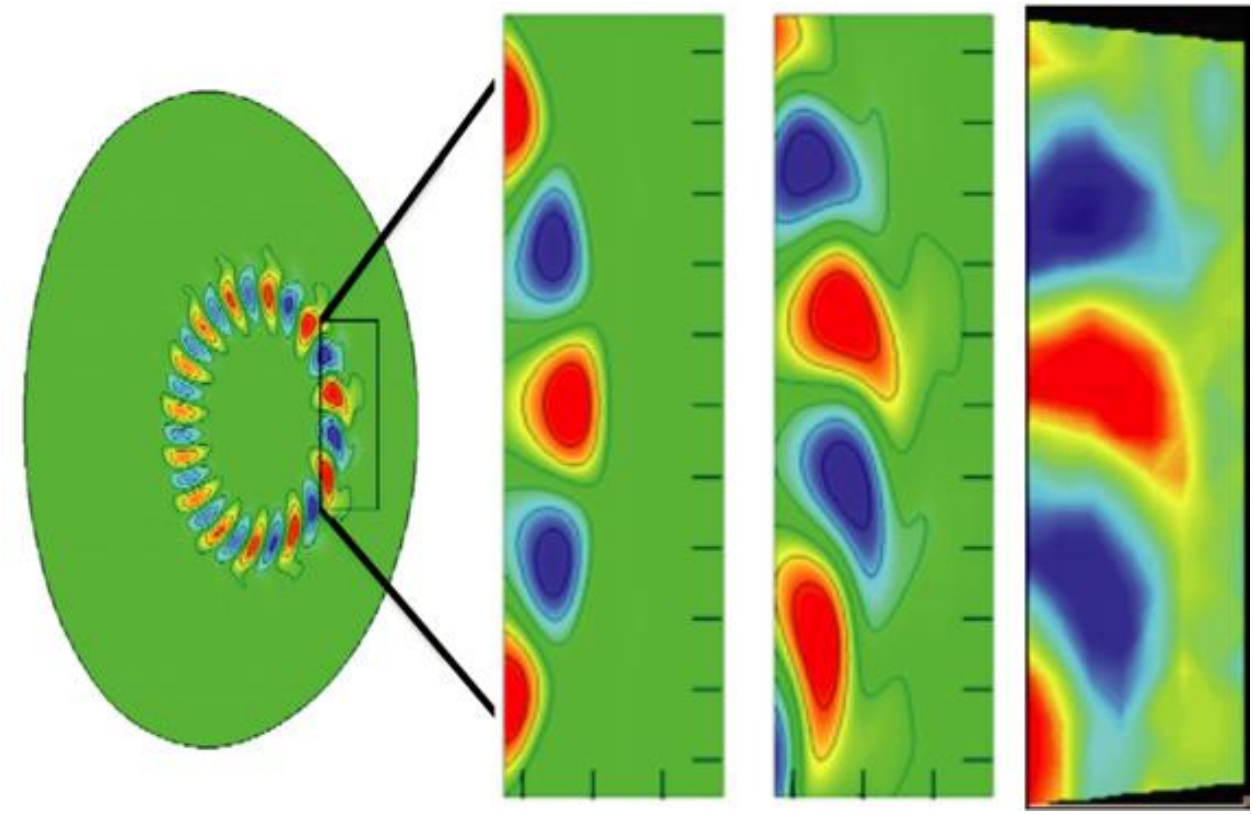
White Paper Proposal

Dec. 15, 2011

Imaging and Visualization of Fusion Science



N.C. Luhmann, Jr.
Principal Investigator
Ph 530-752-5414, Fax 530-754-9070
Email: ncluhmann@ucdavis.edu

University of California, Davis
Department of Electrical and Computer Engineering
One Shields Avenue, Davis, CA 95616

A synthesis of research in plasma turbulence, transport, and MHD stability is necessary to develop a complete understanding and predictive capability for scenario development and performance projections, as well as avoidance and mitigation of disruptions. The proliferation of visualization and imaging diagnostics to new international facilities, such as KSTAR and EAST, provides just such an opportunity. In particular, millimeter-wave imaging diagnostics such as electron cyclotron emission imaging (ECEI) and microwave imaging reflectometry (MIR), have revolutionized our understanding of plasma phenomena where they have been applied. It is critical that these technologies and the scientific involvement from U.S. students, engineers, and physicists that they foster are promoted by the DoE through international collaboration during the coming decades.

