_0\right)^2 / \psi_{\max} \right\rangle$$

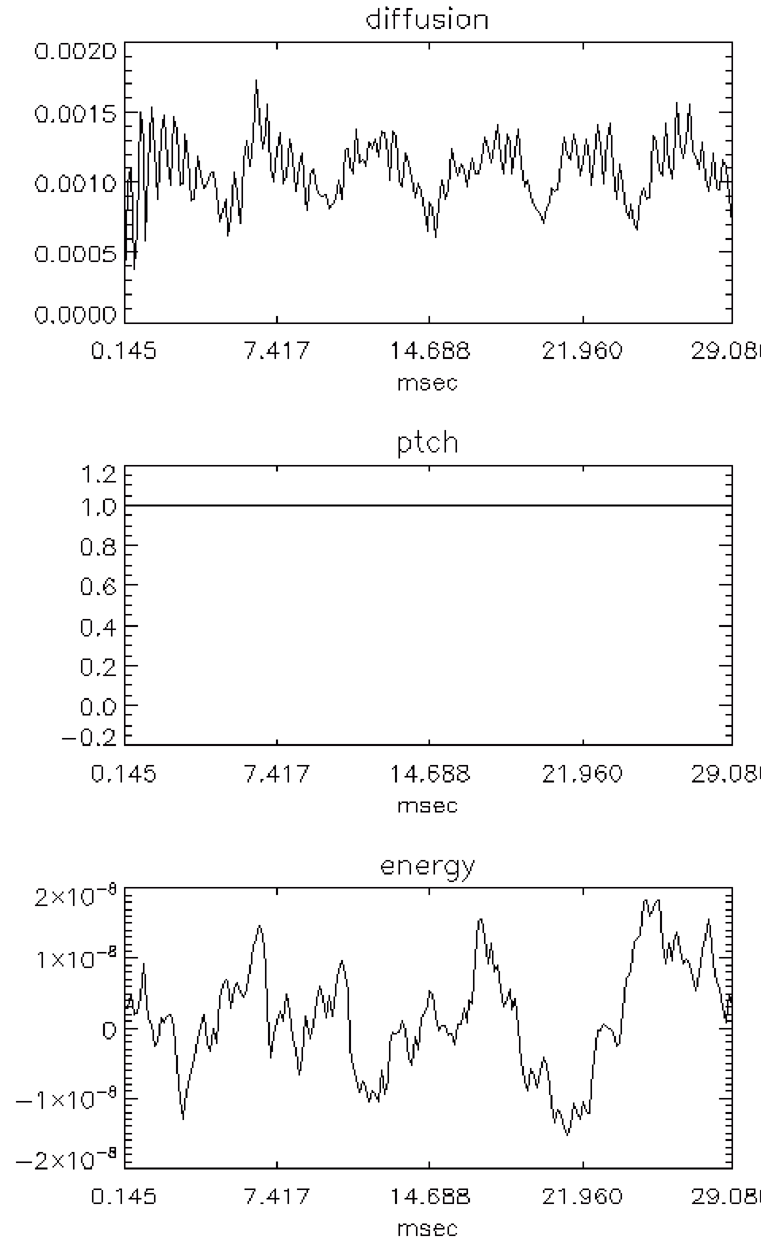




- Particles are passing particles.
- Maximum perturbation values is α_{mn}=2.x10^{-10} to test equilibrium state.
- Diffusion coefficient is 0.0006.

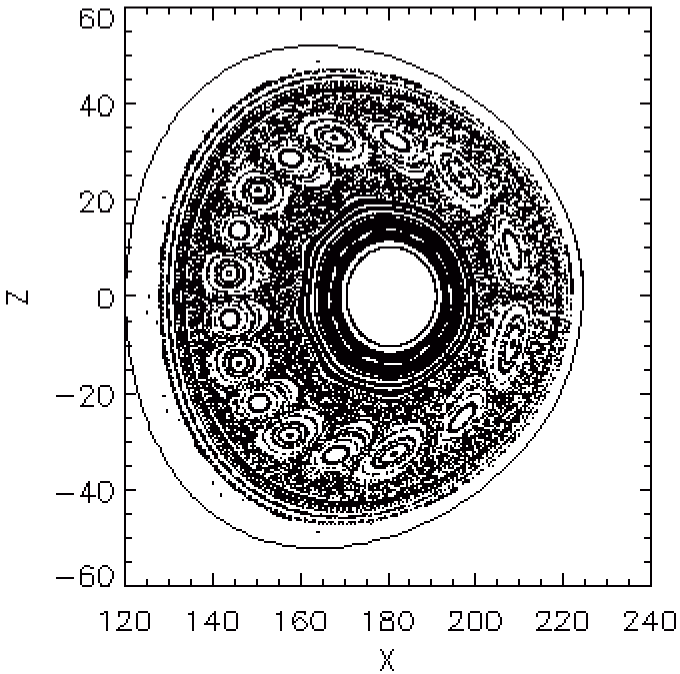
3. Poincare section and Diffusion coefficient – Enhanced perturbation

