ECEI, MIR, RF Spectrometer in KSTAR
– Advanced mm-wave and RF diagnostics

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Outline

(2) MIR
Fast imaging system for $n_e$ fluctuations

(1) Two ECEI systems
Fast & high-resolution imaging system for $T_e$ fluctuations

(3) Fast RF Spectrometer for plasma waves (ion cyclotron, Alfven, whistler, etc)
I. KSTAR 2D ECE Imaging (ECEI)

Simultaneous Imaging of Core and Edge → Study of interaction btw instabilities*

• Space resolution ~ 1x1—2x3 cm²
• $T_e$ resolution (real-time), $\delta T_e / \langle T_e \rangle \approx 2\%$
• Time resolution ~ 2 µs
0. Array of heterodyne detectors

Separate Compartments for amplifiers and diode arrays for better noise shielding‡

Schottky diode on a patch antenna†

†P. Zhang, RSI 2008
‡ Yun, LAPD (2013)
1. Lens System for Imaging

- Lens material: HDPE
- Lens configuration: Cooke triplet or doublet for **flexible zooming** (vertical zoom factor \( \sim 1—3 \))

**Focus lenses**

**Heterodyne Detector Arrays**

**Measured beam profile at the image plane**

**Zoom factor measurement**

**Source Position (mm)**

**Image Position (mm)**
2. Wide-Band Beamsplitter

- Thin Tempered Glass (borofloat33, t=1.1mm, Dk = 4.6)

3. Notch-filter

- Array of copper squares
  - Copper Thickness : 9 um
  - Pattern dimension = 476~512 um

- Dielectric Thickness : 254 um
- Dielectric Constant : 2.20
- Dissipation Factor : 0.0007

Deep and symmetric notching
4. High-pass filters for single-sided mixing

5. Half-wave plate for O1 mode operation at high B

Grooved HDPE plate ~ meta-material
Sawtooth structures modified by ECRH*

Dual flux tubes (DFTs) †
(#6022)

Triple flux tubes
(#5422)

*Crescent tube
(#4004)

\[ \delta T_e / \overline{T}_e \]

\( q \approx 1 \)

Choe, KSTAR Conf. (2013)
Yun, PRL 109 (2012)
Bierwage, to be submitted
Tearing modes*

*m/n=2/1 mode

m/n=3/2 mode

*M. Choi, NF (2014), accepted.

Shot 6123
\( t = 6.788 \text{s} \)

Shot 6304
\( t = 4.322 \text{s} \)
**Edge localized modes (ELMs)**

**Alteration of ELM structure by n=1 magnetic perturbations (MP)**

- * Yun, PoP (2012)
- Jeon, PRL (2012)
- J. Lee, KSTAR Conf. 2013

First simultaneous observation of outboard and inboard ELM filaments†

* Yun, PoP (2012)
  Jeon, PRL (2012)
  J. Lee, KSTAR Conf. 2013

† J. Lee, KSTAR Conf. 2013; Yun, ITPA MHD 2014
KSTAR 3D ECEI

Quasi 3D (year 2012)

- Exact determination of Toroidal mode number *
- Toroidal asymmetry of ELM dynamics

*J. Lee, submitted to RSI.

ECEI-2 (year 2012) Combined with MIR
ECEI-1 (year 2010) Dual arrays
Dual flux tubes\(^\dagger\) in 3D
(Modified Sawtooth by ECH)

- The observed flux tubes are approximately aligned with the model flux tubes of m/n=1/1.
- Naturally explains the changes of the sawtooth period.

\(q = 1\) surface

\(\text{NOT A SIMULATION}\)
II. Microwave Imaging Reflectometry†

- Imaging of 2D density fluctuations
- Dispersion of turbulent fluctuations

Specifications

- Tunable probing frequencies from 78 to 92 GHz
- Frequency spacing = 2 or 4 GHz
- Channels: poloidal 16 and radial 2
- Spatial resolution: 1.6 cm (1/e² width poloidal)
- Channel spacing: 0.6 cm (poloidal), 1~17 cm (radial)
- Detection limit of wave number: $k_\theta = \text{up to } 3 \text{ cm}^{-1}$
- Time resolution: 1 or 2 μs normal (0.5 μs min)

†W. Lee, NF (2014)
Source, array, and electronics

Dual frequency probing source

- Probe beam
- Directional coupler
- Amplifier
- Synthesizer
- Isolator
- Hybrid coupler

