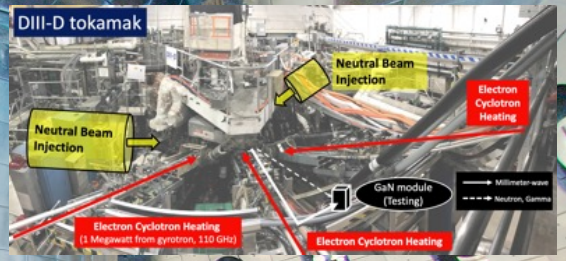
Real-time diagnostics and feedback control in harsh environment

By

Yilun Zhu, UC Davis

with Neville Luhmann Jr., Calvin Domier, Anh-Vu Pham, Omeed Momeni, Guanying Yu, Xiaoliang Li, Xianzi Liu, Pin-Jung Chen, William Tang (Princeton University), and Zhihong Lin(UC Irvine)

FPP Technology Strategic Planning Meeting
09/14/2023



Work supported by DE-FG02- 99ER54531, DE-SC0023500, DE-FC02-04ER54698

Contact: ncluhmann@ucdavis.edu, amzhu@ucdavis.edu

Real-Time Diagnostic and Feedback Control in Harsh Environment University of California, Davis

- **Long range goal*:** High resolution diagnostic on burning fusion reactor
  - Employ microwave diagnostics [minimal access required, robust performance in harsh environment] provide position, shape, real-time monitoring and feedback control for magnetic island and disruption [Survive harsh environment: Neutrons, X-rays, ECH leakge, EM burst during ELM]
- **DIII-D need:**
  - Extensive DIII-D diagnostic suite, ITER relevant high-performance facility with excellent plasma controlling [ECH, NBI, RMP, more] and diagnostics [X-ray, neutron, Gamma]
  - Wideband gap GaN-based diagnostics just developed for fusion. The iteration and upgrade from prototype 2023 needs several years to qualify the technology and into OFES development plan.
  - GaN prototype 2023 has been successfully developed by UC Davis for DIII-D ECE Imaging and available for more diagnostics.

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- **Priority for studies**
  - The GaN diagnostic instrument will be ready in July 2024, 60 days piggyback on DIII-D in first stage of radiation testing *[**Exhibit A**]*
  - O-mode ECE will be ready in March 2024, 10 days piggyback *[**Exhibit B**]*
  - Digital twin diagnostic synthetic module will be ready in October 2023. *[**Exhibit C**]*
  - Robust ECH protection notch filter (waveguide) is developed for W7-X and EAST, will be available on DIII-D and more. *[**Exhibit D**]*

Use DIII-D to validate the burning plasma diagnostic technology

- **Risk and deliverable**
  - Data quality depends on ECH control capability
  - High field boundary position, high field side electron temperature, real-time magnetic island monitoring, robust microwave diagnostics to improve reliability

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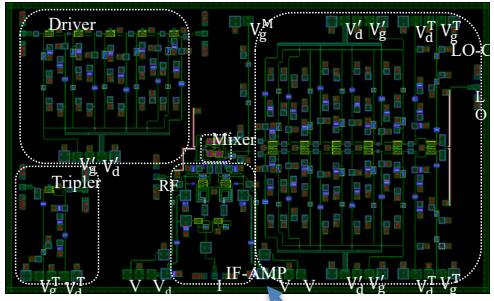
Exhibit A: GaN-based diagnostics for burning fusion plasma

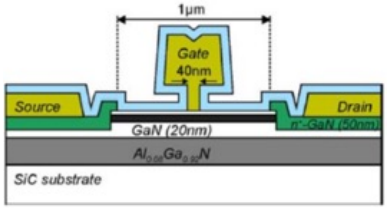
The GaN receiver chip will be used as HIGH TOLERANCE millimeter-wave electronics for plasma diagnostics under harsh environment, including:

Neutron X-ray

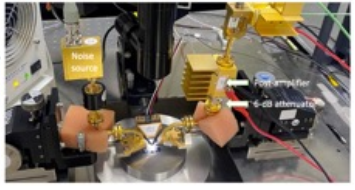
Megawatt gyrotron leakage risk

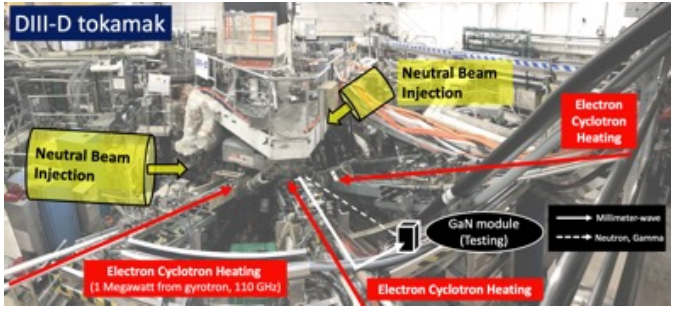
EM burst during ELM





On wafer testing UC Davis campus





- The W-band GaN receiver chip was developed for microwave diagnostics on DIII-D (electron density and temperature) by UC Davis in 2022.
- The GaN approach provides the most promising solution for burning plasma fusion microwave diagnostics: (1)Radiation Hardness, (2) Higher breakdown voltage, (3) Wide bandgap, (4) Reduced cooling requirements
- The first wafers were delivered in April and July 2023.
- Working frequency : 80 – 120 GHz (ECEI, reflectometer)
- Testing status : front-end low Noise Amplifier (Done)
  Mixer and intermediate frequency output (Done)
  Radiation tolerance testing on DIII-D (pending)

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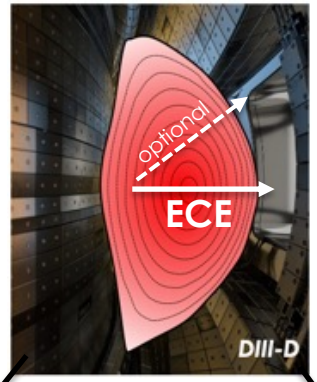
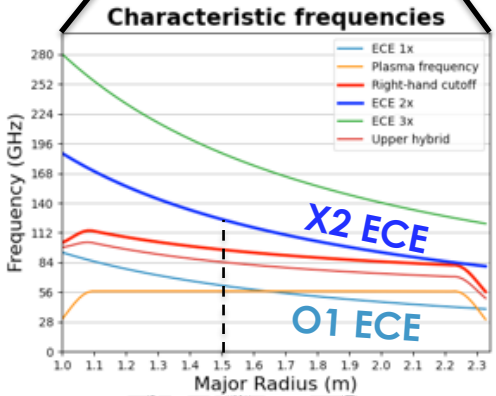
Exhibit B: O-mode ECE will be ready in March 2024

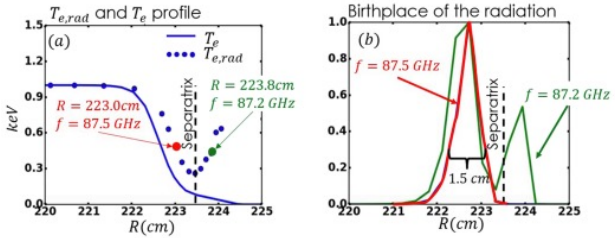




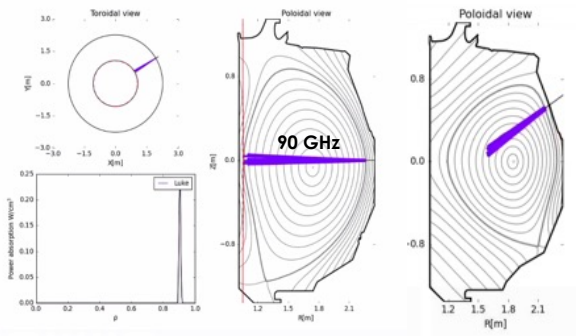
O1 ECE for High Field Side electron temperature measurement

- The 2nd harmonic X-mode ECE diagnostic has limited accessible region due to 3rd harmonic overlap. The high field side ECE data interpretation is complicated.
- The fundamental ECE (O1 mode) provides access for high field side, which could use the reversed path of O-mode ECH.