The University of California at Davis (UC Davis), in collaboration with Princeton Plasma Physics Laboratory (PPPL), has been engaged in developing an advanced millimeter-wave instrument for 3-D, simultaneous imaging and visualization of electron density (n_e) and electron temperature (T_e) fluctuations. The value of 2-D ECEI for T_e fluctuation imaging and physics studies was first demonstrated on TEXTOR with a proof-of-principle instrument; since then it has produced highly visible and widely cited physics results while being continuously improved and implemented anew on ASDEX-Upgrade, DIII-D, KSTAR, and most recently the EAST tokamak. While the unique experimental capabilities of each of these machines have been exploited in different ways, ECEI has at each step proven to be a truly unique and revolutionary diagnostic that allows the researcher to visualize plasma physics in a way no other tool can. These millimeter-wave cameras provide 2D, and even 3D data from localized measurements, with exceptional spatial and temporal resolution, as well as wide radial, vertical, and even toroidal coverage. MIR will provide an analogous 2D measurement of density fluctuations.

Because millimeter-wave imaging systems are well suited to diagnosing fluctuations over disparate spatial (and temporal) scales, they are uniquely well poised to contribute to scenario development and disruption avoidance. New superconducting tokamak facilities, with ample resources for non-inductive current drive and long pulse durations, are ideal for conducting experiments aimed at understanding how complex interactions between plasma turbulance, transport, and MHD stability lead to improved performance, or conversely, plasma disruption. For this reason it is natural that the capabilities be combined, and fortuitous that the U.S. is a world-leader in this diagnostic technology.

Currently, a five-institution collaboration exists between UC Davis, PPPL, POSTECH in Korea, the FOM Institute in the Netherlands, and the University of Science & Technology of China. Interest has also been expressed by a number of other major fusion programs, so this list of devices and participating institutions is expected to continue growing over time. The number of theory and modeling projects that directly benefit from this work is growing almost daily. Recent high profile examples include the contributions of ECEI to code benchmarking among the members of the SciDAC Center for Gyrokinetic Simulation of Energetic Particle Turbulence and Transport (GSEP). The ability of millimeter-wave diagnostics to provide unambiguous validation of theory with respect to energetic particle driven instabilities is but one example of the need for these tools in the scientific community.

The high resolution plasma visualization data obtained with these diagnostics (examples provided in Figs. 1 and 2), as well as the continued development activities which strive to keep expanding the quality and quantity of plasma fluctuation data that can be obtained with these diagnostics, has already proven to be a means to foster international research collaborations

between US scientists and their counterparts on KSTAR, ASDEX-Upgrade and now EAST. Continued US leadership in diagnostic development is essential to maintaining and expanding these international collaborations. Data collected on these devices, as well as others for which similar diagnostic tools may be developed over the next 5-10 years, can serve to provide a wealth of information for plasma theorists and modelers outside of the diagnostic development community. Illustrative of the strength of these collaborations are the quantity and quality of refereed publications over the past five years on advanced in ECEI technology or physics-based papers based largely on ECEI data, as listed in Appendix I.

