

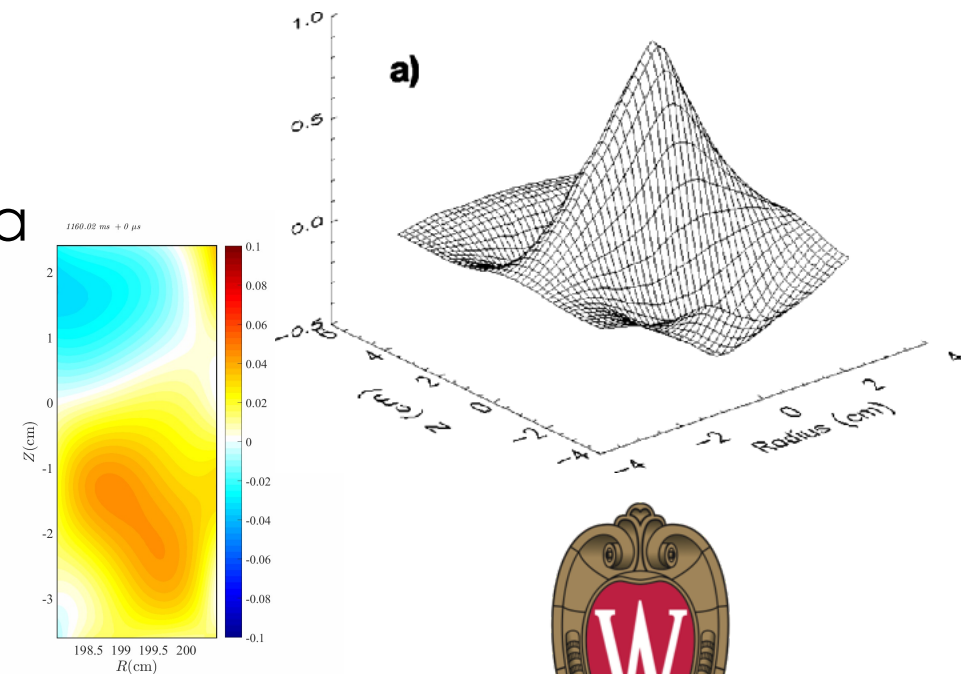
A Collaboration between the University of Wisconsin-Madison and SWIP: Developing Fluctuation Diagnostics for Turbulence Physics*

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****Supported by SWIP-CNNC Contract***



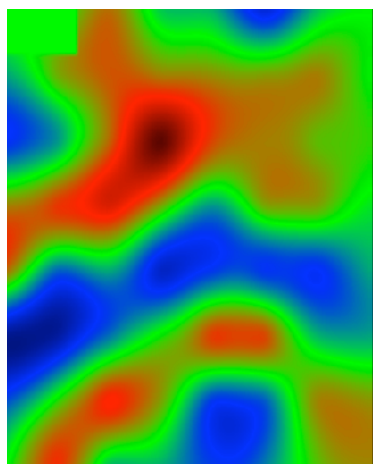
US-PRC
Magnetic Fusion Collaboration Workshop
March 22-25, 2021



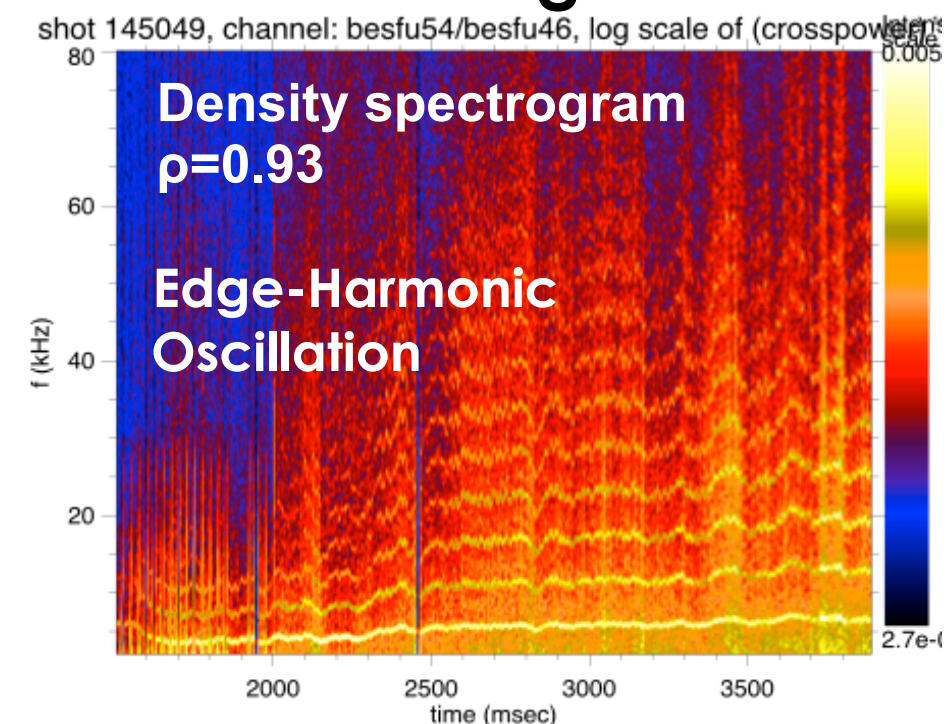
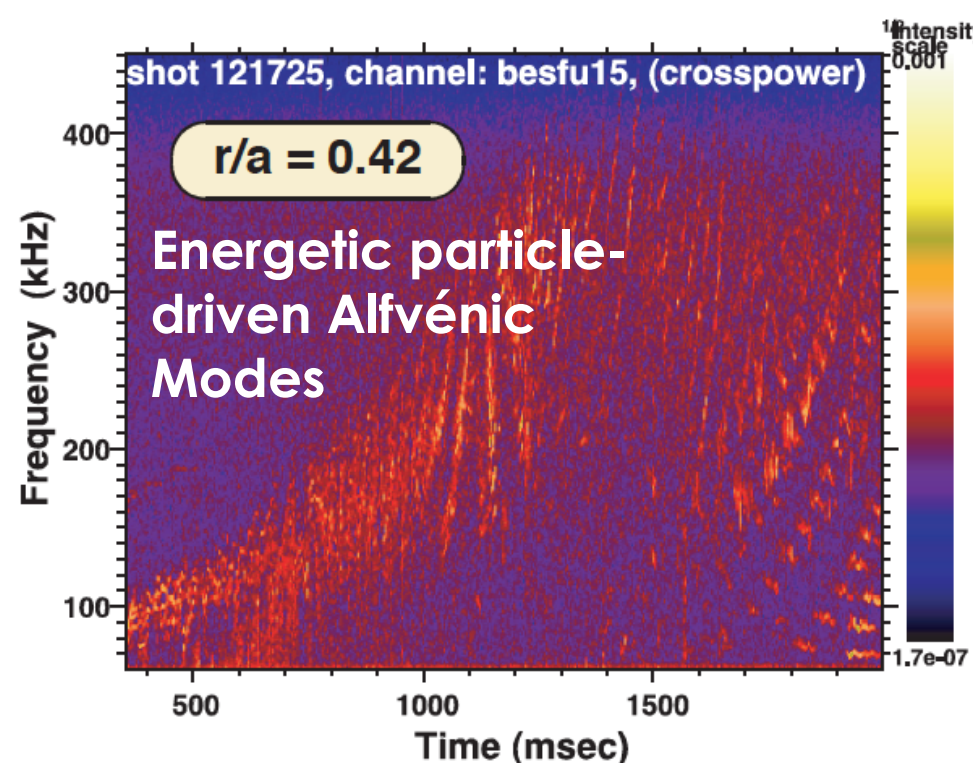
Objectives and Goals for a Collaboration on Fluctuation Measurements for Turbulence & Instability Research