ECE for separatrix shape and position measurements



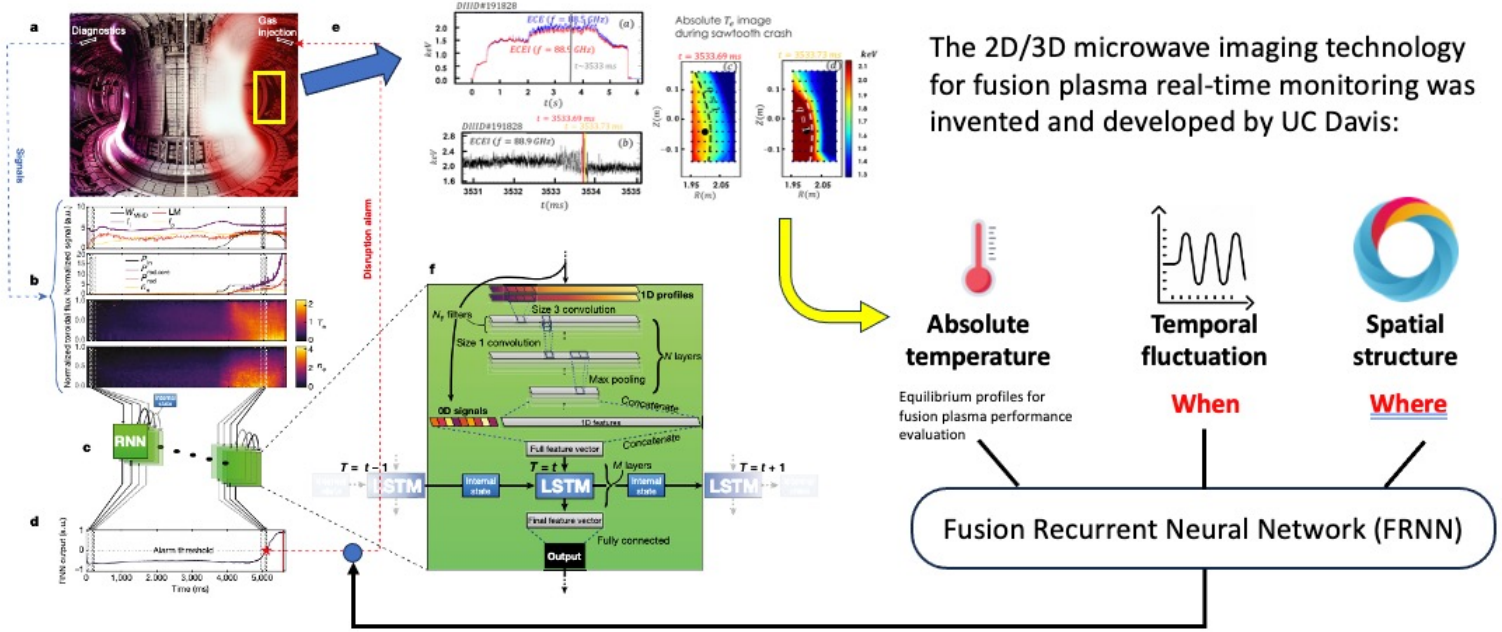
The non-monotonic radiation $T_{e,rad}(R)$ profile is caused by the shine-through effect from the pedestal. (a) The radiation profile from synthetic ECE. (b) The birthplace of the radiation at two frequencies.



BY TORAY on OMFIT

Yu, Guanying, et al. Review of Scientific Instruments 93.10 (2022).

Exhibit C: Digital twin diagnostics for machine learning disruption prediction (collaboration with Princeton University and UC Irvine)



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DANGERS' prediction, feedback-control for fusion operation **SAFETY**

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The digital diagnostic **synthetic ECEI module** will be released on DIII-D OMFIT [October 2023]

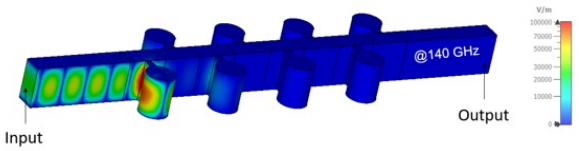
Exhibit D: Robust ECH protection notch filter (waveguide)

The notch filter is implemented to selectively filter out the strong signals at the gyrotron heating frequency from receiver spectrum coupling on the receiving path. Depending on gyrotron heating characterizations and diagnostic requirements, the notch filter shall be designed with consideration of the following aspects.

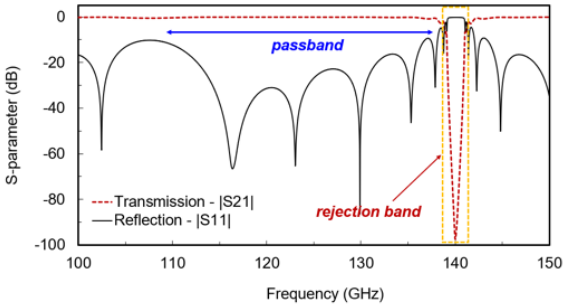
(1) *Rejection band* (2) *Passband* (3) *Power handling capability*

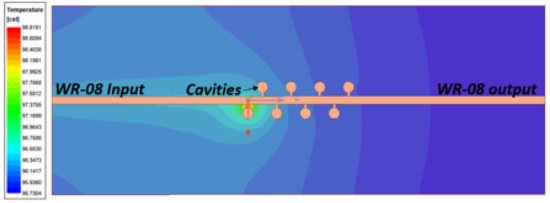
- 140 GHz notch filter has been successfully developed for WX-7 and EAST by UC Davis.
- 105 GHz, 170 GHz approaches are under design.