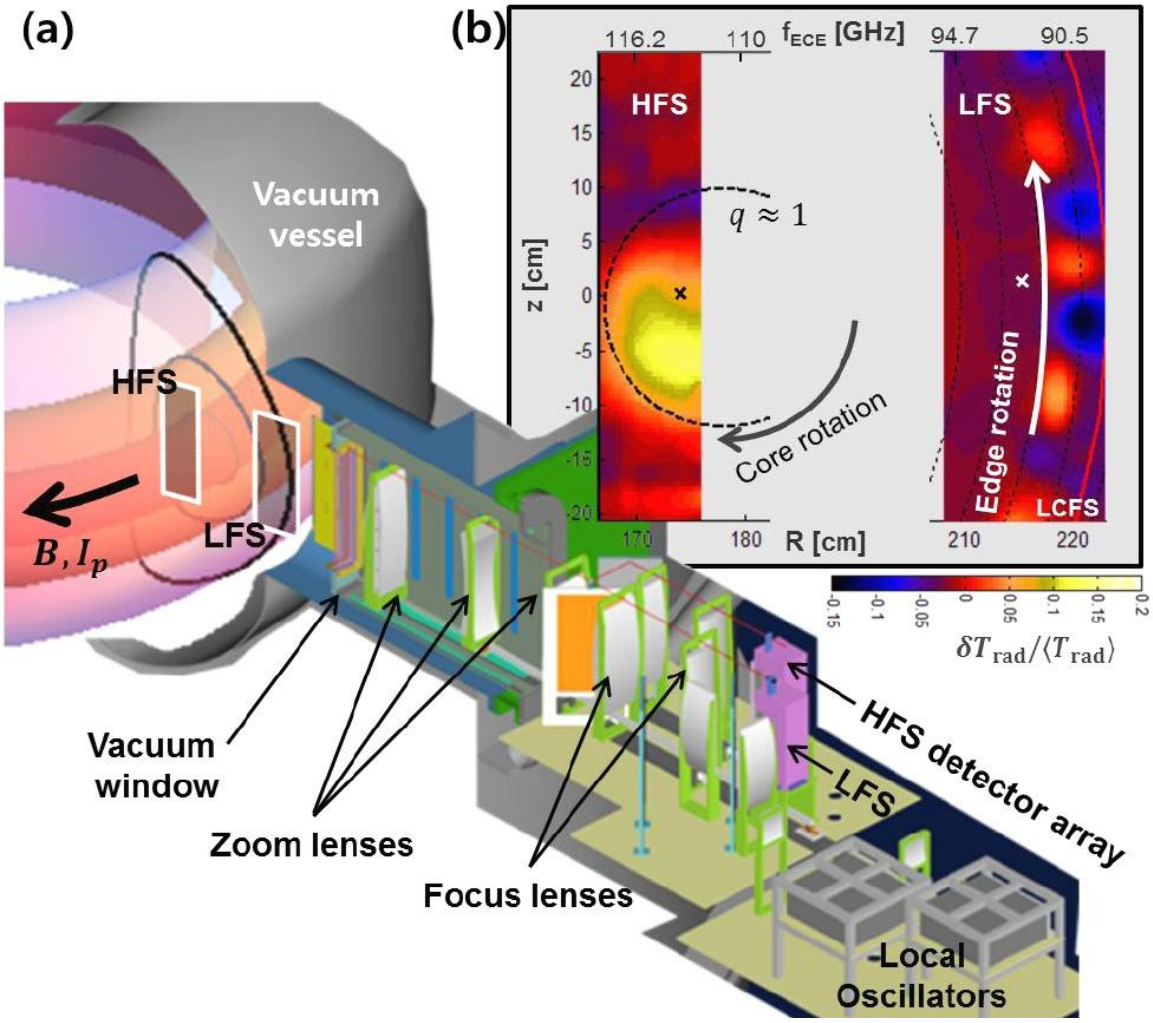


Fig. 1. (a) KSTAR ECEI system. (b) An example of simultaneous high- and low- field side (HFS and LFS, respectively) measurements (shot# 4362, t = 1.741863s). The HFS image shows an internal kink mode in the central region while the LFS image shows ELM filaments in the edge.

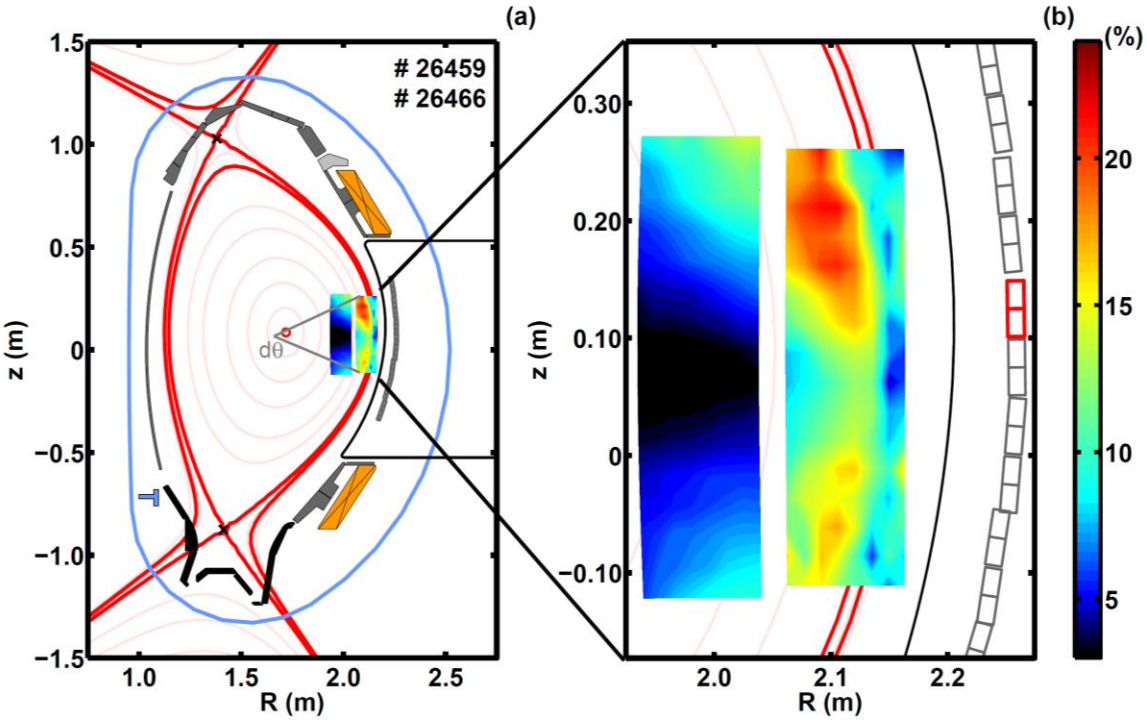


Fig. 2. ECEI data from an ASDEX-Upgrade study of the transition from Type I to Type II ELMs.