- **Goal: Collaborative research through advanced measurement capability**
- **Wide range of instability phenomena impact tokamak plasma performance**
 - Core turbulence characterization: model & simulation testing and validation
 - L-H transition dynamics (see Z. Yan later this workshop), H-mode Pedestal Instabilities
 - Energetic Particle modes: Alfvén eigenmodes; Magnetic perturbation effects
 - Divertor/SOL-pedestal-core interactions; SOL heat flux width
- **Work-force development through university collaboration**
 - Graduate students & Postdoctoral researchers
- **Synergistic Diagnostic activities will benefit China and US MFE Programs**

Ion scale
Turbulence Imaging



2



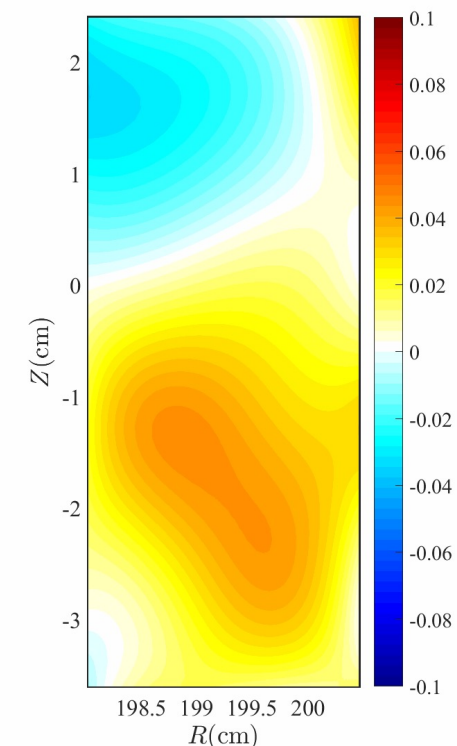
Highlights and Accomplishments

- **Deployed 32-channel BES Diagnostic System at SWIP:**
 - Installed a 16-channel Modular BES Diagnostic System
 - Installed a new 16-channel Integrated BES Diagnostic System
 - Loaned a 16-channel NSTX-U BES Diagnostic (~1 year: 2018-2019)
- **Performed Experiments at HL-2A:**
 - Led turbulence experiment on ρ^* scaling of turbulence on HL-2A
 - Led experiment on L-H physics with applied magnetic perturbations
 - Supported experiment on ExB Staircase turbulence + others
- **Multiple On-going Activities**
 - Jointly designing integrated multichannel Imaging BES for wide-field 2D turbulence measurements
 - Related diagnostic studies under consideration
 - Ongoing research seminars at SWIP
 - Graduate student/scientific staff research collaborations
 - *Thesis research project for graduate student*
- **Multiple publications and conference presentations**

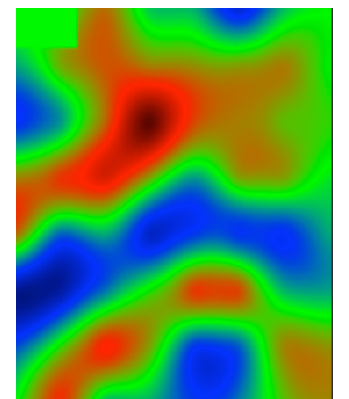
Turbulence
Imaging

HL-2A

1160.02 ms + 0 μ s



DIII-D

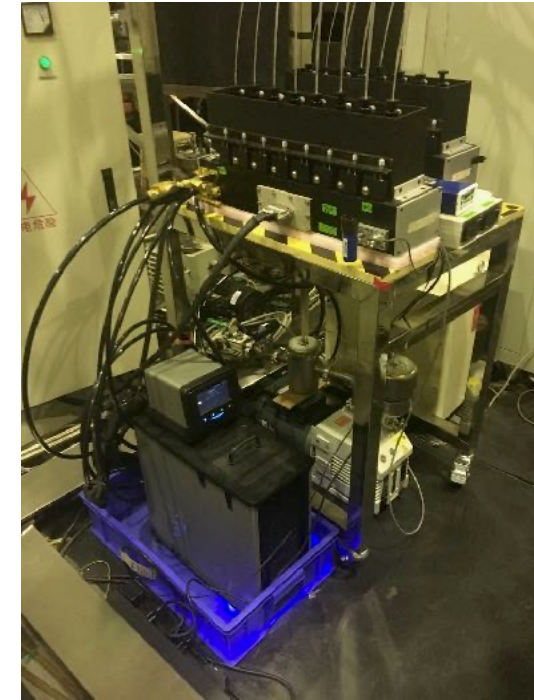


Diagnostic Development Activities

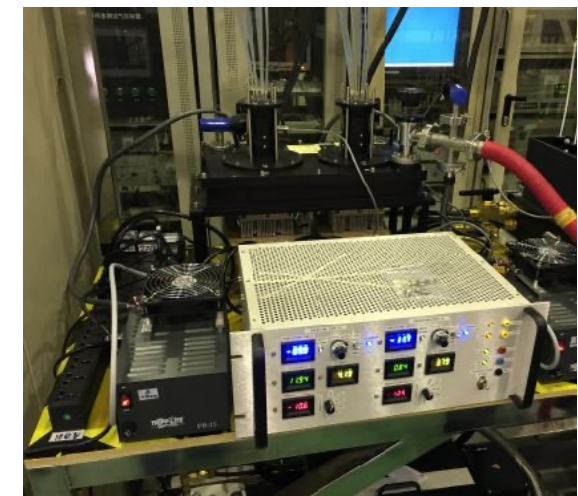
Implemented a Multiphase Approach to Developing BES on HL-2A & HL-2M

- **Objective: Develop a high-performance, multichannel 2D Beam Emission Spectroscopy diagnostic for HL-2A and HL-2M tokamaks to measure low-k density fluctuations**
 - $\Delta R \sim 1$ cm, $\Delta Z \sim 1.2$ cm, $f = 2$ MHz, 2D Imaging capability
- **Phase 1: Build a modernized “NSTX-style” BES system**
 - 2 8-channel modules, deployed in 2017
- **Phase 2: Design and build a new, novel integrated system**
 - 2 8-channel arrays; more economical (reduced \$/channel)
 - Thermo-electrically cooled; integrated optical system, single filter
 - Deployed March, 2019
- **Phase 3: Design and build a large-scale imaging BES**
 - 64-channel array-based advanced imaging BES diagnostic
 - Underway through multi-institute collaboration: UW, DIII-D, SWIP
 - Designed at UW; related DIII-D CXI diagnostic being built, tested
 - Seek to built SWIP-BES system later this year: deploy 2022-23