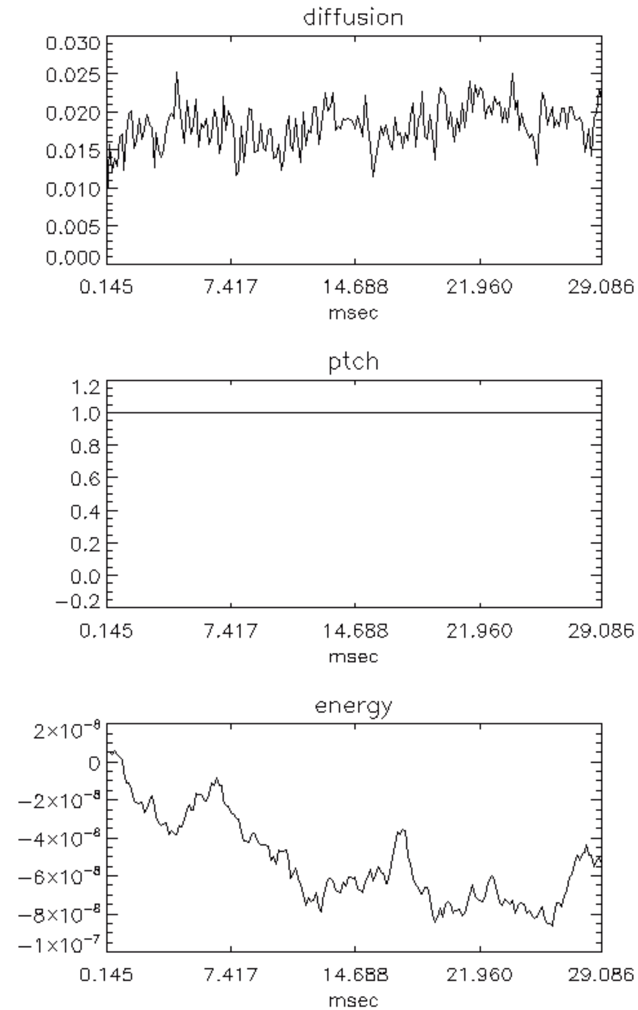




- Maximum perturbation values is α_{mn}=2.x10^{-6} to test equilibrium state.
- Magnetic island is formed at the perturbed position
- Diffusion coefficient increase to 0.001.

Poincare section and diffusion coefficient – Strong perturbation





- Maximum perturbation values is α_{mn}=2.x10^{-3} to test equilibrium state.
- Magnetic island has different with enhanced perturbation case. Island number is twice to former case.
- Diffusion coefficient becomes 10 times to former case.

Summary of the current theoretical study

1.Set of codes for self-consistent simulation of MHD instability and particle transport is being prepared.
2.Solovev equilibrium and KSTAR equilibrium from EFIT are test and they are stable.
3.Simple arbitrary perturbation is assumed and diffusion coefficient are obtained.
4.Enhanced perturbation increases diffusion.
5.Missing connections in simulation codes will be corrected.

