Development and application of advanced microwave profile/fluctuation diagnostics for burning plasma in 2021

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(1)*In collaboration with:*

UC Davis: Neville Luhmann, Jr. Calvin Domier, Yuan Zheng, Guanying Yu, Xianzi Liu, Ying Chen, Xiaoguang Liu

PPPL: Ahmed Diallo, Yang Ren, William Tang, Ge Dong

Bridge12: Jagadishwar Sirigiri

Elve Speed, Inc: Diana Gamzina

Stanford: Srabanti Chowdhury

SWIP: Min Jiang, Zhongbing Shi, Ruihai Tong, Kairui Fang

ASIPP: Guosheng Xu, Ran Chen, Pengjun Sun, Xiaoliang Li

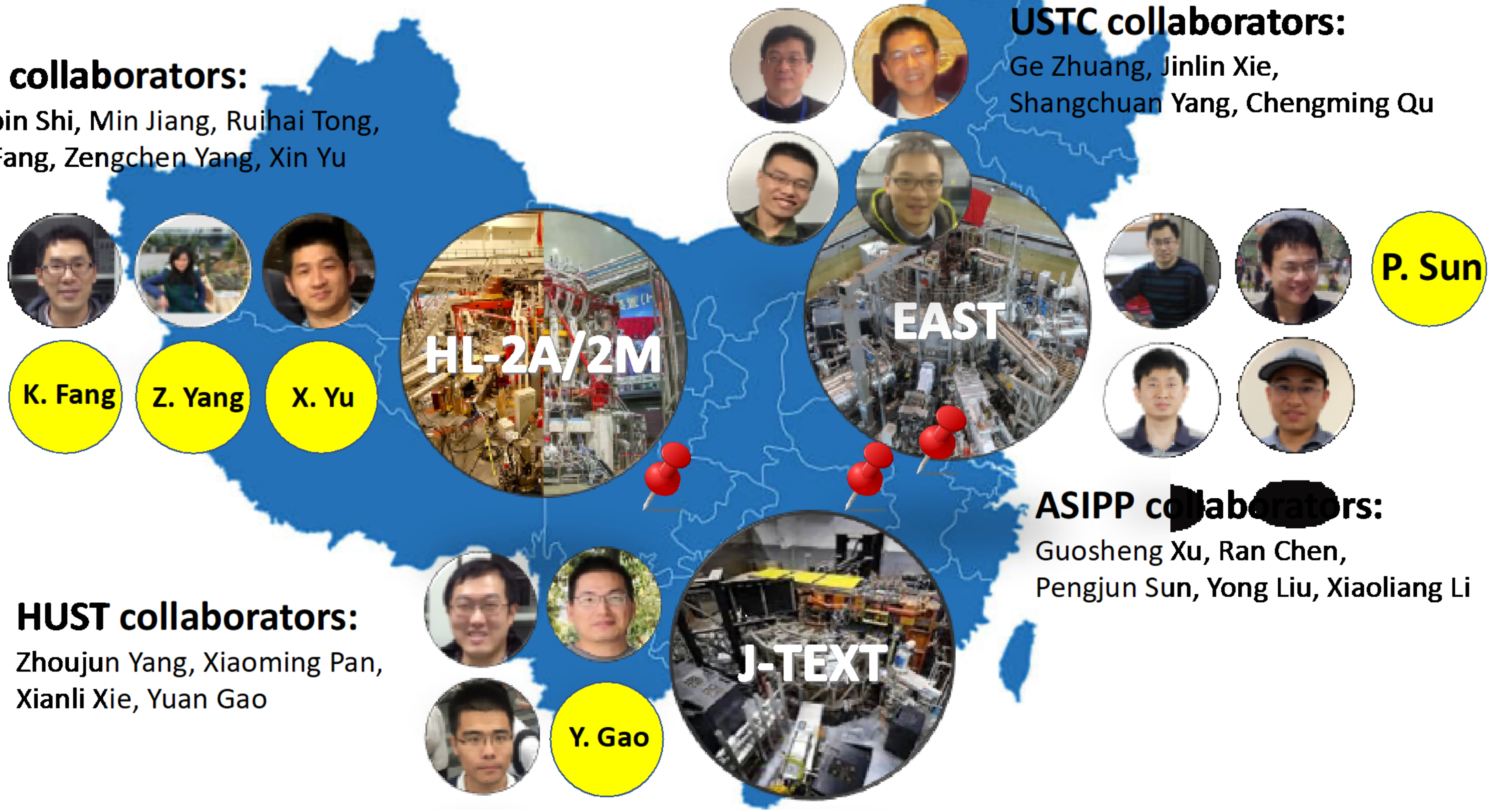
USTC: Jinlin Xie, Ge Zhuang, Chengming Qu

HUST: Zhoujun Yang, Yuan Gao

Extensive Diagnostic Development and Physics Collaborations

SWIP collaborators:
Zhongbin Shi, Min Jiang, Ruihai Tong,
Kairui Fang, Zengchen Yang, Xin Yu