(a)

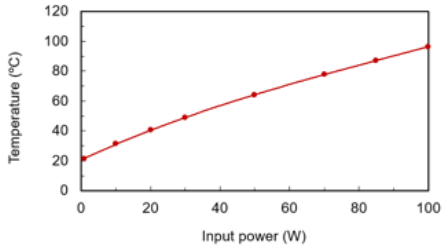


(b)



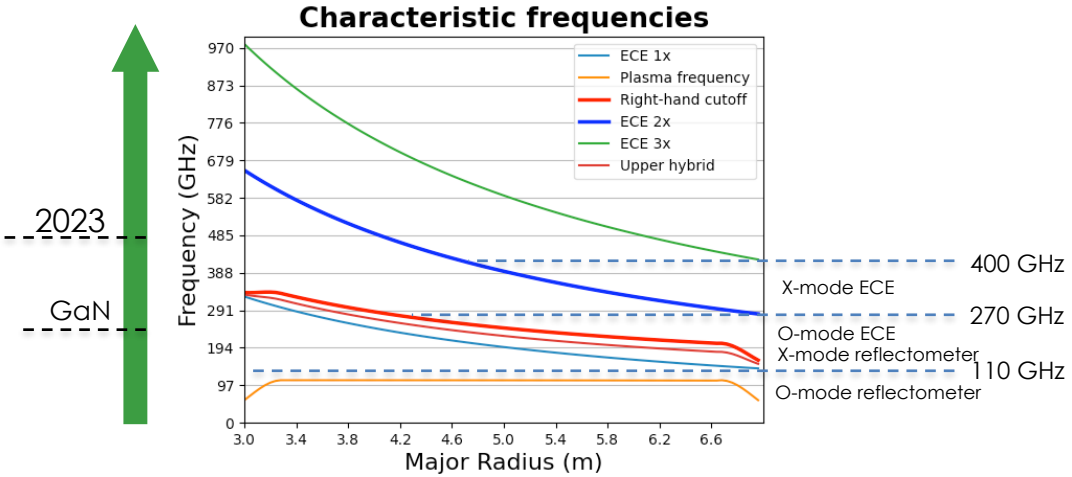


Power handling



UC Davis high magnetic field tokamak diagnostic development

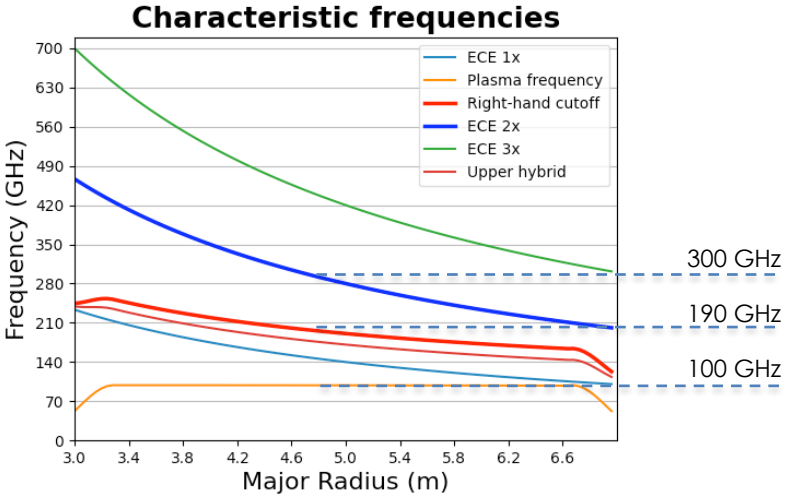
$B_T = 7\ T,\ \overline{n_e} = 15 \times 10^{19} m^{-3}$



O-mode reflectometer up to 110 GHz
X-mode reflectometer up to 270 GHz

X2 Electron Cyclotron Emission up to 400 GHz
O1 Electron Cyclotron Emission up to 270 GHz

$B_T = 5\ T,\ \overline{n_e} = 12 \times 10^{19} m^{-3}$



O-mode reflectometer up to 100 GHz
X-mode reflectometer up to 190 GHz

X2 Electron Cyclotron Emission up to 300 GHz
O1 Electron Cyclotron Emission up to 190 GHz

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Summary

We develop burning plasma diagnostics, and apply on DIII-D to validate the technology for burning fusion plasma, including:

- **GaN-based electronics** to survive harsh environment. *Prototype 2023 has been developed and will apply on DIII-D in July 2024.*
- **High-integration level Electron Cyclotron Emission** (ECE, O1 mode) for high field temperature measurement, and separatrix position measurement. *The hardware are ready to apply. Beam propagation simulation required. Will be on in March 2024.*
- **Digital twin diagnostic (synthetic ECEI)** for machine learning disruption prediction. *It will release on DIII-D OMFIT in October 2023.*
- **Robust ECH protection notch filter** (waveguide) for microwave components.