Appendix I: Refereed Publications, January 2007 - Present

A). Invited and Plenary Presentations

[1] C.W. Domier, N.C. Luhmann, Jr., Hyeon K. Park, Zhengang Xia, Peiling Zhang, "Advances in Millimeter Wave/THz Plasma Diagnostics Instrumentation," *Conference Digest of the Joint 32nd International Conference on Infrared and Millimetre Waves, and 15th International Conference on Terahertz Electronics*, Cardiff, UK, September 3-7, 2007, **Vol. 1**, pp. 8-11. **Plenary Paper.**

[2] H.K. Park, "Microwave Imaging Project and Physics of the Sawtooth Crash in Tokamak Plasma", **Invited Talk** presented at the *Microwave Workshop*, Kyushu University, Japan, March 24-25, 2008.

[3] P. Zhang, C.W. Domier, T. Liang, X. Kong, B. Tobias, Z. Shen, N.C. Luhmann, Jr., H. Park, I.G.J. Classen, M.J. van de Pol, A.J.H. Donné, and R. Jaspers, "The Next Generation of Electron Cyclotron Emission Imaging Diagnostics" **Invited Talk** presented at the *17th Topical Conference on High Temperature Plasma Diagnostics*, Albuquerque, NM, May 11-15, 2008.

[4] N.C. Luhmann, Jr., I.G.J. Classen, C.W. Domier, A.J.H. Donné, R. Jaspers, X. Kong, T. Liang, A. Mase, T. Munsat, H.K. Park, Z. Shen, B.J. Tobias, M.J. van de Pol, "Microwave Imaging and Visualization Diagnostics Developments for the Study of MHD and Microturbulence," **Plenary Address** presented at the *First International Workshop on "Frontiers in Space and Fusion Energy Sciences (FISFES)* in Tainan, Taiwan, November 6-8, 2008.

[5] Hyeon K. Park, "Visualization Technique for MHD and Transport Physics in Tokamaks," **Invited Talk** presented at the *19th International Toki Conference on Advanced Physics in Plasma and Fusion Research*, Toki-City, Japan, December 8-11, 2009.

[6] N.C. Luhmann, Jr., "Recent developments in microwave plasma imaging", **Invited Talk** presented

at the *International Workshop on Microwave Devices, Systems, and their Applications 2010*, KASTEC, Kyushu University, March 16-17, 2010.

[7] H.K. Park, "2D ECE Imaging Program for Fluctuation Studies on the KSTAR and DIII-D Tokamaks," **Invited Talk** presented at the *16th joint workshop on ECE and ECRH*, Sanya, China, April 12-15, 2010.

[8] A.J.H. Donné, "Imaging Techniques for Microwaves Diagnostics," **Invited Talk** at the *International Conference on Plasma Diagnostics*, Pont-à-Mousson, France, April 12-16, 2010.

[9] I.G.J. Classen, J.E. Bloom, W. Suttrop, E. Schmid, M. Garcia-Munoz, B. Tobias, C.W. Domier, N.C. Luhmann, Jr., H.K. Park, ASDEX Upgrade Team, "2D Electron Cyclotron Emission Imaging at ASDEX Upgrade," **Invited Talk** presented at the *18th Topical Conference on High-Temperature Plasma Diagnostics*, Wildwood, NJ, May 16-20, 2010.

[10] H.K. Park, M. Choi, I. Hong, M. Kim, J.C. Kim, W. Lee, G.S. Yun, B. Tobias, C.W. Domier, X. Kong, T. Liang, N.C. Luhmann, I. Classen, J.E. Boom, A.J.H. Donné, "Visualization of Fusion Plasma Physics via Millimeter Wave Imaging Techniques (Plenary)," *2010 35th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz 2010)*, Rome, Italy, Sept. 5-10, 2010.

[11] B. Tobias, "Electron Cyclotron Emission Imaging of MHD Activity on the DIII-D, TEXTOR, ASDEX-U, and KSTAR Tokamaks (Invited)," *52nd Annual Meeting of the APS Division of Plasma Physics*, Chicago, Illinois, Nov. 8-12, 2010, Paper GI2.2 (2010).