USTC collaborators:
Ge Zhuang, Jinlin Xie,
Shangchuan Yang, Chengming Qu



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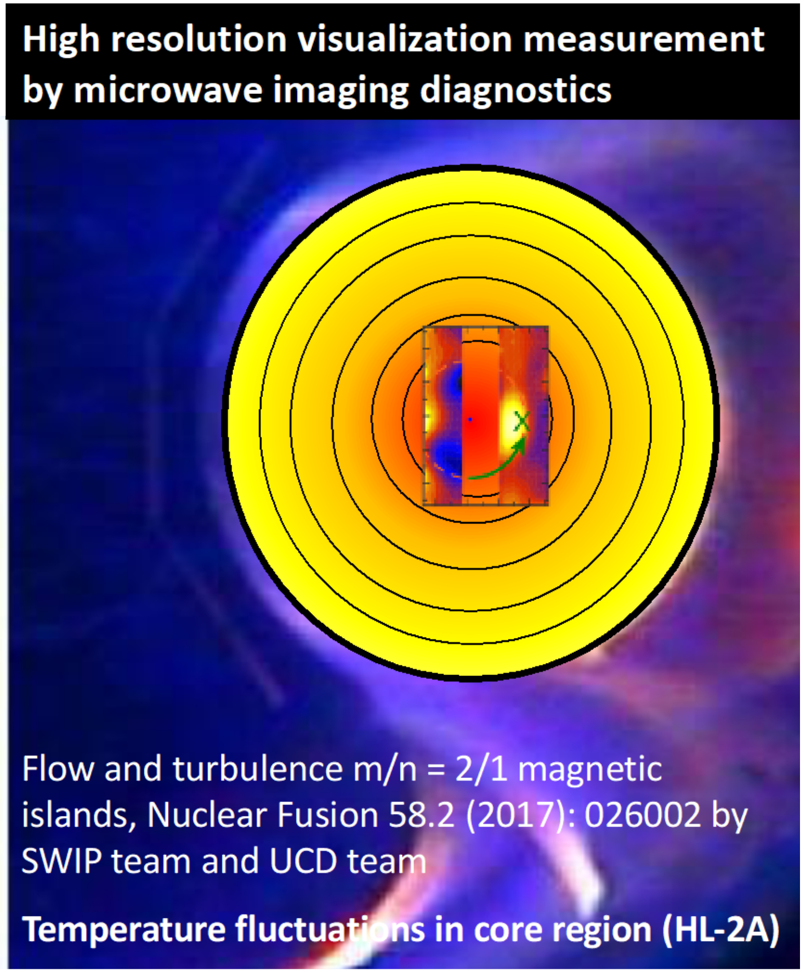
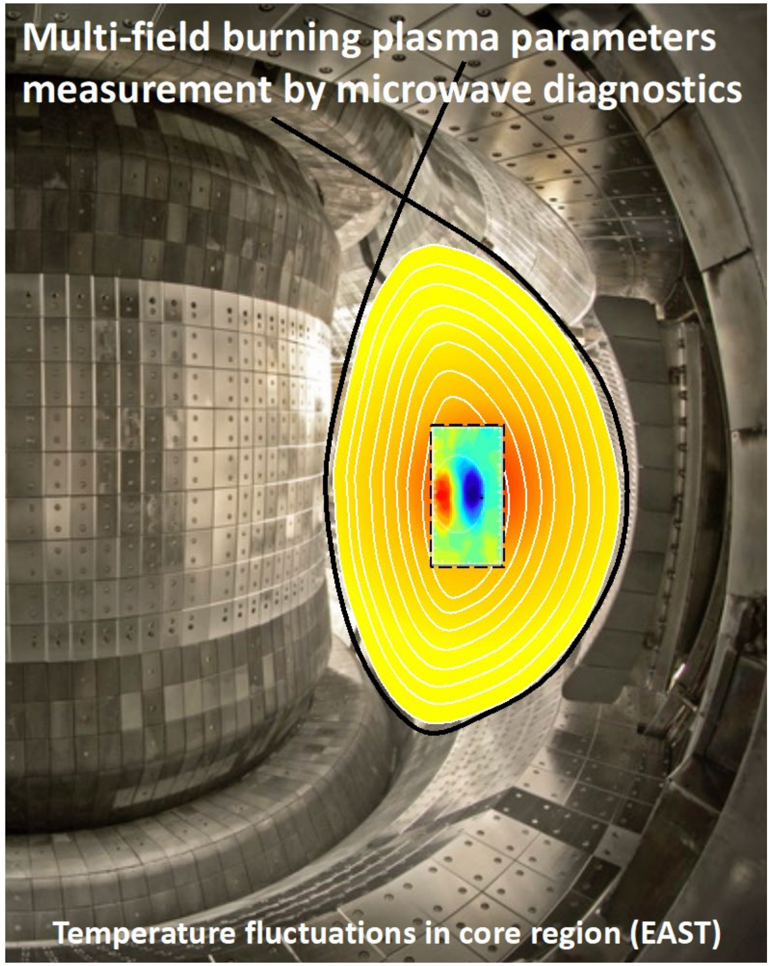
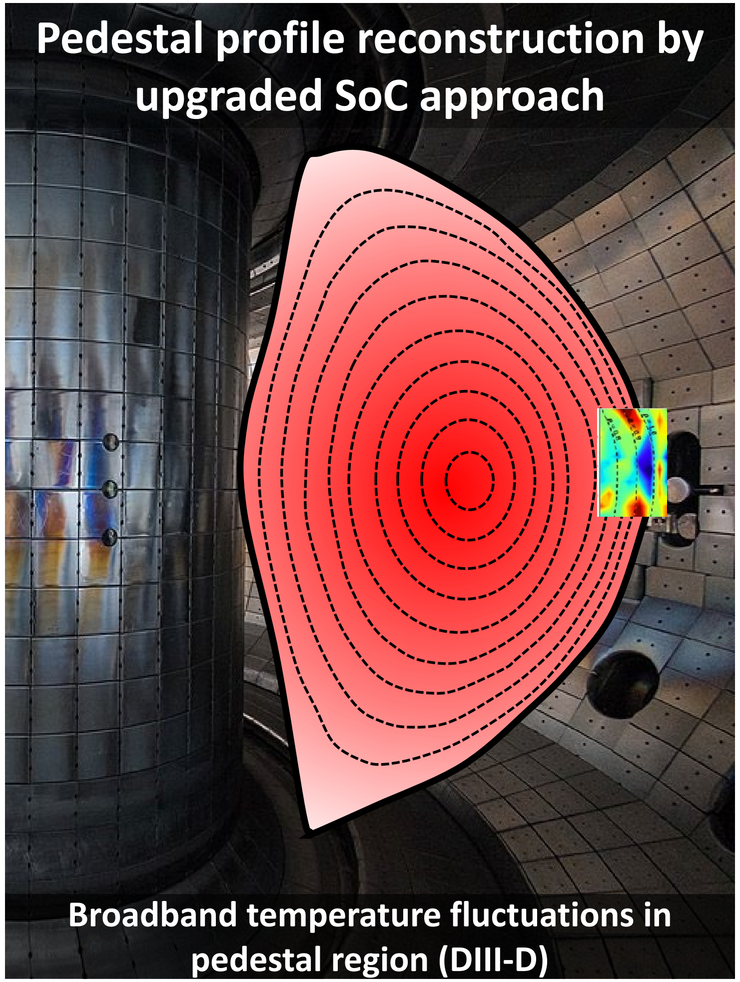
ASIPP co[redacted]labo[redacted]rs:
Guosheng Xu, Ran Chen,
Pengjun Sun, Yong Liu, Xiaoliang Li