KSTAR future plan

2010 KSTAR Experimental Plan

Operation Schedule : 2010. 6 ~ 2010. 9

Operation Parameter	B_T	I_P	t_p	Te	Shape
	~ 3 T	~ 1 MA	~ 10 s	~ 1 keV	Double null

Magnetic control	TF : up to 3.5T PF : +10kA ~ −10kA IVCC : VS, RS, FEC
Heating operation	ECH(84G) : 0.5MW, 2s ICRH(45M) : 1MW, 10s NBI : 1.0MW, 10s
Diagnostics	Resistive Bolometer / Imaging Bolometer MD / mm-WI / ECE / Hα / filterscope / Vis.TV PD / XCS / Soft X-ray Bolometer (resistive) ECE (110 ~ 162GHz) Hard X-ray / ECEI / IRTV Thomson Scattering Charge Exchange Spectroscopy

KSTAR Diagnostics

Red : 2010 Plan

Magnetic Feedthrough
Inspection Illuminator
Visible/H-alpha TV
Survey IR TV
CES (Background)

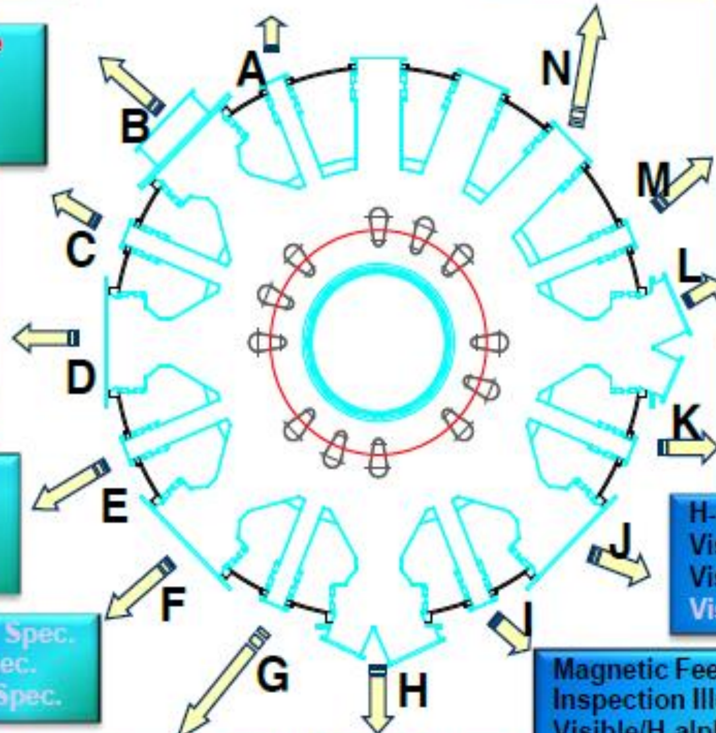
X-ray Crystal Spec.(Horizontal)
Thomson S.(Beam Dump)

Thomson Optics
Div. Thomson Optics

Reciprocating Langmuir Probe
Bolometer Array
Edge probe array
X-ray Pinhole Camera

Magnetic Feedthrough
~~Inspection Illuminator~~
MSE
CES
BES

Soft X-ray Array
Survey IR TV
Imaging Bolometer
Visible/H-alpha TV
X-ray PHA
Multichord Vis. Spec.
X-ray Pulse Height Anal.
Impurity Pellet Injector



Bolometer Array
Thomson S. (Laser Input)
CX-NPA

ECE Radiometer (3.0T)
ECE GPC
Diagnostic Neutral Beam
LIF (Optics)

Magnetic Feedthrough
~~Inspection Illuminator~~
Survey IR TV
Movable Langmuir Probe