[12] N.C. Luhmann, Jr., "The Next Twenty Years in Plasma and Fusion Science (Plenary)," *20th International Toki Conference (ITC-20)*, Toki-City, Japan, Dec. 7-10, 2010, Paper PL-4.

[13] I.G.J. Classen, "Investigation on fast particle driven instabilities by 2D electron cyclotron emission imaging on ASDEX Upgrade and DIII-D (Invited)," *38th European Physical Society Conference on Plasma Physics*, Strasbourg, France, June 27 – July 1, 2011, Paper I2.105.

[14] G.S. Yun, "Two-dimensional imaging of edge-localized filaments in KSTAR H-mode plasmas," *53rd Annual Meeting of the APS Division of Plasma Physics*, Salt Lake City, Utah, Nov. 14-18, 2011, Paper YI2.5.

B). Refereed Journal Publications

[1] I.G.J. Classen, E. Westerhof, C.W. Domier, A.J.H. Donné, R.J.E. Jaspers, N.C. Luhmann, Jr., H.K. Park, M.J. van de Pol, G.W. Spakman and TEXTOR Team, "Effect of Heating on the Suppression of Tearing Modes in Tokamaks," *Physical Review Letters* **98**, 035001 (2007).

[2] T. Munsat, H.K. Park, I.G.J. Classen, C.W. Domier, A.J.H. Donné, N.C. Luhmann, Jr., E. Mazzucato, M.J. van de Pol, TEXTOR team, "Localization of the Magnetic Reconnection Zone During Sawtooth Crashes in Tokamak Plasmas," *Nuclear Fusion* **47**, pp. L31-L35 (2007).

[3] H.K. Park, N.C. Luhmann, Jr., A.J.H. Donné, C.W. Domier, T. Munsat, M.J. van der Pol, TEXTOR team, "New Insights to the Sawtooth Oscillation ("m/n = 1/1 mode") in Hot Plasmas based on High Resolution 2-D Images of T_e Fluctuations," *Plasma and Fusion Research* **2**, S1002 (2007).

[4] Zuowei Shen, Lu Yang, N.C. Luhmann, Jr., C.W. Domier, N. Ito, Y. Kogi, Y. Liang, A Mase, H. Park, E. Sakata, W. Tsai, Z.G. Xia, P. Zhang, "Advanced Microwave/Millimeter-Wave Imaging Technology," *Plasma and Fusion Research* **2**, S1019 (2007).

[5] Z. Shen, N. Ito, Y. Liang, L. Lin, C.W. Domier, M. Johnson, N.C. Luhmann, Jr., A. Mase, E. Sakata, "Protection Filters in ECEI Systems for Plasma Diagnostics," *Plasma and Fusion Research* **2**, S1030 (2007).

[6] I.G.J. Classen, R.J.E. Jaspers, H.K. Park, G.W. Spakman, M.J. van der Pol, C.W. Domier, A.J.H. Donné, N.C. Luhmann, Jr., E. Westerhof, M.W. Jakubowski, TEXTOR team, "Imaging Meso-Scale

Structures in TEXTOR with 2D-ECE," *Plasma and Fusion Research* **2**, S1031 (2007).

[7] Naoki Ito, Atsushi Mase, Yuichiro Kogi, Nariaki Seko, Masao Tamada, Zuowei Shen, Lu Yang, Calvin W. Domier, Neville C. Luhmann, Jr., Eliji Sakata, "Advanced Fabrication Method of Planar Components for Plasma Diagnostics," *Plasma and Fusion Research* **2**, S1042 (2007).

[8] T. Munsat, H.K. Park, I.G.J. Classen, C.W. Domier, A.J.H. Donné, N.C. Luhmann, Jr., E. Mazzucato, M.J. van de Pol, TEXTOR team, "Localization of the Magnetic Reconnection Zone During Sawtooth Crashes in Tokamak Plasmas," *Nuclear Fusion* **47**, L31 (2007).

[9] P. Zhang, C.W. Domier, T. Liang, X. Kong, B. Tobias, N.C. Luhmann, Jr., H. Park, I.G.J. Classen, M.J. van de Pol, A.J.H. Donné, R. Jaspers, "The Next Generation of Electron Cyclotron Emission Imaging (ECEI) Diagnostics (**Invited**)," *Review of Scientific Instruments* **79**, 10F103 (2008).