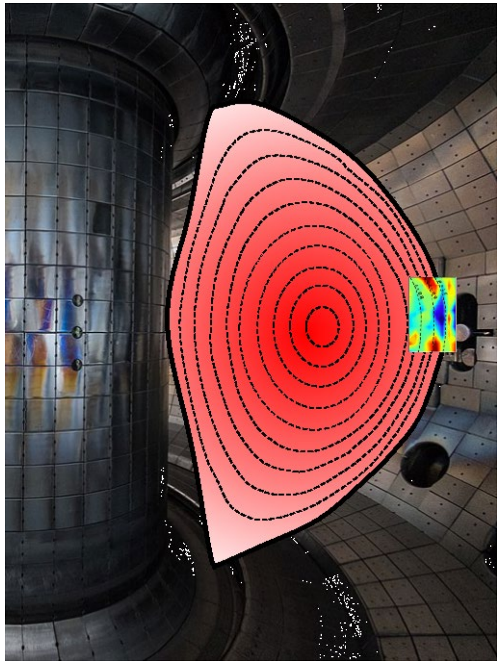
HUST collaborators:
Zhoujun Yang, Xiaoming Pan,
Xianli Xie, Yuan Gao

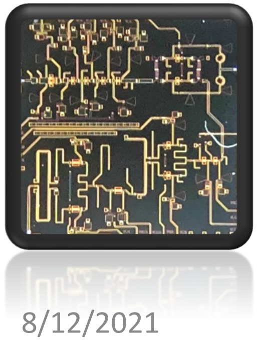
Long-term collaboration, focusing on burning plasma physics











Abstract

Over the past 20 years, microwave diagnostic technology and plasma physics contributions have provided epoch-making developments, including new instrument applications, real-time monitoring and feedback control, neural network assistance on data analysis and interpretation, and harsh environment resistant diagnostics for burning plasmas.

Currently, UC Davis and PRC teams (from USTC, ASIPP, SWIP and HUST) are working on extremely high resolution diagnostic developments including Ultra Short Pulse Reflectometers (USPR), THz high-k scattering systems, cutting edge system-on-chip (SoC) microwave passive and active imaging systems, multi-field co-located and simultaneous measurement in 2021.

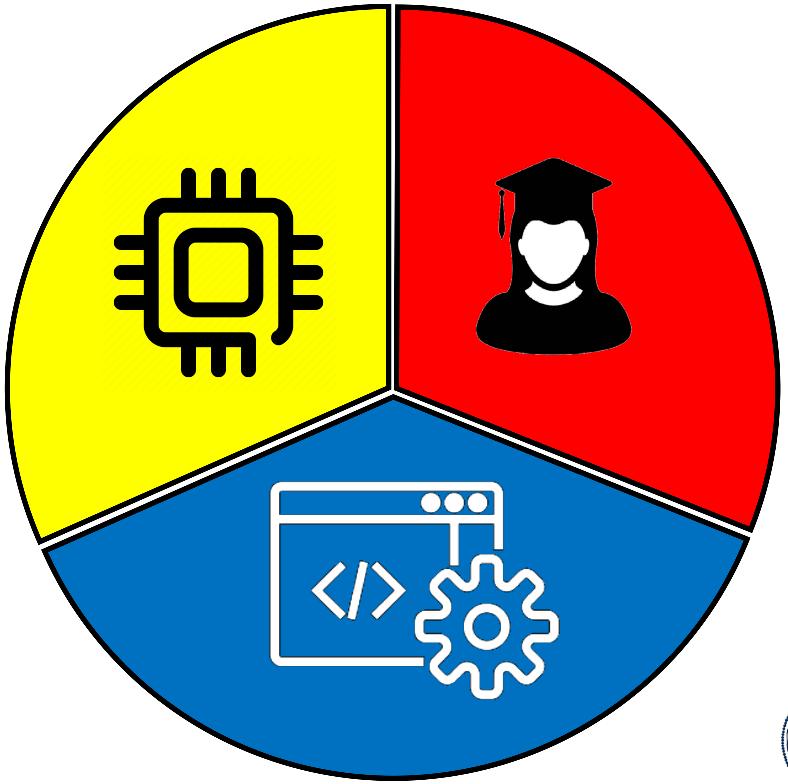
Facilitated by cutting-edge developments by collaborators: (Wide Bandgap GaN and Diamond: Stanford); (MM-Wave and THz Vacuum Electronics: Bridge12 Technologies and Elve Speed, Inc.); and (Machine Learning/AI: Princeton and PPPL)

A brief overview of the advanced microwave diagnostics will be presented.

Outline

Diagnostics Technology

1.Ultra Short Pulse Reflectometer
2.High-k scattering system
3.System-on-Chip approach



Education

1. Young researchers
2. PhD students
3. Exchange program
4. Virtual meetings

Data interpretation

1. Man-free data processing
2. Synthetic diagnostics
3. AI prediction and feedback

Outline

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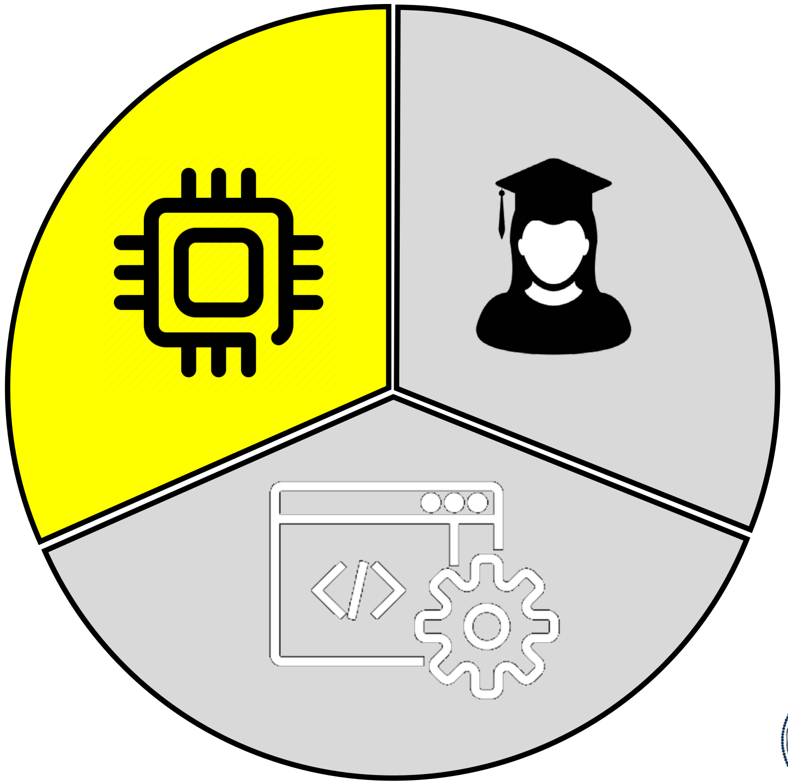


Diagnostics Technology

Ultra Short Pulse Reflectometer (EAST)

Need:

Real-time density profile evolution (SOL, pedestal region) with μs and sub-cm level resolution.