H-alpha Monitor
Visible Survey Spec.
Visible Filterscope
Visible Brems. Array

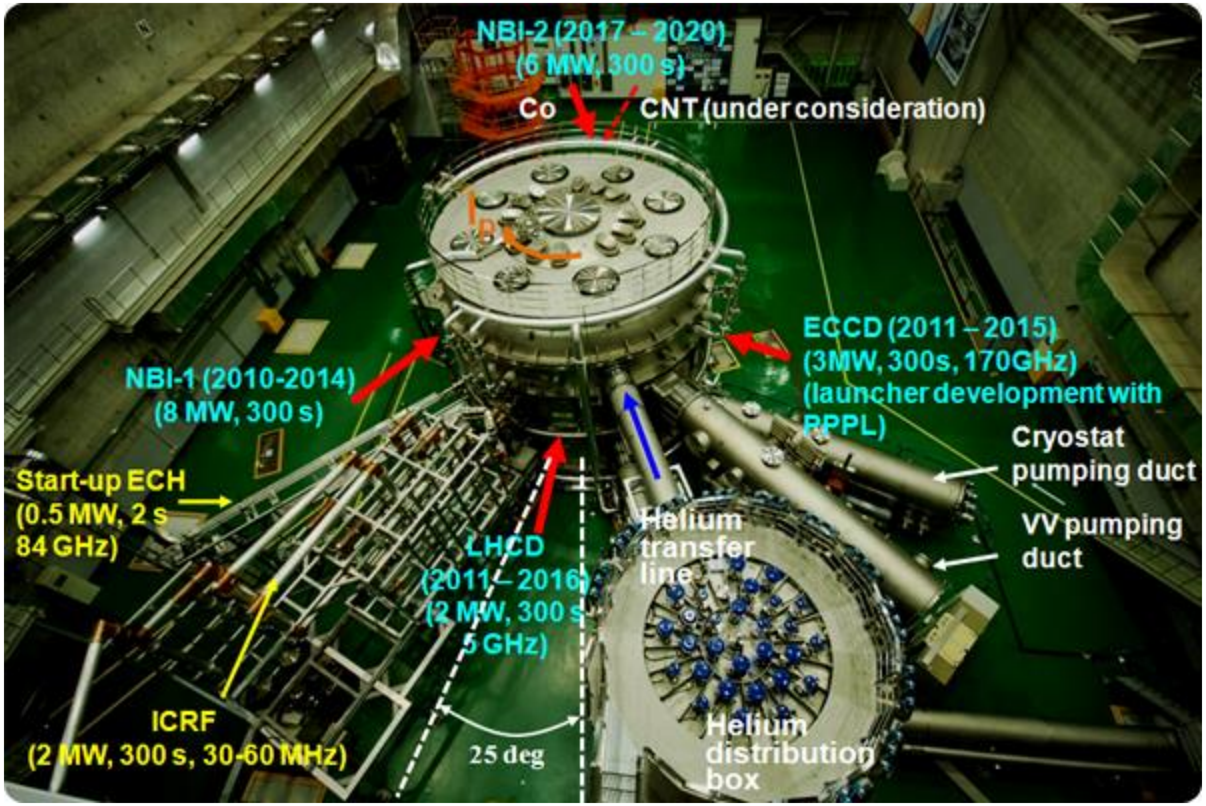
X-ray Crystal Spec.
Soft X-ray Spec.
VUV Survey Spec.

Magnetic Feedthrough
Inspection Illuminator
Visible/H-alpha TV
Survey IR TV
MSE(II)

mm-Wave Interferometer
Reflectometer
MIR
ECEI

Visible/H-alpha TV
(FAST)
Tan. FIR Int.
(Laser Input)