Phase 1

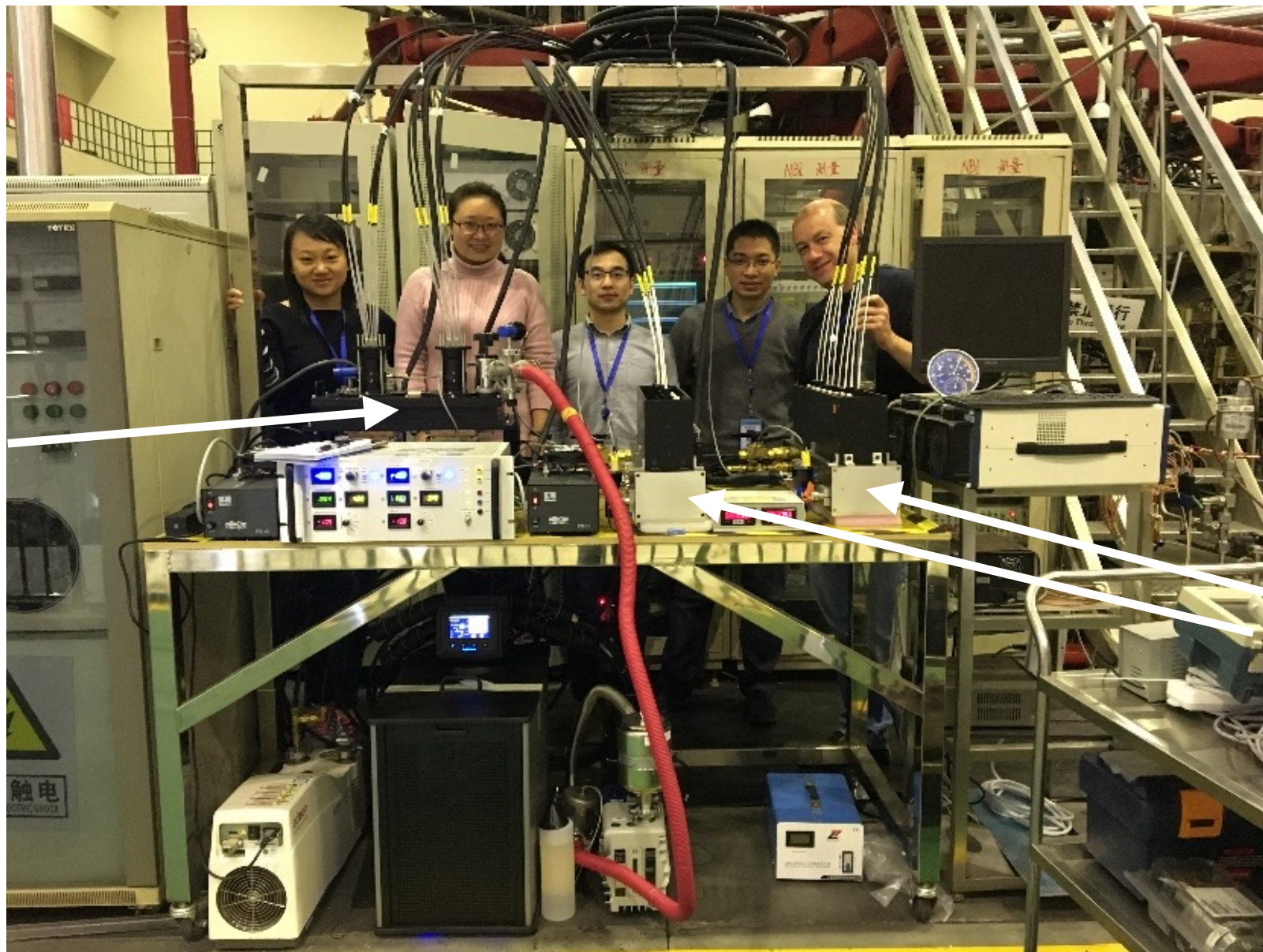


Phase 2



Phase 2 Integrated BES System Installed at SWIP for HL-2A

- An integrated BES diagnostic with 16 channels, 8 per module (*2) developed by UW for SWIP and is installed at HL-2A Tokamak
 - More economical system (\$/channel); improved performance



**16-channel
Integrated
BES**

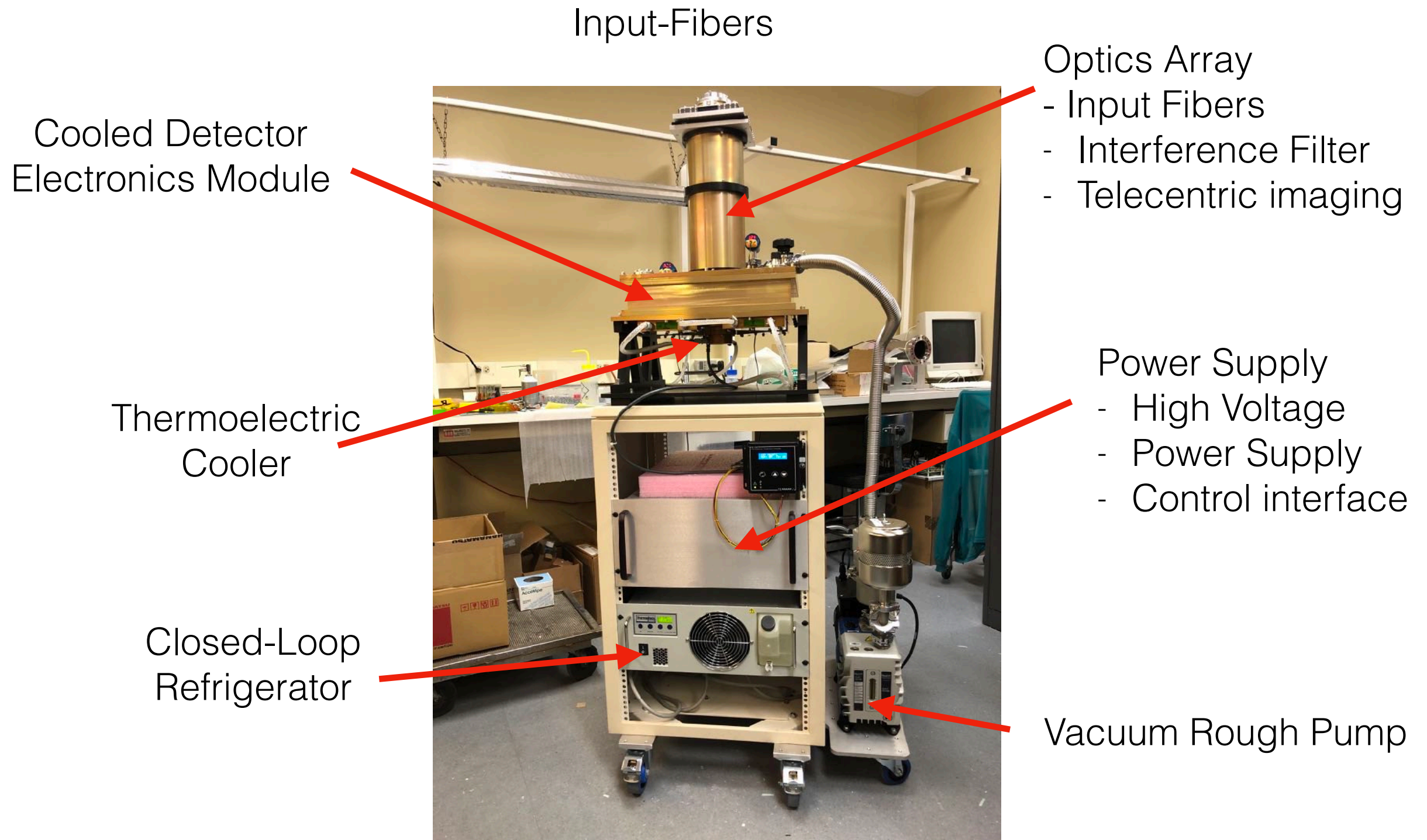
Zheng Yan, Ting Wu,
Yifan Wu, Rui Ke,
George McKee
at SWIP installing new
systems

**16-channel
NSTX-U BES
System
(on loan)**

Joint Diagnostic Development Effort for Fluctuation Diagnostics Offers Benefits to US & China FES Programs