[10] G.W. Spakman, G.M.D. Hogeweij, R.J.E. Jaspers, F.C. Schüller, E. Westerhof, J.E. Boom, I.G.J. Classen, E. Delabie, C. Domier, A.J.H. Donné, M.Yu. Kantor, A. Krämer-Flecken, Y. Liang, N.C. Luhmann Jr, H.K. Park, M.J. van de Pol, O. Schmitz, J.W. Oosterbeek and the TEXTOR Team, "Heat Pulse Propagation Studies Around Magnetic Islands Induced by the Dynamic Ergodic Divertor in TEXTOR," *Nuclear Fusion* **48**, 115005 (2008).

[11] Xu Xiao-Yuan, Wang Jun, Yu Yi, Wen Yi-Zhi, Yu Chang-Xuan, Liu Wan-Dong, Wan Bao-Nian, Gao Xiang, N.C. Luhmann, C.W. Domier, Jian Wang, Z.G. Xia, Zuowei Shen, "Electron temperature fluctuation in the HT-7 tokamak plasma observed by electron cyclotron emission imaging," *Chinese Physics B* **18**, 1153-1160 (2009).

[12] B. Tobias, X. Kong, T. Liang, A. Spear, C.W. Domier, N.C. Luhmann, Jr., I.G.J. Classen, J.E. Boom, M.J. van de Pol, R. Jaspers, A.J.H. Donné, H.K. Park, and T. Munsat, "Advancements in electron cyclotron emission imaging demonstrated by the TEXTOR ECEI diagnostic upgrade," *Review of Scientific Instruments* **80**, 093502, (2009).

[13] T. Munsat, C.W. Domier, X. Kong, T. Liang, N.C. Luhmann, Jr., B.J. Tobias, W. Lee, H.K. Park, G. Yun, I..G.J. Classen, and A.J.H. Donné, "Electron cyclotron emission imaging in tokamak plasmas," *Applied Optics* **49**, pp. E20-E30 (2010).

[14] X. Xu, J. Wang, Y. Wen, Y. Yu, A. Liu, T. Lan, C. Yu, B. Wan, X. Gao, Y. Sun, N.C. Luhmann, Jr., C.W. Domier, Z.G. Xia and Z. Shen, "Experimental investigation of m/n = 1/1 and high-order harmonic modes during the sawtooth oscillation in a low β tokamak plasma," *Plasma Physics & Controlled Fusion* **52**, 015008 (2010).

[15] T. Liang, B. Tobias, X. Kong, C.W. Domier, N.C. Luhmann, Jr., W. Lee, G.S. Yun, and H.K. Park, "Innovations in Optical Coupling of the KSTAR ECEI Diagnostic," *Review of Scientific Instruments* **81**, 10D909 (2010).

[16] X. Kong, C.W. Domier, and N.C. Luhmann, Jr., W. Lee, G.S. Yun, and H.K. Park, "Antenna Development for High Field Plasma Imaging," *Review of Scientific Instruments* **81**, 10D923 (2010).

[17] B. Tobias, C.W. Domier, T. Liang, X. Kong, L. Yu, G.S. Yun, H.K. Park, I.G.J. Classen, J.E. Boom, A.J.H. Donné, T. Munsat, R. Nazikian, M. van Zeeland, R.L. Boivin, N.C. Luhmann, Jr., "Commissioning of electron cyclotron emission imaging instrument on the DIII-D tokamak and first data," *Review of Scientific Instruments* **81**, 10D928 (2010).

[18] I.G.J. Classen, J.E. Boom, W. Suttrop, E. Schmid, B. Tobias, C.W. Domier, N.C. Luhmann, Jr., A.J.H. Donné, R. Jaspers, P.C. deVries, H.K. Park, T. Munsat, M. García-Muñoz, P.A. Schneider, "2D electron cyclotron emission imaging at ASDEX Upgrade (invited)," *Review of Scientific Instruments* **81**, 10D929, (2010).

[19] G.S. Yun, W. Lee, M.J. Choi, J.B. Kim, H.K. Park, C.W. Domier, B. Tobias, T. Liang, X. Kong, N.C. Luhmann, Jr., and A.J.H. Donné, "Development and Prospect of ECE Imaging System for KSTAR," *Review of Scientific Instruments* **81**, 10D930 (2010).

[20] J.B. Kim, W. Lee, G.S. Yun, H.K. Park, C.W. Domier, N.C. Luhmann, Jr., "Data acquisition and

processing system of the electron cyclotron emission imaging system of the KSTAR tokamak," *Review of Scientific Instruments* **81**, 10D931 (2010).