Long-range Plan of Heating Devices



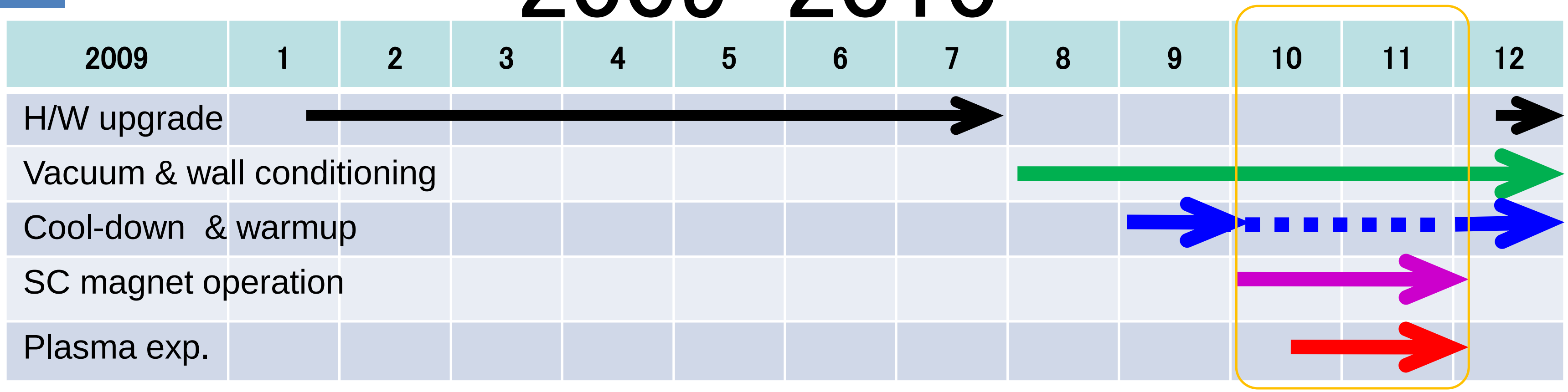
Short & Mid-term Experiment Plan

	FY 2008	FY 2009	FY 2010	FY 2011	FY 2012
Operation (Vac,CD & WU)	'08. 3 ~ '08. 8 (6 mon.)	'09. 8 ~ '09.11 (5 mon.)	'10.6 ~ '10. 11 (6 mon.)	'11. 4~ '11. 9 (6 mon.)	'12. 2 ~ '12. 7 (6 mon.)
Experimental Goals	• First plasma startup • 2nd Harmonic ECH pre-ionization	• 1st Harmonic ECH Pre-ionization • Startup stabilization	• Shaping control & vertical stabilization • Heating	• Confinement (L-H) • Stabilization • Heating	• Plasma–Wall Interaction • Profile control • RWM, ELM control • Off-axis current drive
Target Operation Parameters	• B_T ~ 1.5 T • I_P > 0.1 MA • t_P > 0.1 s • Te > 0.3 keV • Ti ~ 0 keV • Flux ~ 1 Wb • Shape ~ Circular • Gas : H_2	• B_T ~ 3 T • I_P > 0.3 MA • t_P > 2 s • Te > 0.3 keV • Ti ~ 0.3 keV • Flux ~ 2 Wb • Shape ~ Circular • Gas : H_2, D_2	• B_T ~ 3 T • I_P < 1 MA • t_P ~ 10 s • Te ~ 1 keV • Ti ~ 1 keV • Flux ~ 4 Wb • Shape ~ DN(double null) • Gas : H_2, D_2	• B_T ~ 3 T • I_P < 1.5 MA • t_P ~ 10 s • Te ~ 1 keV • Ti ~ 3 keV • Flux ~ 6 Wb • Shape ~ DN & SN • Gas : D_2	• B_T ~ 3 T • I_P < 2 MA • t_P > 100 s (0.5 MA) • Te ~ 1 keV • Ti ~ 5 keV • Flux ~ 8 Wb • Shape ~ DN & SN • Gas : D_2
PFC & Wall conditioning	• Inboard limiter (belt) • Gas puff	• Inboard limiter (w/o cooling) • Boronization	• Divertor / Passive plate • PFC baking • In-vessel coil	• Cryopump operation • PFC cooling	• PFC cooling • *Pellet*
Magnetic control	• TF : 1.5 T • PF : 4 kA unipolar	• TF : up to 3.5 T • PF : +/-4 kA	• TF : up to 3.5 T • PF : +/-10 kA • IVCC : VS, RS	• TF : up to 3.5 T • PF : +/-15 kA • IVCC : FEC. RMP	• TF : up to 3.5 T • PF : +/-20 kA • IVCC : RMP, RWM
Heating operation	• ECH(84G): 0.5MW, 0.4s	• ECH(84GHz): 0.5MW, 2s • ICRH(45MHz): 0.3MW, 10 s	• ECH(84/110GHz): 0.5MW • ICRH(45MHz): 1MW, 10 s • NBI: 1.0MW, 10s • LHCD: 0.5MW, 2s	• ECH(84/110GHz): 0.5MW • ICRH(45MHz): 2MW, 10 s • NBI: 2.5MW, 10s • LHCD: 0.5MW, 2s • ECCD(170GHz): 1MW, 10s	• ECH(84/110GHz): 0.5MW • ICRH(45MHz): 2MW, 300 s • NBI :5MW, 300s • LHCD : 1MW, 2s • ECCD(170GHz): 1MW, 300s
Diagnostics	• MD (77 Ch)/ MMWI / ECE / Hα / filterscope / VS / TV	• MD/ MMWI / ECE / Hα / filterscope / VS / TV • PD / XCS / Bolometer / Reflect. / Soft X-ray / (Hard –X ray)	• MD / MMWI / ECE / Hα / filterscope / VS / TV • PD / XCS / Bolometer / Reflect. / Soft X-ray / Hard X-ray • TS / neutron / IR TV / ECEI / CES	• MD / MMWI / ECE / Hα / filterscope / VS / TV • PD / XCS / Bolometer / Reflect. / Soft X-ray / Hard X-ray • TS / neutron / IR TV / ECEI / CES • MSE / FIR / neutron	• MD / MMWI / ECE / Hα / filterscope / VS / TV • PD / XCS / Bolometer / Reflect. / Soft X-ray / Hard X-ray • TS / neutron / IR TV / ECEI / CES • MSE / FIR / CES / neutron • MIR / BES / CI /