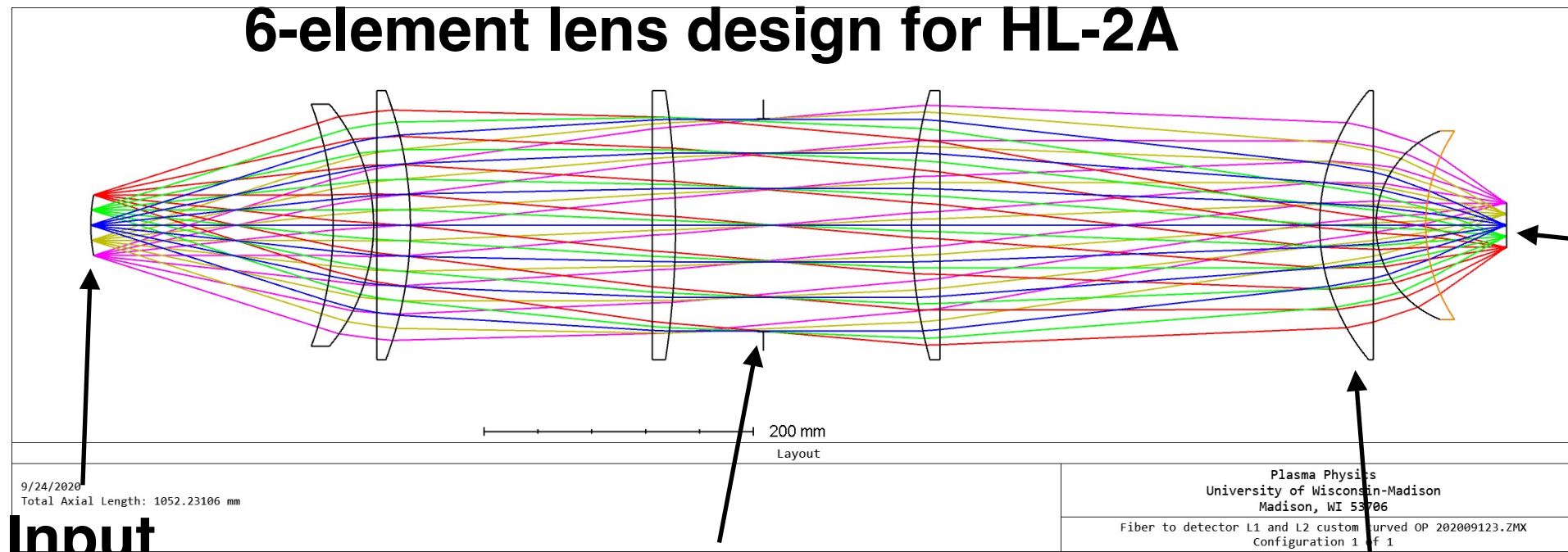
- **By combining development resources with SWIP and US programs (DIII-D, NSTX-U, potentially others), have designed integrated system**
 - Comparable or better performance than previous generation of modular detectors
 - Simpler deployment at remote facilities
 - *Smaller, more compact system*
 - *Only requires AC power, network linkages (no cryo, vacuum, coolant, external chiller)*
 - Significantly lower costs-per-channel
- **SWIP collaboration provided unique opportunity to pursue the integrated development path**
- **Benefits to diagnostic activities in US:**
 - Charge eXchange Imaging deployment @DIII-D
 - BES-Expansion @DIII-D
 - UF-CHERS, SHS Improvements at DIII-D
 - Application to NSTX-U, +

64-Channel APD-based Integrated Imaging CXI System: Foundation for Phase 3 SWIP-BES Diagnostic



High-Throughput Telecentric Optical System Designed to Relay Input Fiber Light to Detector and Provide Spectral Filter

6-element lens design for HL-2A

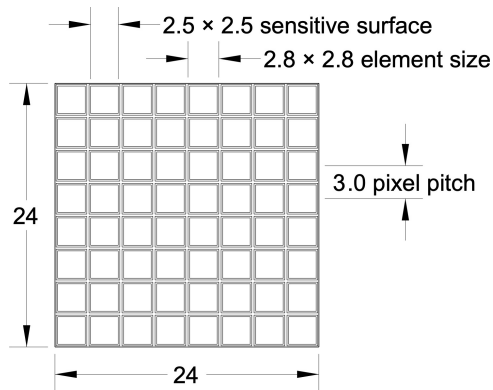


Photodiode Array (Chilled, in Vacuum)

Input Fiber Array

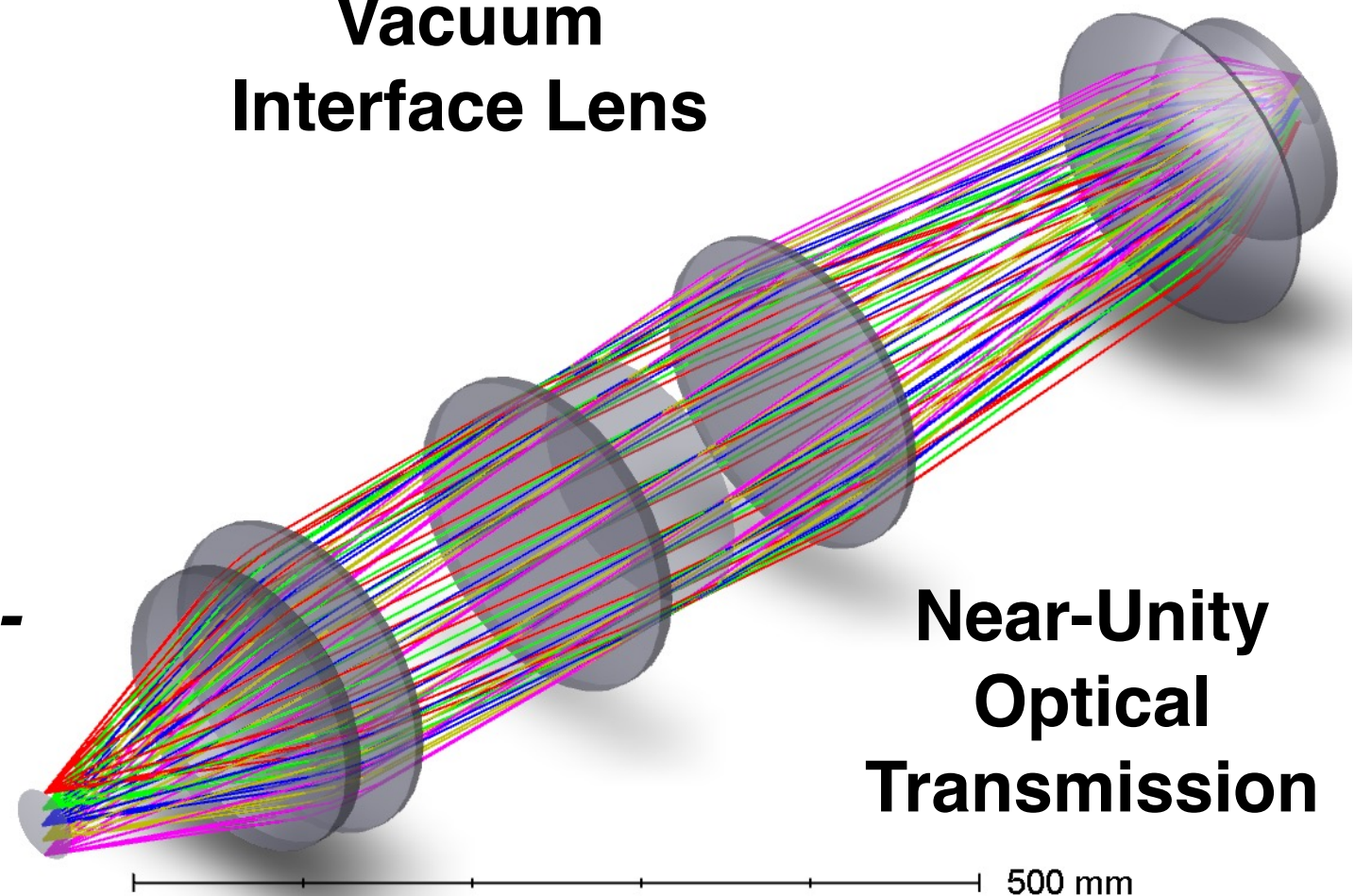
Interference Filter at Aperture Stop $\lambda=659-661$ nm

Vacuum Interface Lens



Photodiode Array (Hamamatsu 8x8)