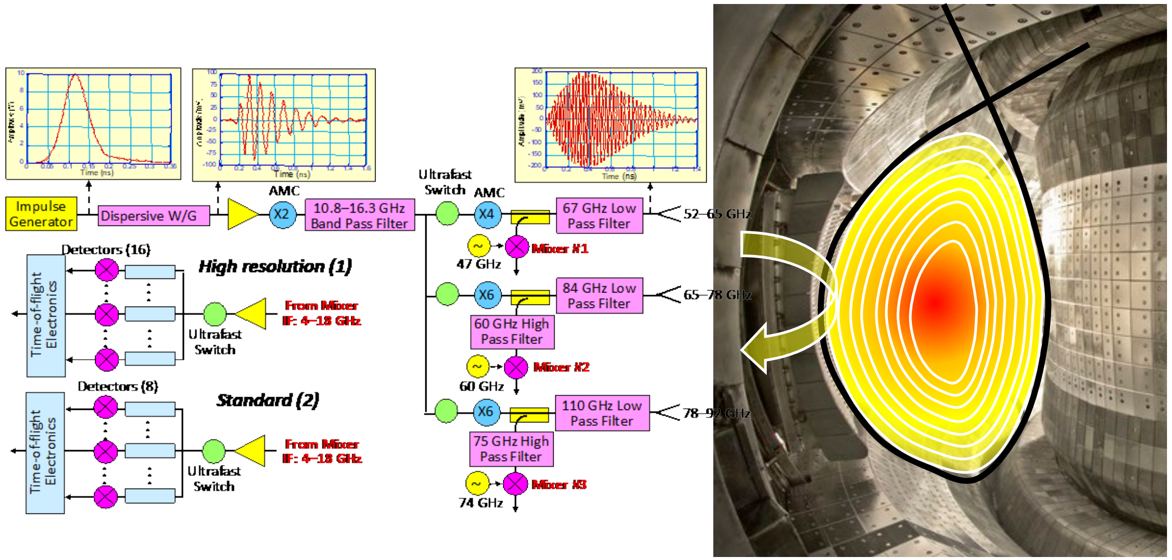
Grassy ELM, L-I-H transition, high beta scenario

Approach:

The time-of-flight measurements provide the density profile with ultra-short pulse technology. The filter bank provides 32 radial channels simultaneously measuring SOL and pedestal regions.

Benefits:

Density profile differences in key phases (ELM crashing, inter-ELM, ELM suppression, radial transport)



Collaboration by ASIPP and UC Davis, estimate installation and beginning of operation in Dec. 2021

Challenges:

Ultra-Short Pulse Generator, ToF module, Beam tracing, EM noise shielding, Real-time analysis.

Diagnostics Technology

High-k Scattering Diagnostics System (EAST)

Need:

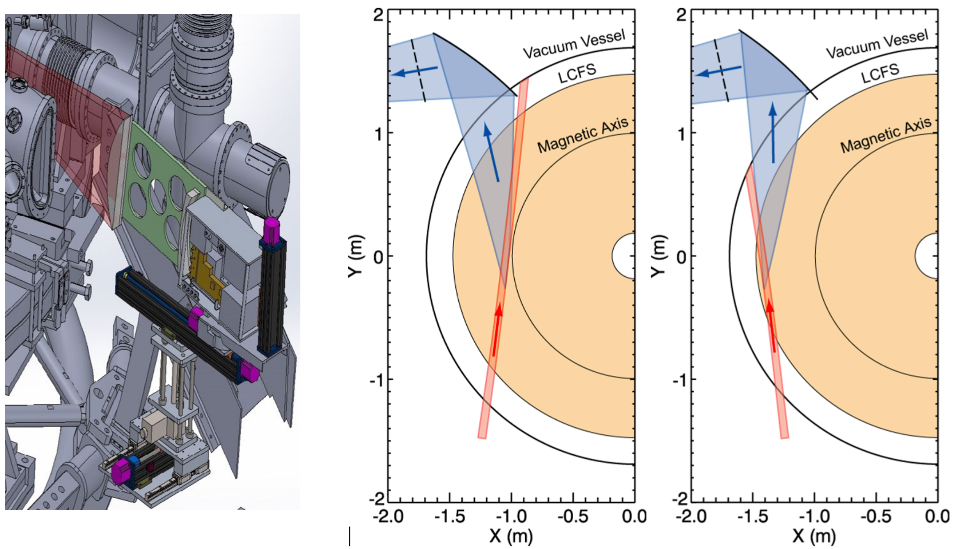
High spatial wavenumber diagnostics to directly observe the ω and k spectra of electron scale turbulent fluctuations and characterize the effect on electron thermal transport.

Approach:

A 4-channel High-k Tangential Scattering system for EAST is designed and under development for high-k density fluctuation (up to 30 cm^{-1}) measurements.

Benefits:

Electron thermal transport is anomalous in all EAST confinement regimes. The turbulence and transport properties of EAST motivates efforts to measure electron gyro-scale fluctuations to investigate the connection between ETG turbulence and electron thermal transport.



Collaboration by ASIPP and UC Davis, estimate installation and beginning of operation in Dec. 2021

Challenges:

High power source, collective optics, data interpretation.