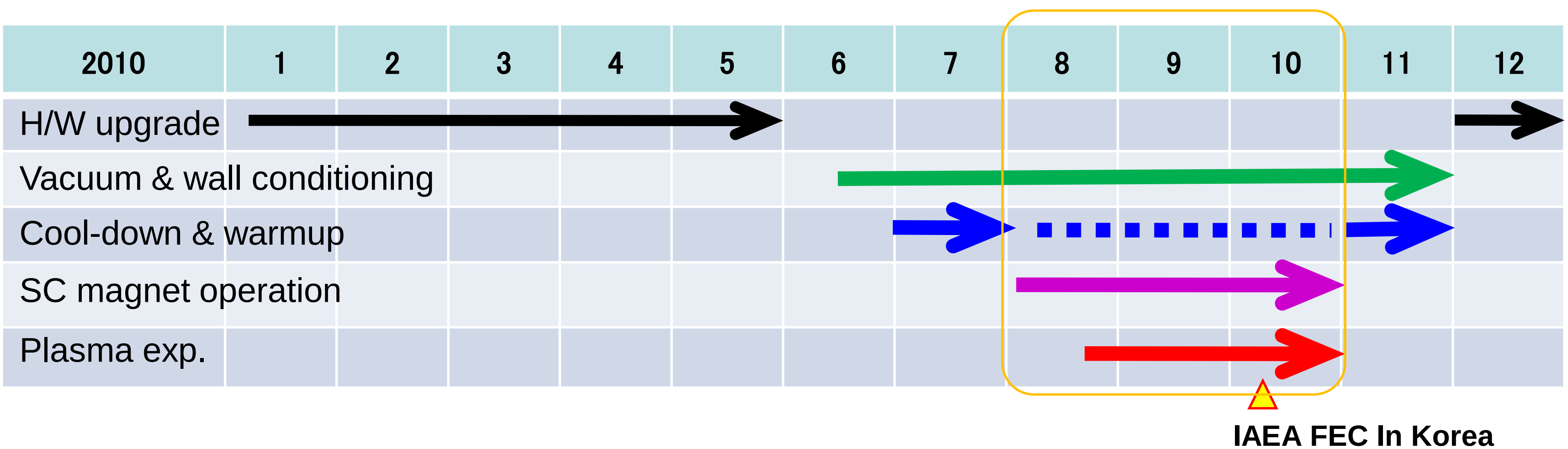
Heating and Current Drive System in KSTAR