D. DenHartog - UW-Madison

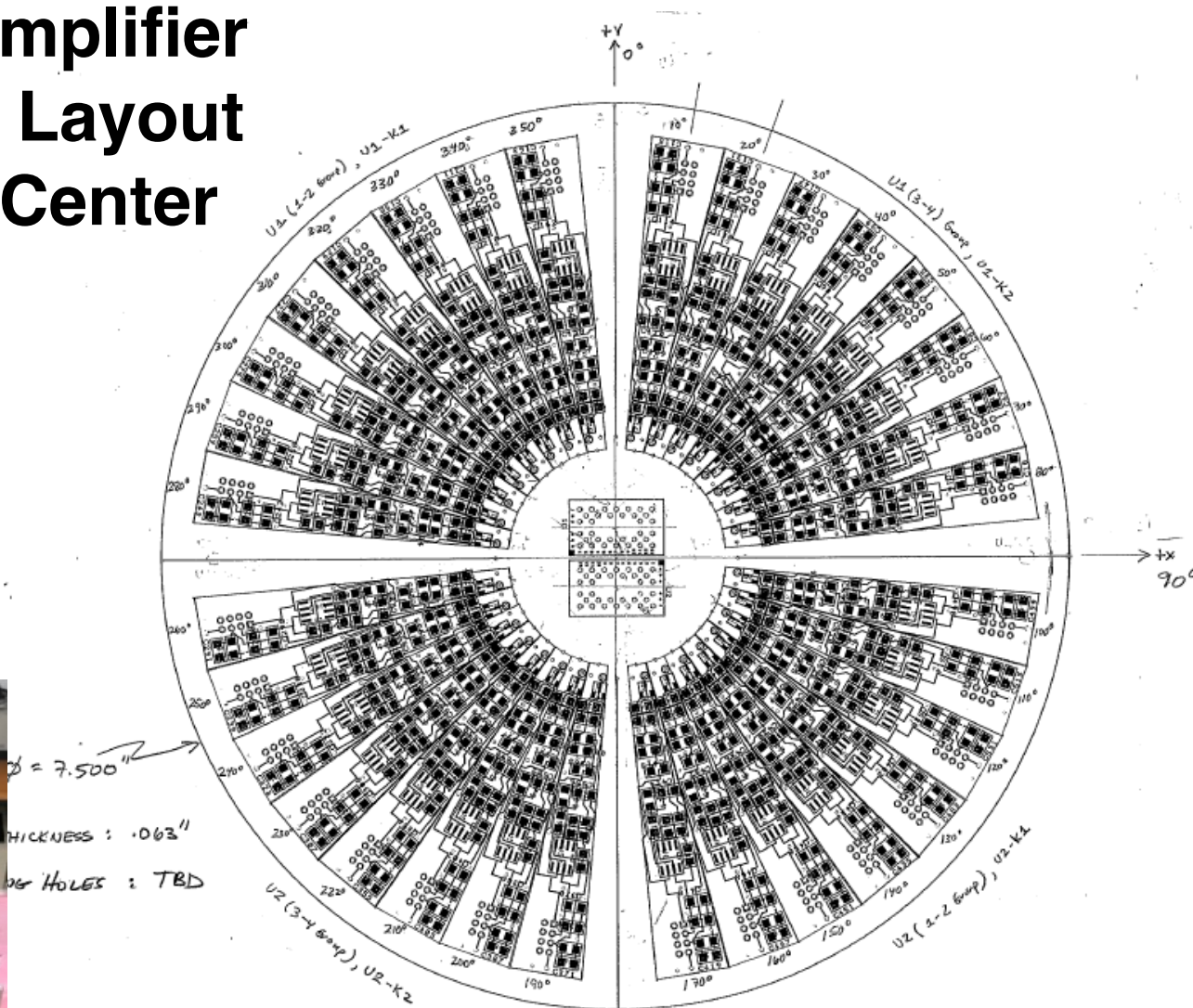
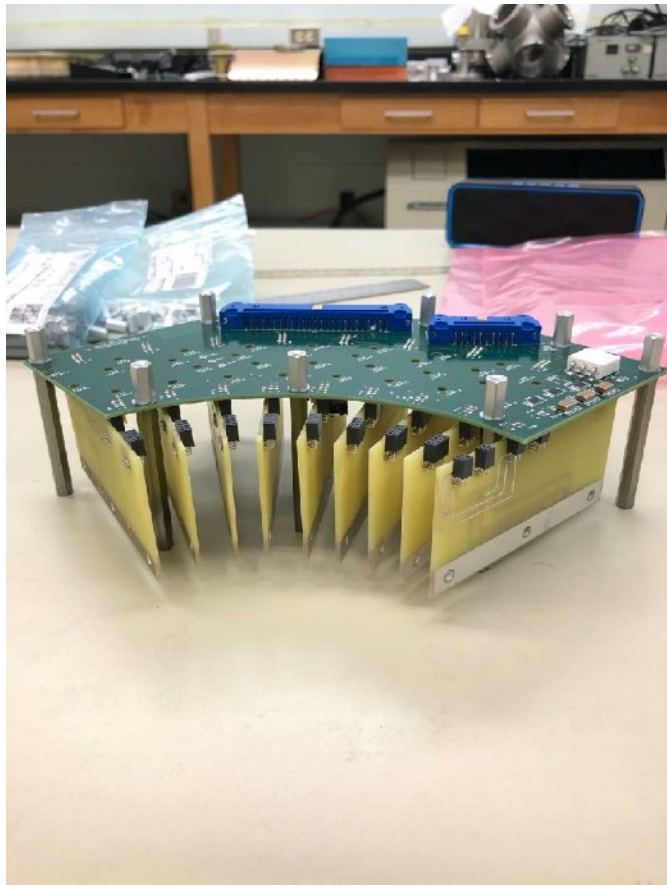


Near-Unity Optical Transmission

2D APD/PD Array and Pre-Amplifier Electronics Compressed into Single TEC-Cooled Detector Module

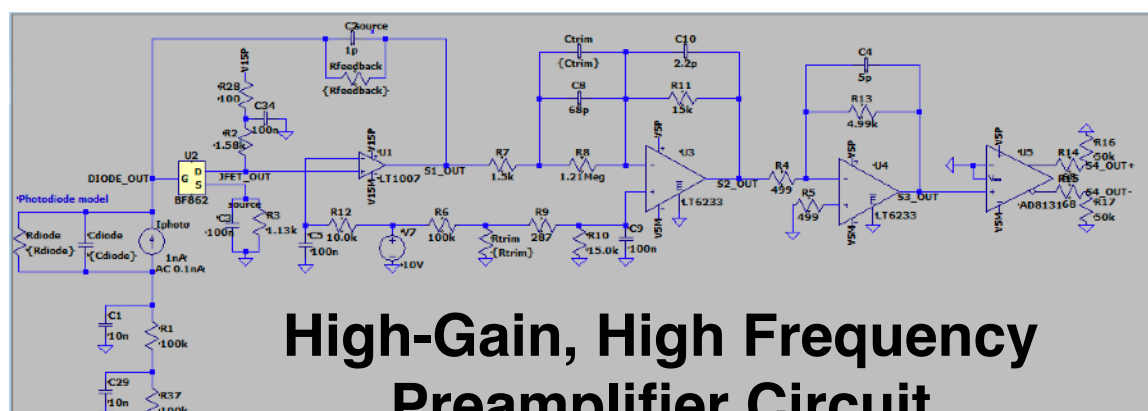
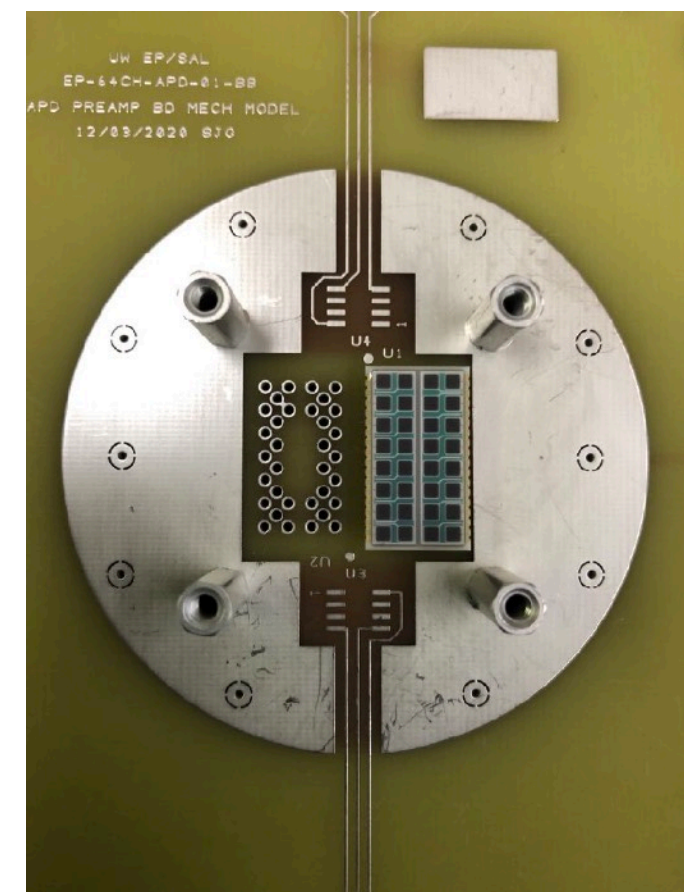
Radial Preamp
Electronics Layout
Detector@Center