Diagnostics Technology

System-on-Chip microwave module (EAST, HL-2A, J-TEXT)

Need:

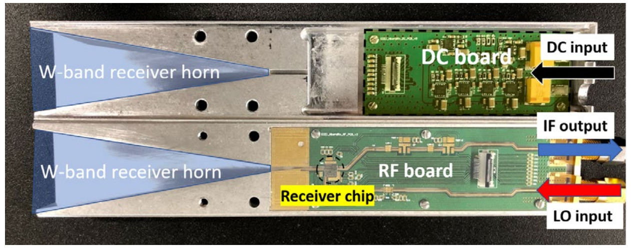
Develop burning plasma microwave diagnostic systems with SNR improvement, integrated, much stronger radiation resistance. (HTPD 2020 Invited talk)

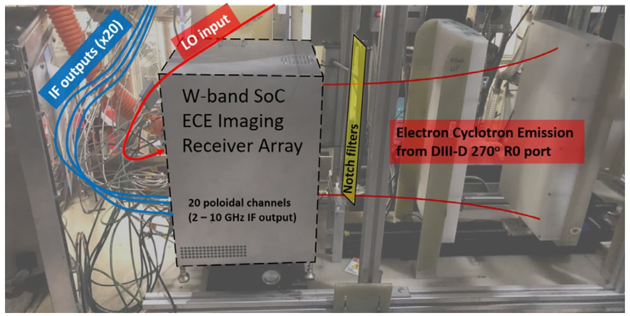
Approach:

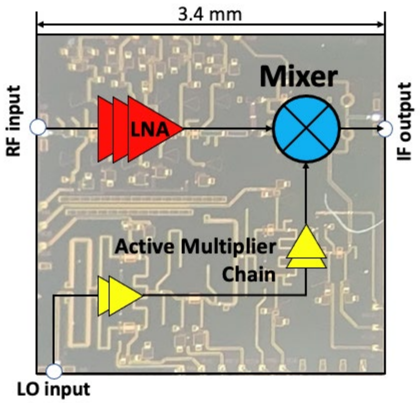
Design, fabricate and install System-on-Chip approach microwave transmitter/receiver modules on HL-2A, EAST and J-TEXT.

Benefits:

Enhance current diagnostics sensitivity, improve signal-to-noise ratio with high integration system. Working in radiation harsh environments. (EM, X-ray, neutron)







Estimate installation and beginning of operation in early 2022

Challenges:

ECH/LHCD shielding, personnel travel support

Outline

Diagnostics Technology

1.Ultra Short Pulse Reflectometer
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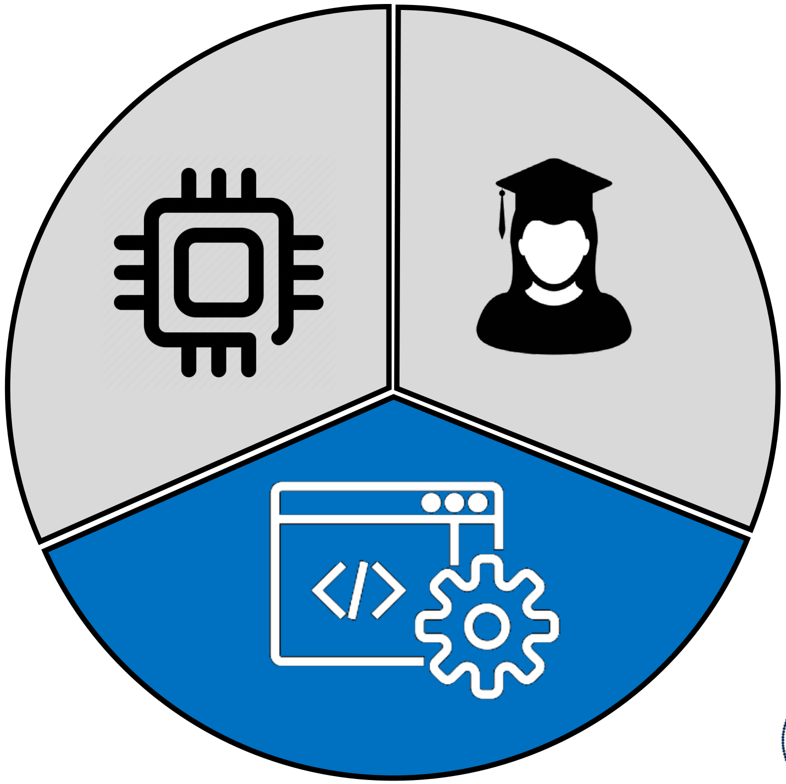
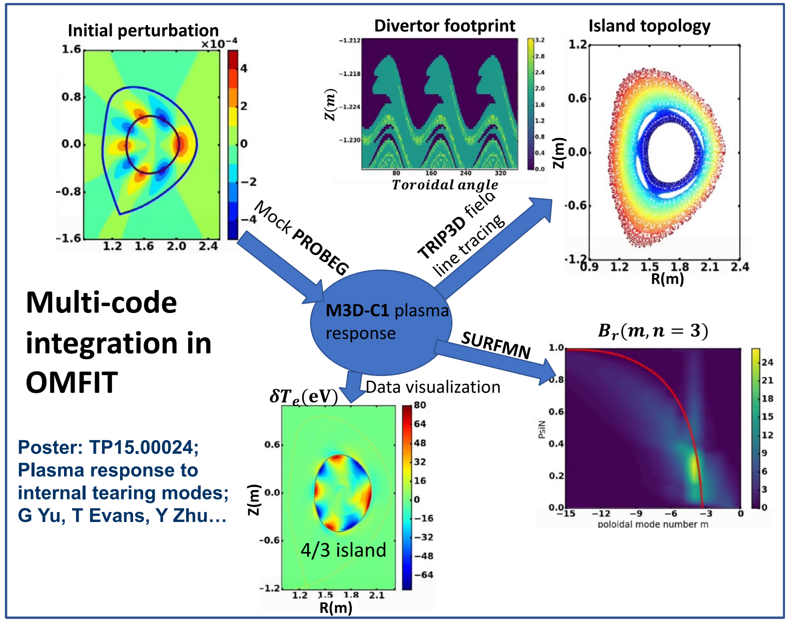
Data interpretation

1. Man-free data processing
2. Synthetic diagnostics
3. AI prediction and feedback



Diagnostics Technology

Man-free data processing



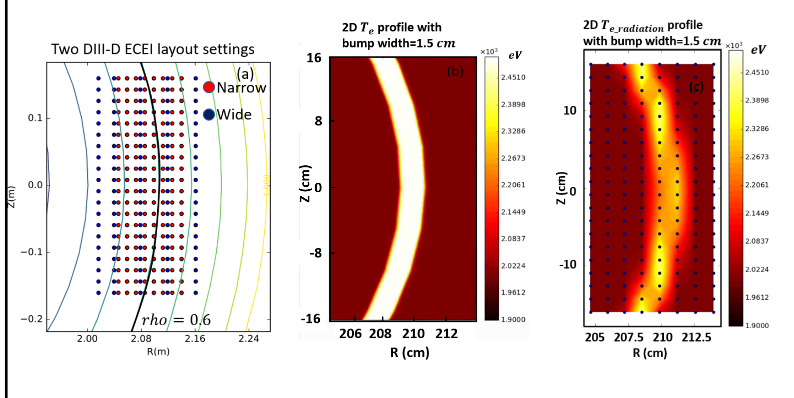
Multi-code integration in OMFIT

Poster: TP15.00024; Plasma response to internal tearing modes; G Yu, T Evans, Y Zhu…