Planned Operation Schedule in 2009-2010

2009 Operation



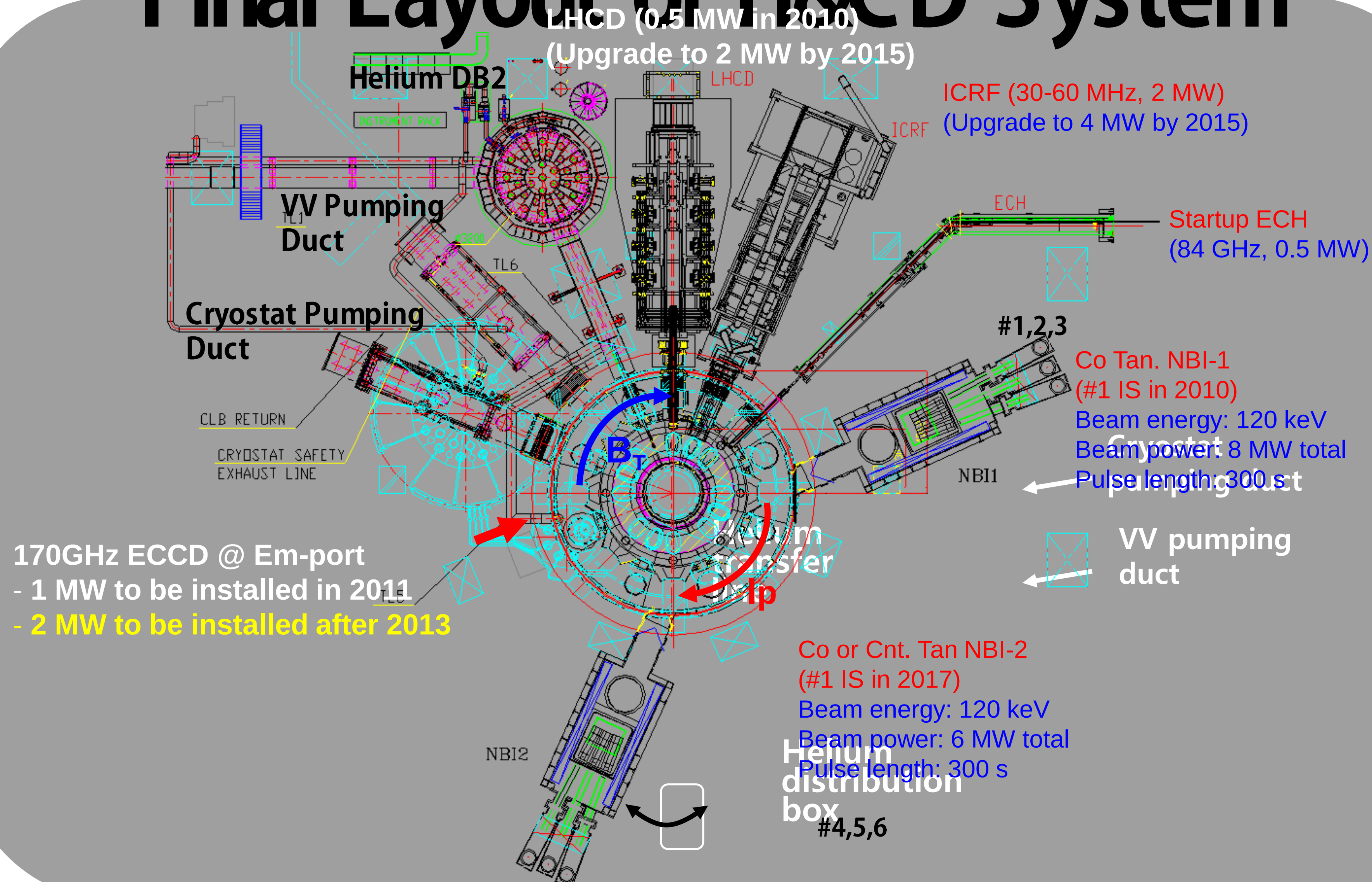
2010 Operation



Specifications of KSTAR H&CD

KSTAR	Specification	Role	ITER
NBI	14 MW, 300 s D0/H0 -Two beam lines -Three ion sources per each beam line -Positive based ion source at 120 keV	ystem -Ion heating & CD -H-mode in initial phase -Counter beam for plasma rotation control	33 MW D0 -Two beam lines -1 MeV D- ion source
ICRF	30 – 60 MHz, 8 MW, 300 s -Sources: Four 2MW transmitter	-Ion & electron heating in high density -On- and off-axis CD -ICW wall cleaning between shot (w/ pure TF field and/or TF and Bv)	35–60MHz, 25 MW CW - 10 x 2.5 MW CW transmitters
LHCD	5 GHz, 2 MW, 300 s - 4 x 500 kW CW klystrons	-Electron heating & CD -LH-assisted startup & CD in rising phase -Off-axis CD for plasma current profile control -RS-mode	5 GHz (or 3.7 GHz), 25 MW CW (50 x 500 kW CW klystrons)
ECH/CD	84(or 110)GHz, 0.5 MW, 2 s -84 GHz, 0.5 MW gyrotron 170 GHz, 3 MW, 300 s - 3 x 1 MW CW gyrotrons	• 84(or 110)GHz ECH Startup system -Assisted startup using pre-ionization •170 GHz ECCD system -2nd harmonic EC heating & CD -NTM stabilization leading to high beta -Sawteeth mode control (heating around q=1 surface)	170 GHz, 24 MW CW - 24 x 1 MW CW gyrotrons

Final Layout of H&CD System



Summary

- KSTAR plasma milestones are achieved.
- Korea-Australia collaboration on MHD sawteeth and suprathermal electron modes are well underway.
- To get meaningful results in 2010 campaign, stronger collaboration is required for precise data interpretation.

Thank you for your attention !