[21] B. Tobias, N.C. Luhmann, Jr., C.W. Domier, X. Kong, T. Liang, S. Che, R. Nazikian, L. Chen, G. Yun, W. Lee, H.K. Park, I.G.J. Classen, J.E. Boom, A.J.H. Donné, M.A. Van Zeeland, R. Boivin, Y. Nagayama, T. Yoshinaga, D. Kuwahara, S. Yamaguchi, Y. Kogi, A. Mase, and T. L. Munsat, "Recent progress on microwave imaging technology and new physics results," *Plasma and Fusion Research* **6**, 2106042 (2011).

[22] B.J. Tobias, I.G.J. Classen, C.W. Domier, W.W. Heidbrink, N.C. Luhmann, Jr., R. Nazikian, H.K. Park, D. A. Spong, and M.A. Van Zeeland, "Fast Ion Induced Shearing of 2D Alfvén Eigenmodes Measured by Electron Cyclotron Emission Imaging," *Physical Review Letters* **106**, 075003 (2011).

[23] B.J. Tobias, R.L. Boivin, J.E. Boom, I.G.J. Classen, C.W. Domier, A.J.H. Donné, W.W. Heidbrink, N.C. Luhmann, T. Munsat, C.M. Muscatello, R. Nazikian, H.K. Park, D.A. Spong, A.D. Turnbull, M.A. Van Zeeland, G.S. Yun, and DIII-D Team, "On the application of electron cyclotron emission imaging to the validation of theoretical models of magnetohydrodynamic activity," *Physics of Plasmas* **18**, 056107 (2011).

[24] M.A. Van Zeeland, W.W. Heidbrink, R.K. Fisher, M. García Muñoz, G.J. Kramer , D.C. Pace, R.B. White, S. Aekaeslompolo, M.E. Austin, J.E. Boom, I.G.J. Classen, S. da Graça, B. Geiger, M. Gorelenkova, N.N. Gorelenkov, A.W. Hyatt, N. Luhmann, M. Maraschek, G.R. McKee, R.A. Moyer, C.M. Muscatello, R. Nazikian, H. Park, S. Sharapov, W. Suttrop, G. Tardini, B.J. Tobias, Y.B. Zhu, and DIII-D and ASDEX Upgrade Teams, "Measurements and modeling of Alfvén eigenmode induced fast ion transport and loss in DIII-D and ASDEX Upgrade," *Physics of Plasmas* **18**, 056114 (2011).

[25] B. Tobias, A.J.H. Donné, H.K. Park, J.E. Boom, M.J. Choi, I.G.J. Classen, C.W. Domier, X. Kong, W. Lee, T. Liang, N.C. Luhmann, Jr., T. Munsat, L. Yu, and G.S. Yun, "Imaging Techniques for Microwave Diagnostics," *Contributions to Plasma Physics* **51**, pp. 111–118 (2011).

[26] G. S. Yun, W. Lee, M. J. Choi, J. Lee, H. K. Park, B. Tobias, C. W. Domier, N. C. Luhmann, Jr., A. J. H. Donn, J. H. Lee, and KSTAR Team, "Two-Dimentional Visualization of Growth and Burst of the Edge-Located Filaments Filaments in KSTAR H-Mode Plasmas", *Physical Review Letters* **107**, 045004 (2011).

[27] E. Wolfrum, M. Bernert, J.E. Boom, A. Burckhart, I.G.J. Classen, G.D. Conway, T. Eich, R. Fischer, A. Gude, A. Herrmann, N.C. Luhmann, Jr. M. Maraschek, R. McDermott, H.K. Park, T. Puumltterich, J. Vicente, B. Wieland, M. Willensdorfer, "Characterization of edge profiles and fluctuations in discharges with type-II and nitrogen-mitigated edge localized modes in ASDEX upgrade," *Plasma Physics and Controlled Fusion* 53, 085026, (2011).

[28] B. Tobias, C.W. Domier, N.C. Luhmann, Jr., J.E. Boom, I.G.J. Classen, A.J.H. Donné, G.S. Yun, H.K. Park, R. Nazikian, "Sawtooth Precursor Oscillations on DIII-D", accepted for publication in *6th Triennial Special Issue of the IEEE Transactions on Plasma Science, Images in Plasma Science*, (2011).

Appendix II: Background

Electron cyclotron emission (ECE) occurs at harmonics of the cyclotron frequency, ω_{ce}, which in a tokamak depends on its major radius R and leads to a 1:1 mapping between ω_{ce} and R. In plasmas with sufficiently high density and temperature, the ECE intensity is proportional to the local T_e value. ECEI images this emission onto a vertically aligned mixer array, allowing each array element to collect wide bandwidth radiation that is subsequently resolved into frequency bands. This, in essence, attaches a multi-channel radiometer to each array element and generates 2-D time-resolved T_e profile and fluctuation images (see Fig. 3).