ECEI module is developed by G. Yu, Y. Zhu, S. Smith, O. Meneghini and OMFIT team

Data for Discovery (D4D) workshops in 2019- 2020

Synthetic diagnostics

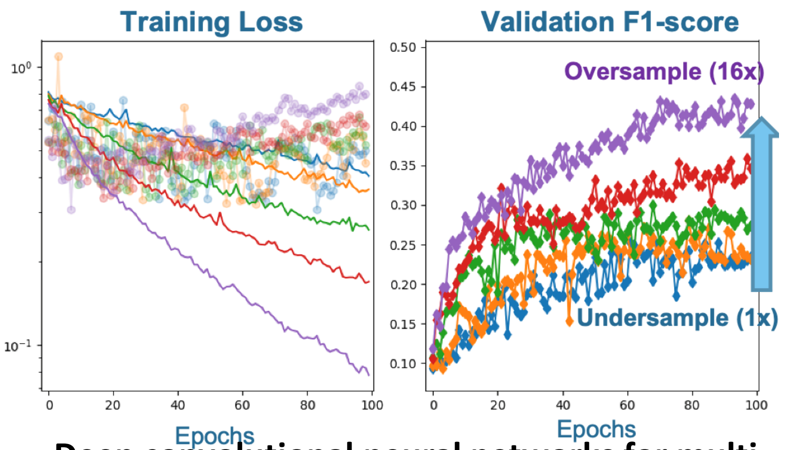


Synthetic ECEI diagnostic is used to simulate the radiation from a 2D bump structure

Synthetic ECEI/MIR are developed and used by PPPL, UC Davis, USTC, SWIP teams

Front-end optics qualification (2019)
ECE accessible region simulation (2020)

AI prediction and feedback



Deep convolutional neural networks for multi-scale time-series classification and application to tokamak disruption prediction using the Electron Cyclotron Emission imaging (ECEI) diagnostic on DIII-D

High Temperature Plasma Diagnostics Conference Invited talk (2020)

Outline

Talent is the engine of development.
Talent's development is a long-term reward.

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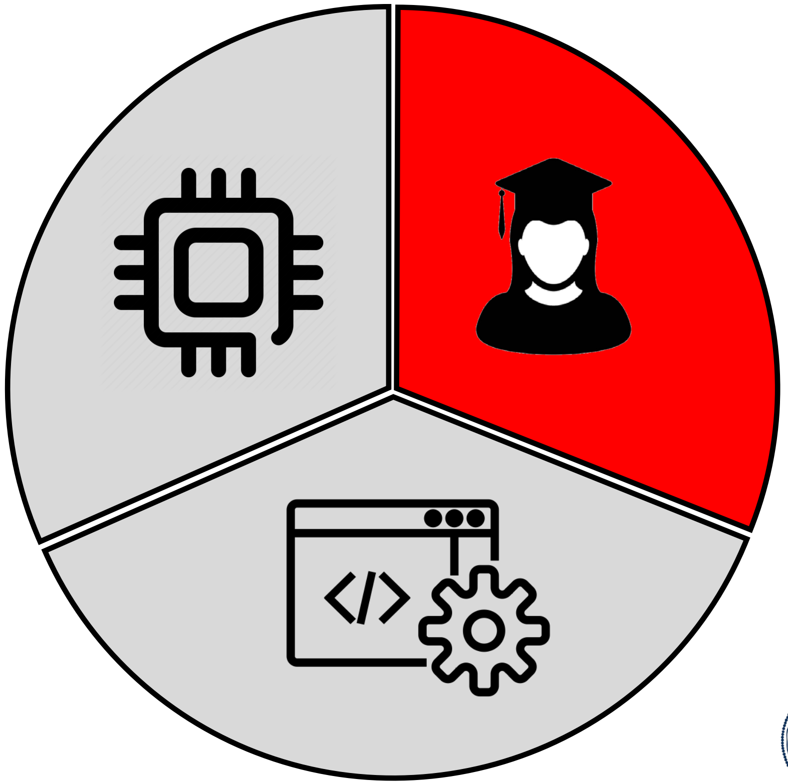
3.System-on-Chip approach



Education
1. Young researchers
2. PhD students
3. Exchange program
4. Virtual meetings

Data interpretation
1. Man-free data processing
2. Synthetic diagnostics
3. AI prediction and feedback

Exchange and Education (UC Davis)

Dr. Yilun Zhu
UC Davis scientist
PhD graduate from USTC
[HT-7, EAST, J-TEXT, DIII-D, NSTX-U]

Dr. Guanying Yu
UC Davis postdoc
Master graduate from USTC
[EAST, DIII-D, NSTX-U]

Ying Chen
UC Davis PhD student
Bachelor graduated from Xidian University
[SoC developer]

Xianzi Liu
UC Davis PhD student
Bachelor graduated from USTC
[EAST, NSTX-U]

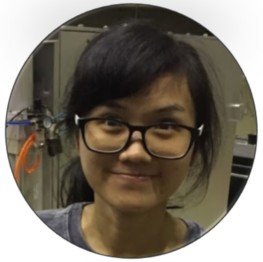
Yingchu Wang
UC Davis master student
[Data interpretation]

Shasha Qiu
UC Davis master student
[USPR developer]

https://sites.google.com/view/mmwave/home

Exchange and Education (UC Davis)

Dr. Yuan Zheng
Scientist
[2017-present]
[Vacuum Electronics Devices]



Dr. Min Jiang
SWIP researcher
[2016-2017]

Dr. Chen Luo
Postdoc
[2015-2017]

Dr. Xing Hu
UCD PhD
[2011-2017]

Dr. Fengqi Hu
UCD PhD
[2011-2017]

Dr. Meijiao Li
UCD PhD
[2011-2017]

Dr. Jinhua Cao
UCD PhD
[2016-2019]

Dr. Ming Chen
UCD PhD
[2012-2018]

Xiaoming Pan
Exchange student from Huazhong University of Science and Technology
[2016-2017]