Sector Layout
with "Fin Board"
PCB Preamp



$\phi = 7.500''$
THICKNESS: .062"
Holes: TBD

Multichannel
Imaging Detector
Array
(@Image Plane)



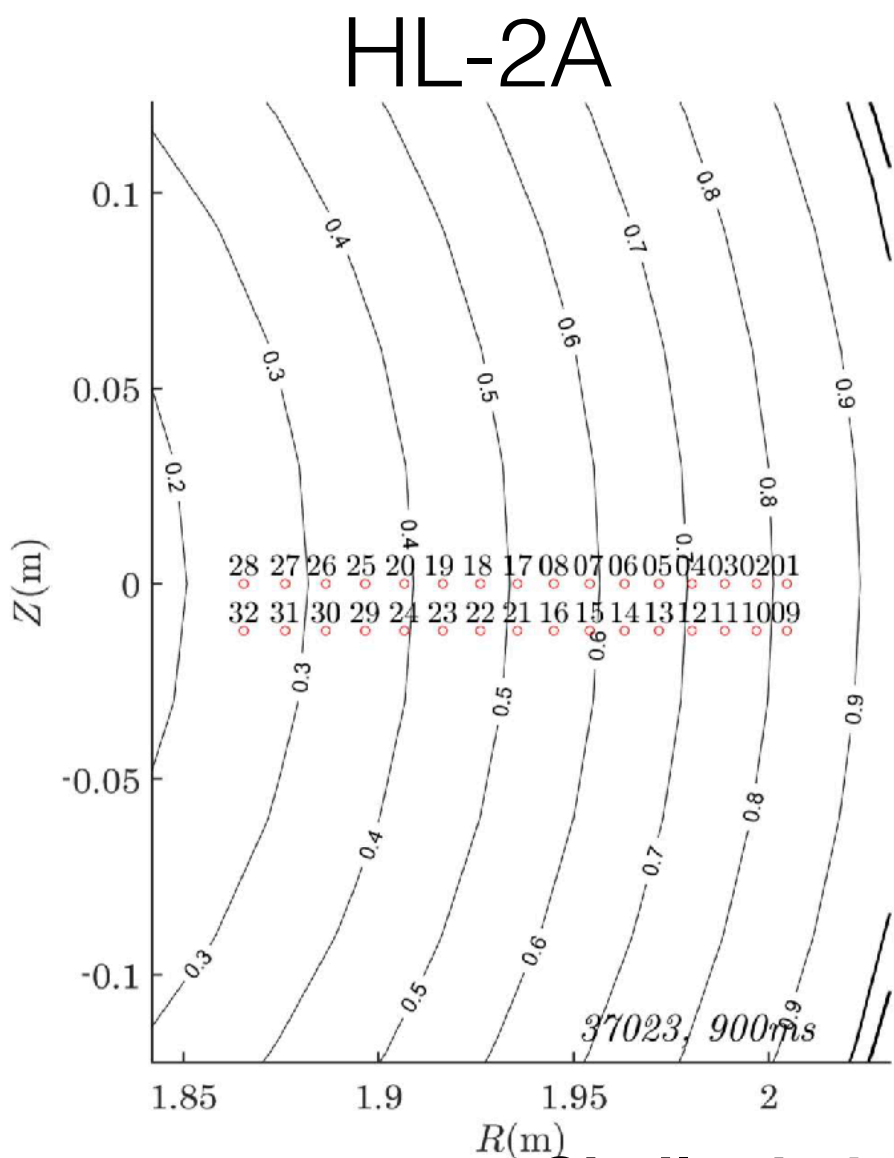
High-Gain, High Frequency
Preamplifier Circuit
 $f=2$ MHz, $G=10$ MOhm

Scientific Projects

Scientific Research Activity

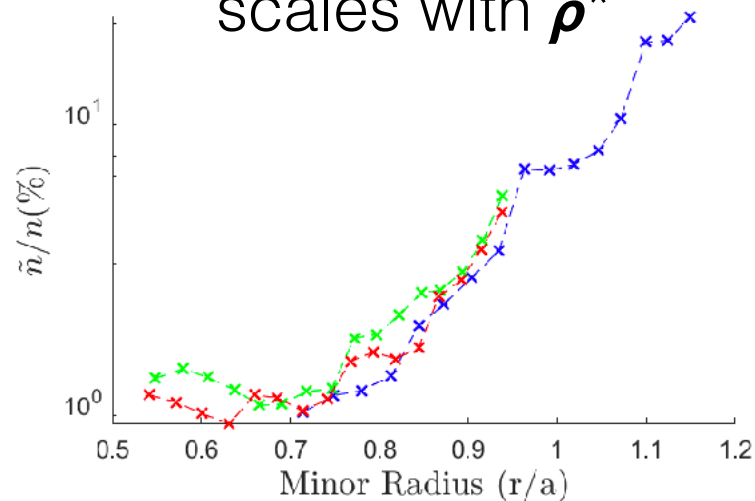
ρ^* Scaling of Turbulence Characteristics Measured at HL-2A