Upgraded to 4 frequencies in 2014

LO source

- X6 Synthesizer
- Isolator
- Amplifier
- Directional coupler

MIR electronics

- Reference channel
  - 1.0 GHz
  - 3.0 GHz
  - Diplexer
  - BPF
  - 16-way power divider

- Detected IF signals
- IF amplifier

- Ref. IF signals
- Ref. mixer (fundamental)

- MIR array
  - (16 channels)

- Detected IF signals
- IF amplifier

- Reflected beam

One of 16 detection channels

- Digitizer
  - 32 chs
  - 0.5 MS/s
  - 14 bits
Imaging optics

(a) Launching optics

Cut-off layer  Plasma facing lens  Vacuum window

(b) Receiving optics

Focusing lens

(c)

Normalized response of each detector
\sim 1.6 \text{ cm } 1/e^2 \text{ width.}
Spectral change of turbulent density fluctuations

* ECH
** r/a ~ 0.3

** r/a ~ 0.6

** r/a ~ 0.7
Lab-frame poloidal flow ($V^*_\theta$) of density fluctuations

Cross-coherence, $\gamma^2_{xy}(f) = \|G_{xy}(f)\|^2 / \sqrt{G_{xx}(f) G_{yy}(f)}$

Cross-power, $G_{xy}(f) = \langle x^*(f) \cdot y(f) \rangle_{\text{time}}$
Time evolution of $V^*_\theta$ during L-H transition†

†W. Lee, LAPD16, Madison, WI, 2013
A prototype **8-channel RF spectrometer**† has been developed in 2011 to detect **RF emissions** during MHD events such as sawtooth crashes and edge-localized mode (ELM) crashes.

A **wide-band antenna** was installed *outside the vessel* near the ECEI system (next slide).

†J. Leem, JINST 2012
Similar filter-bank RF spectrometer is installed at LHD for comparative study (collaboration w/ T. Akiyama)

Upgrade planned for fine-resolution full-band measurement and polarization measurement for the 2014 KSTAR campaign.
Example of RF burst at the ELM crashes

H-mode discharge
\( B_0 = 2.3 \, \text{T}, I_p = 550 \, \text{kA}, n_{e0} \sim 2 \times 10^{19} \, \text{m}^{-3}, \)
\( W_{\text{tot}} = 220 \, \text{kJ}, \quad \text{NBI} = 2.7 \, \text{MW} \)

(1) The RF captures the exact timing of ELM crash.
(2) Rapid enhancement and saturation of the RF emission level (around 200 MHz) is commonly observed during the inter-crash period. Modulation in the RF emission level is also often observed.

Possible mechanism: Mode conversion of ion cyclotron harmonic waves to compressional (fast) waves through the lower hybrid resonance

A useful diagnostic for pedestal evolution
Summary

- Visualization is an essential tool for complex MHD and turbulence physics.
- Achieved **quasi-3D ECE imaging** at the KSTAR tokamak through technological innovations.
- Realized **MIR**; measured the wave dispersion of density fluctuations.
- Fast RF diagnostic proved to be very useful for studying MHD crash dynamics, plasma waves, etc.

*Work supported by NRF Korea, Japan-Korea Collaboration program and US DoE.*
ECEI window of operation

\[ n_{e0} = 5 \times 10^{13} \text{ cm}^{-3} \]
\[ T_{e0} = 3 \text{ keV} \]
ECE downshift

Near the pedestal foot and outside, ECE signals come mostly from inside, a well-known phenomenon called *downshift*.

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**JET H-mode pedestal**

E. de la Luna et al., 34th EPS (2007)

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**Localized ECE**

**ECE downshift (not localized)**

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**Parameters**

- $T_e$ (keV)
- $n_e$
- $\tau$ (ms)
- $j$ ($\mu$A/cm$^2$)
- $j_{eff}$ ($\mu$A/cm$^2$/GHz)
- $R_{LCS}$ (m)

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**Figure**

- #70548 (t=58.61 sec)
- ECE (LFS)
- Edge LIDAR
- HRTS

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**Equations**

- $\tau_{max} = 17.9$
- $j = 6.86$
- $j_{eff} = 1.35$

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**Values**

- $(\mu$W/cm$^3$/GHz)