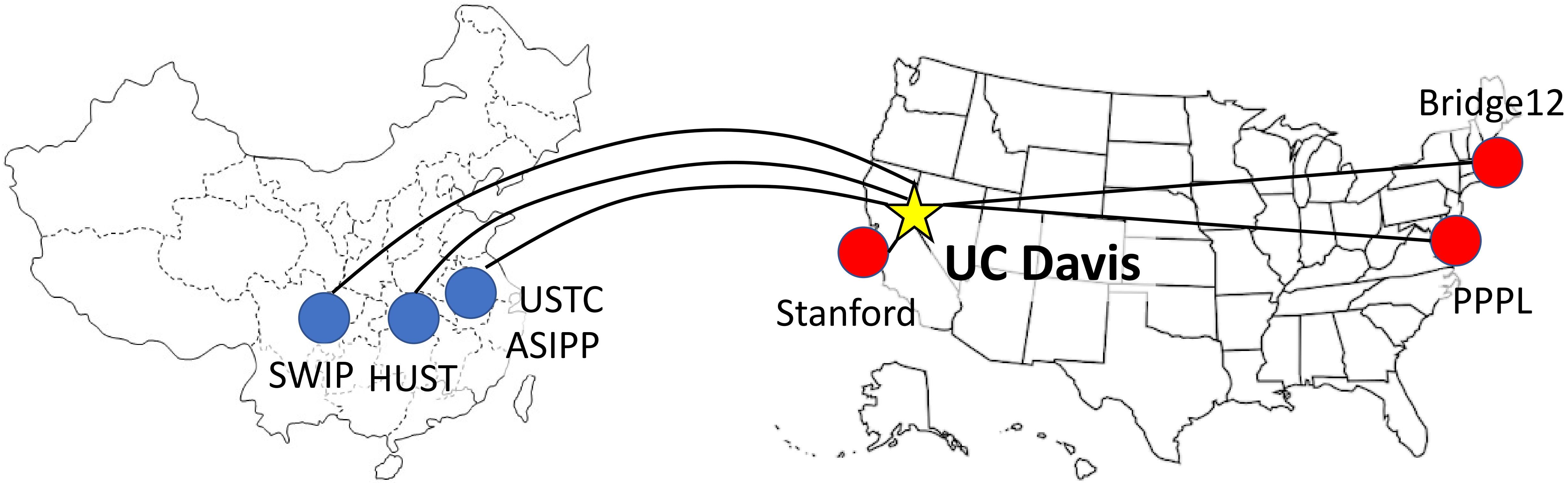
Xiaoliang Li
Exchange student from University of Science and Technology
[2019-2020]

Over 10 more undergraduate students visit and join in fusion plasma education program in previous 5 years.

Training and Education resources

Burning plasma physics
MCF facilities
Rapidly growing teams

Burning plasma Physics
Radiation resistant electronics
High power, high frequency sources



Major collaborators

William Tang
Principal Research Physicist, PPPL

Yang Ren
Research Physicist, PPPL
[High-k scattering developer, NSTX-U, EAST]

Jagadishwar Sirigiri
President and COO Bridge12 Technologies, Inc.

Diana Gamzina
President and Founder, Elve Speed, Inc.

Srabanti Chowdhury
Professor of Electrical Engineering (EE), Stanford

Wide bandgap materials, devices, and systems

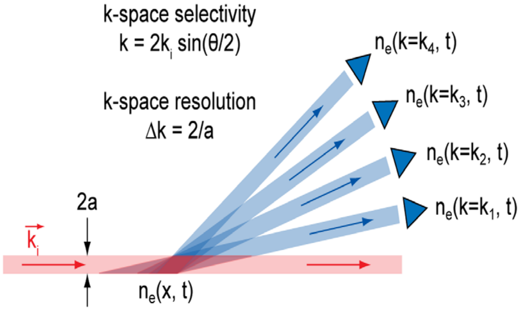
High Power Terahertz Systems for Burning Plasmas Diagnostics and Heating

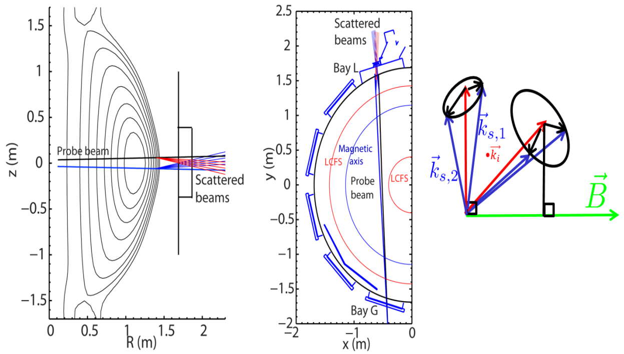
Jagadishwar Sirigiri

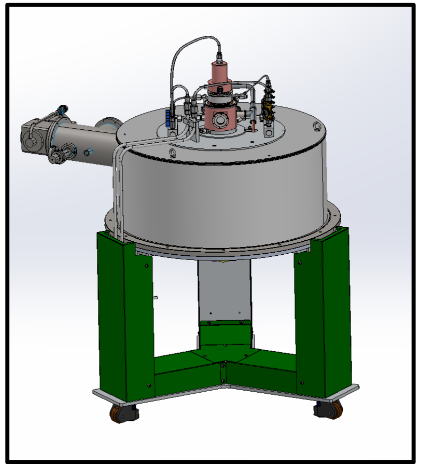
President and COO Bridge12 Technologies, Inc.

346 GHz BWO — **395** GHz, 500 W Gyro-TWT — **693** GHz for high-k scattering — **792** GHz DNP

263 GHz, 5 W — **460** GHz, 30 W — 5 W, *Gyrotron(CW)* / 50 mW, *TWT (CW)* — 1 kW, *Gyrotron*

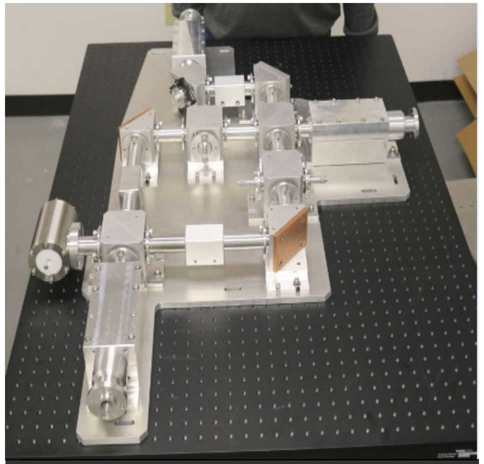






693 GHz Gyrotron,
5W CW output

Volume = 2 m^3
High-k scattering in 2022



460 GHz Quasi optical
Power Combiner

Overmoded corrugated waveguide
line from gyrotron to an NMR probe

Jagadishwar R. Sirigiri, M. Pasagadagula – Bridge12 Technologies, Inc.