BES configured to measure radial profile of low-k density fluctuations

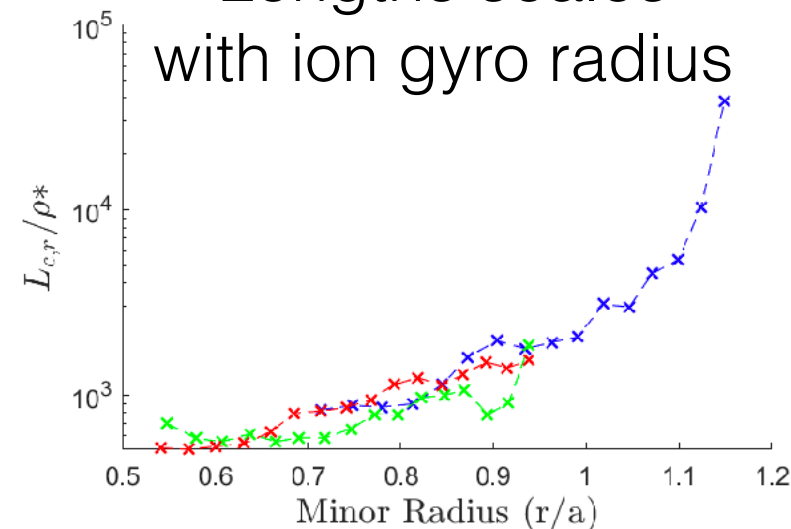


Similar behavior to that observed at DIII-D

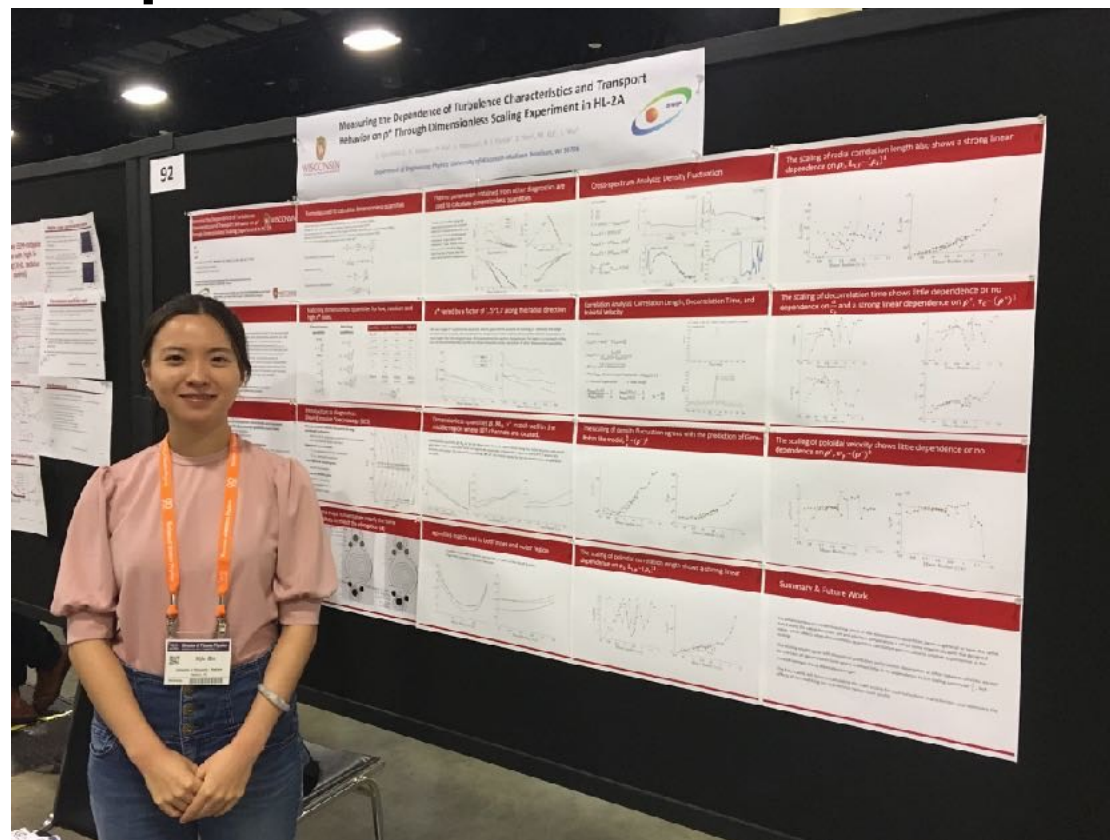
Density fluctuation amplitude, \tilde{n}/n scales with ρ^*



Radial Correlation Lengths scales with ion gyro radius



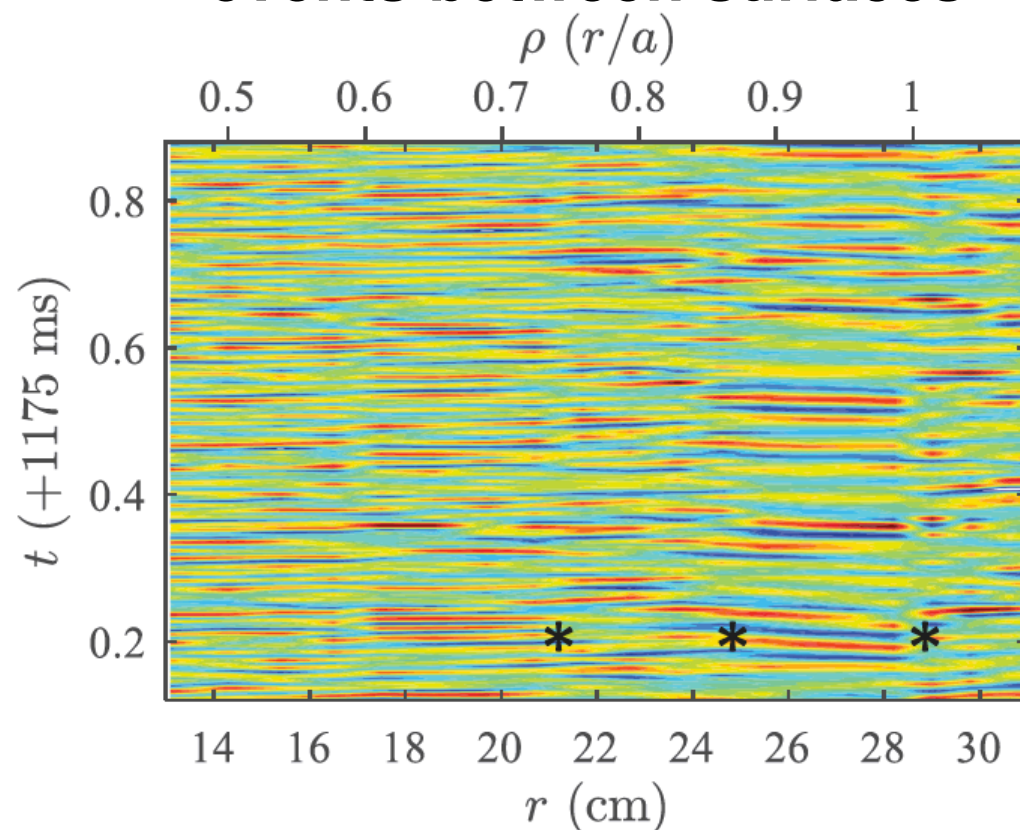
UW Graduate Student Xijie Qin presents results at APS-2019



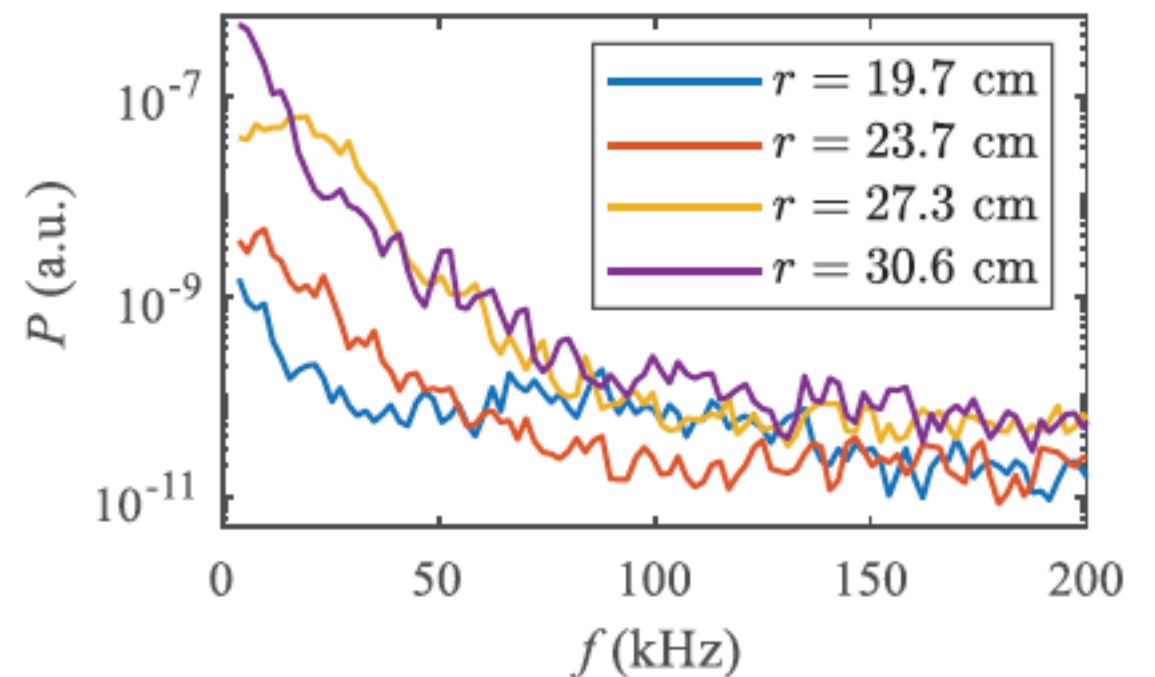
ExB Staircase Observed with BES in HL-2A

- **Turbulence features consistent with theoretically predicted ExB shear layers observed**
 - Tilted eddy structures and propagation velocity reversals of turbulence near profile T_e corrugation surfaces
 - Meso-scale transport events observed between corrugations
- **Contributed to Ph.D. dissertation by Tsinghua student, Wenbin Liu**