Microwave reflectometry is a radar technique employed to infer the electron density characteristics by probing the density-dependent cutoff layer. The fundamental issue confronting reflectometry of density fluctuations concerns the interpretation of the measured amplitude and phase of the reflected waves. Unless the fluctuation level is extremely low and/or the fluctuation wavelength at the cutoff layer is very long, conventional reflectometry methods face a challenge in interpreting the measured amplitude and phase except for measurements near the plasma edge. MIR is a technique in which large aperture optics at the plasma edge are used to collect as much of the scattered wavefront as possible and optically focus an image of the cutoff surface onto an array of detectors (see Fig. 4), thus restoring the integrity of the phase measurement.

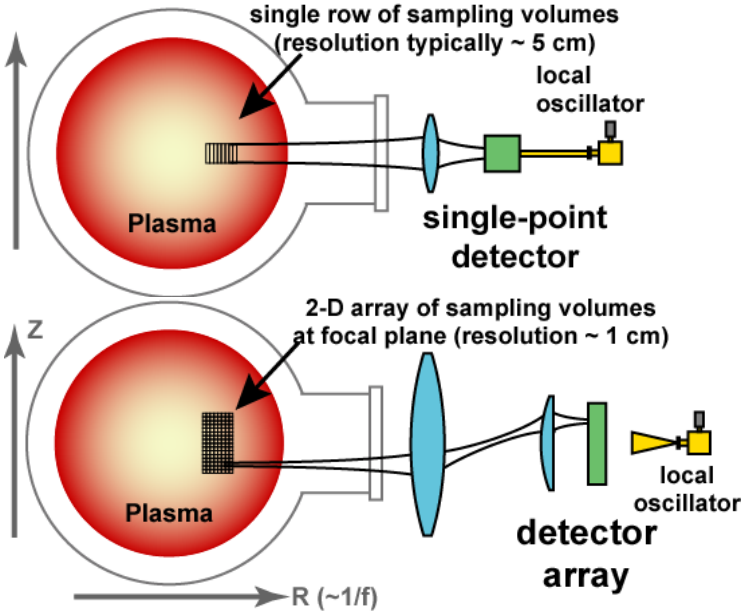


Fig. 3. Schematic diagram of the physical principles governing ECE (top) and ECEI (bottom) systems.

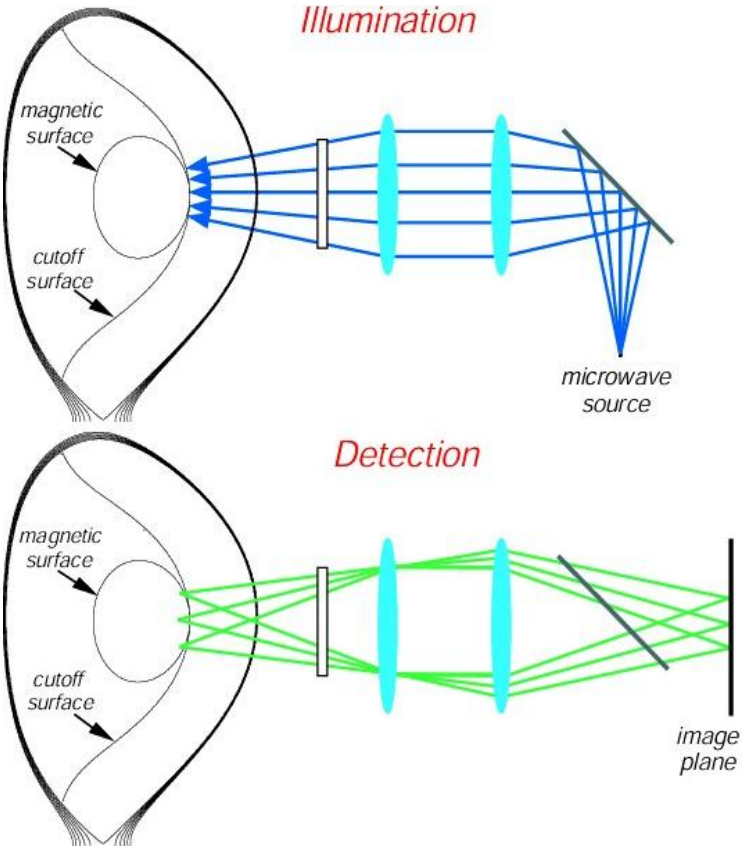


Fig. 4. Schematic illustration of the physical principles governing MIR systems.