High performance microwave diagnostics with strong radiation resistance

Srabanti Chowdhury

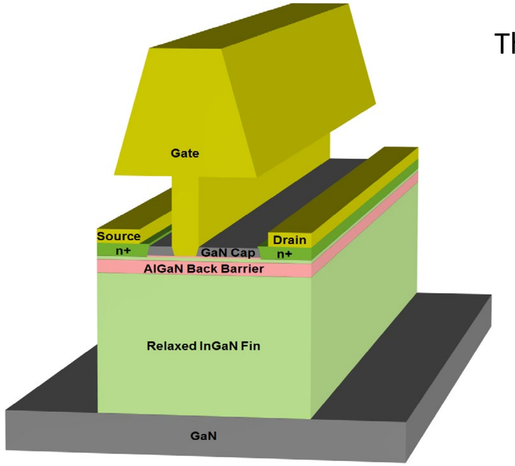
Professor of Electrical Engineering (EE), Stanford

Wide bandgap materials, devices, and systems

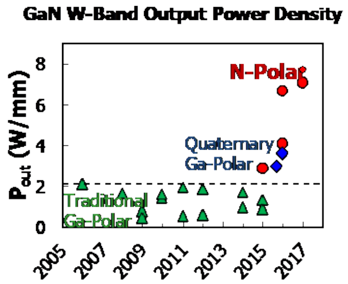
Solution:
GaN semiconductors for current and future high frequency-high power devices

Need high frequency:
In implementing microwave diagnostics on reactor plasmas, there is a slight increase in required operating frequencies mandating some technology developments.

Need high power:
ITER level facilities can produce net fusion power and will generate radiation levels, i.e., neutrons and gamma rays, that are orders of magnitude higher than present-day experimental machines.



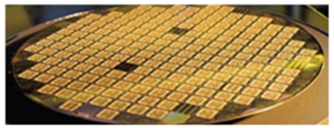
Thermal management (GaN) and high-temp designs



Available for density, temperature measurements for reactor

To achieve over 20Watts operation in mm-wave domain (94GHz, 240GHz and 300GHz) : target an f_{max} greater than 600GHz

Device integration for power on a chip and co-located sensor electronics



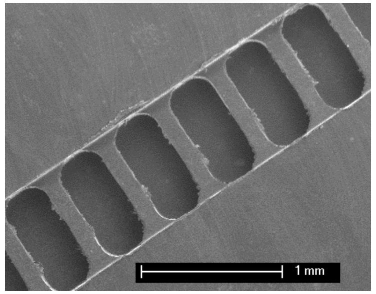
Baliga, B. Jayant, ed. *Wide Bandgap Semiconductor Power Devices: Materials, Physics, Design, and Applications*. Woodhead Publishing, 2018.

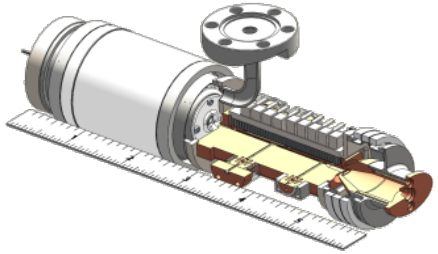
Advanced Manufacturing of Millimeter Wave and Near-THz TWTs

Diana Gamzina

President and Founder, Elve Speed, Inc.

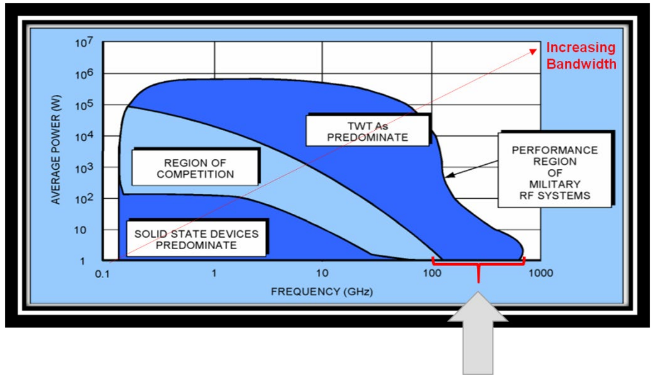
Concept





Goal: Accelerate the lengthy and cumbersome process of manufacturing TWTs while maintaining microscale tolerances and nanoscale surface finish.

Impact

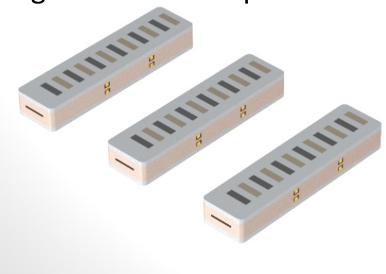


Low Cost High Power Amplifiers

Approach

Elve Speed is transforming how TWTs are produced

- **Agile Assembly**
- **Automation**
- **Novel Materials**



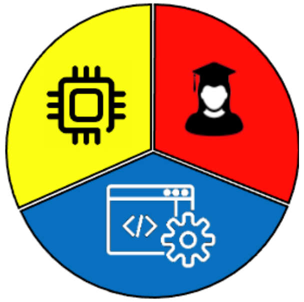
Context

TWT Benefits:
- wide bandwidth
- high power
- high efficiency

Drawback:
- complex to manufacture

Manufacturing of TWTs is a complex, manual process:

Precision fabrication, alignment, and integration of multiple components and sub-assemblies.



- Instruments
- Data interpretation
- Education

Summary

- UC Davis team maintains close collaborate with USTC, ASIPP, SWIP and HUST team on cutting edge diagnostics technology developments and microwave diagnostics data interpretation study in 2021.
- The Ultra Short Pulse Reflectometer, high-k scattering, and the prototype of System-on-Chip module will be applied on EAST (HL-2A).
- The automatic data analysis module was developed and will be available for multiple ECE Imaging system. Synthetic diagnostics database and AI prediction study is under developing in 2021.
- Talent is the engine of development. Talent's development is a long-term reward. There are 23 Chinese young researchers, graduate students and exchange students visited UC Davis for burning plasma diagnostics study in the previous 5 years (2016-2020).
- 47 scientific publications have been published since 2016 by the collaboration between UC Davis and USTC, ASIPP, SWIP and HUST .
- More resources need for the collaboration in 2021 and future.

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