Meso-Scale fluctuation events between surfaces



BES Power Spectra at multiple radii



W. Liu, Y. Chen, R. Ke, G. McKee, Z Yan, G. Tynan et al., Phys. Plasmas **28**, 012512 (2021)

UW-SWIP Personnel Exchanges Fostered New Research Activities

- **Graduate Student: Rui Ke (Xinghua University, now SWIP)**
 - Spent 6 months at DIII-D working with UW scientists (McKee, Yan)
 - Learned diagnostics, supported experiments, analyzed data
- **Graduate Student: Yifan Wu (USTC-Hefei)**
 - Spent 12 months at DIII-D and at UW
 - Assisted with Integrated BES development, Pedestal fluctuations in SH-Mode
- **Graduate Student: Xijie Qin (University of Wisconsin)**
 - Currently spending 9 months at SWIP (pandemic response!)
 - Pursuing HL-2A experiment on intrinsic rotation-turbulence research
 - Will continue at DIII-D in future
- **Post-doctoral researcher: Lucas Mortan (University of Wisconsin, TAE)**
 - Travelled to SWIP for loaned system installation
- **G. McKee, Z. Yan (UW) travel frequently to SWIP**
 - Diagnostic activities, experiments
 - Presented multiple physics seminars

Multiple Scientific Publications Presentations Enabled Through Diagnostic Collaboration

- **Initial beam emission spectroscopy diagnostic system on HL-2A tokamak**
 - R. Ke, Y.F. Wu, G.R. McKee, Z. Yan, *et al.*, Rev. Sci. Instrum. **89**, 10D122 (2018)
- **Simulation of neutral beam attenuation and its influence to beam emission spectroscopy diagnostic on HL-2A tokamak**
 - Yifan Wu *et al.* Journal of Instrumentation, 2018, **13**(10):P10026-P10026,
- **Evidence of $E \times B$ staircase in HL-2A L-mode tokamak discharges**
 - W. Liu, Y. Chen, R. Ke, G. McKee, Z Yan, G. Tynan *et al.*, Phys. Plasmas **28**, 012512 (2021)
- **Development of a 32-channel Beam Emission Spectroscopy diagnostic based on Neutral Beam Injection on HL-2A tokamak**
 - Yifan Wu *et al.* Fusion Engineering and Design, 2020, **156**:111734
- **Multi-scale interaction between tearing modes and micro-turbulence in HL-2A plasmas**
 - Min Jiang *et al.*, Plasma Science and Technology, 2020, **22**(8):080501
- **Edge-coherent oscillation providing nearly continuous transport during ELM mitigation by $n = 1$ resonant magnetic perturbation in HL-2A**
 - Tengfei Sun *et al.* Nuclear Fusion, 2021, **61**(3):0360,

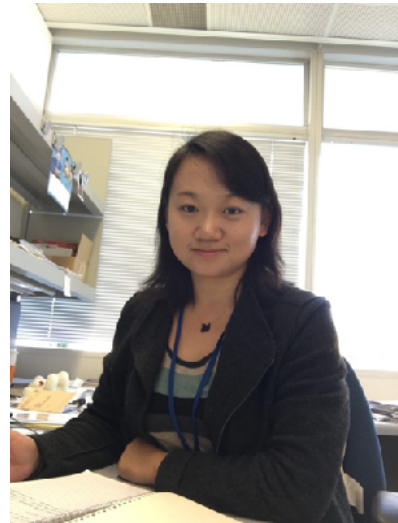
Multiple Technical Presentations Enabled Through Diagnostic Collaboration

- **Development of Beam Emission Spectroscopy on HL-2A**
 - Y. Wu, R. Ke, M. Xu, G. McKee, Z. Yan et al., *High Temperature Plasma Diagnostics Conference*, San Diego, CA (2018)
- **Integrated 2D BES for the HL-2A/2M Tokamaks**
 - Z. Yan, K. Jaehnig, G. McKee et al., *High Temperature Plasma Diagnostics Conference*, San Diego, CA (2018)
- **Measuring Turbulence Characteristics on ρ^* in HL-2A**
 - X. Qin, G. McKee, R. Ke, L. Morton, R. Fonck Z. Yan, M. Xu, T. Wu, *American Physical Society-Div. of Plasma Phys.*, Fort Lauderdale, FL (2019)
- **SWIP Scientific Seminars**
 - *Impact of Fuel Ion Isotope Mass on Confinement, Turbulence and the L-H Transition in DIII-D**, G. McKee, December, 2019
 - *Bursty Wiggles: A Pedestal-to-SOL Transport Mechanism During RMP-ELM Suppression*, G. McKee, June 2018
 - *Turbulence and Transport Response to 3D Resonant Magnetic Perturbations in ELM-Suppressed Plasmas*, G. McKee, November, 2016
 - *Turbulence and sheared flow structures behind the isotopic dependence of the L-H power threshold*, Z. Yan, December, 2017

UW and SWIP Colleagues Participate Actively in Collaboration



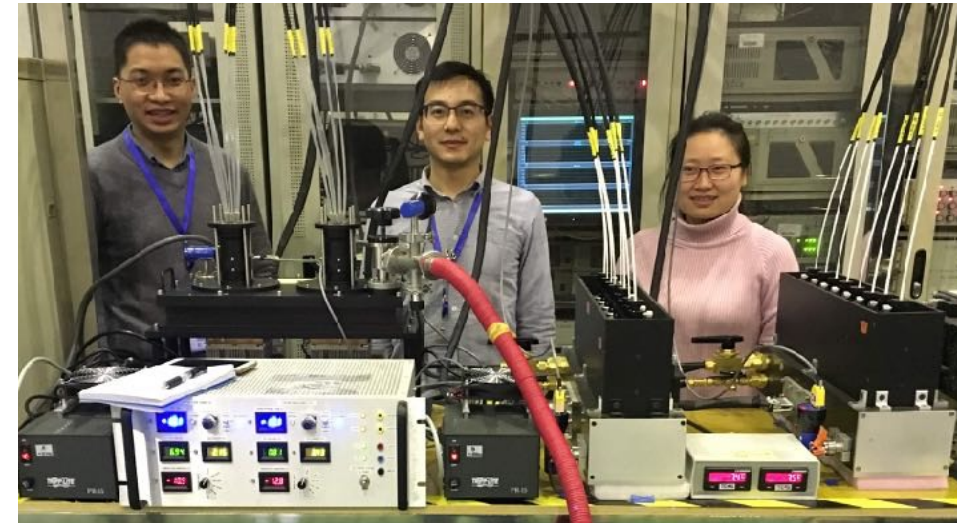
G. McKee, UW
Senior Scientist



Z. Yan, UW
Assoc. Scientist



X. Qin, UW
Graduate Student



Rui Ke (SWIP)
Yifan Wu (USTC)
Ting Wu (SWIP)



K. Jaehnig, UW
Instrumentation
Specialist



B. Geiger, UW
Assistant
Professor

↑
Ph.D Plan:

- Joint HL-2A & DIII-D
- Role of Turbulence in
- Driving Intrinsic Rotation



Min Xu (SWIP)

Future Activities for UW-SWIP Collaboration

- **Develop and deploy Phase 3 BES diagnostic on HL-2A**
 - 64-channel integrated imaging BES diagnostic for wide-field turbulence and flow measurement and analysis (complement existing 32-channel capability from Phases 1 & 2 development)
- **Evaluate HL-2M designs options for implementation**
 - Detector systems can be deployed to HL-2M
 - Requires new optical design to view neutral beam and fiber array
- **Consider complementary turbulence diagnostic systems**
 - **UF-CHERS**: T_i and V_{TOR} measurement
 - **CXI**: high-spatial resolution pedestal fluctuation measurements
 - **Lyman-alpha BES**: high SNR, high spatial resolution; challenging engineering
 - **Spatial Heterodyne Spectroscopy (SHS)**: magnetic and electric field fluctuations
- **Turbulence and Transport Research**
 - Intrinsic Rotation and the Role of Turbulence (X. Qin, UW student) on HL-2A
 - Core transport, L-H physics, RMP, LHCD/ECH impacts, EP-xAE
- ***US and China fusion programs are benefitting from joint diagnostic development and research projects: HL-2A, HL-2M, DIII-D, NSTX-U***

