Long Pulse High Performance Scenarios & Control in EAST

D. Humphreys
for Scenarios and Control Project Team

LEHIGH UNIVERSITY

GENERAL ATOMICS

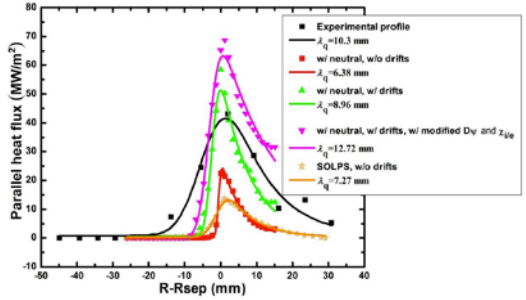
Fusion Energy Sciences

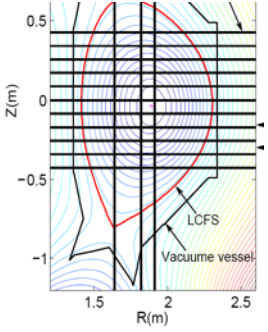
PPPL PRINCETON PLASMA PHYSICS LABORATORY

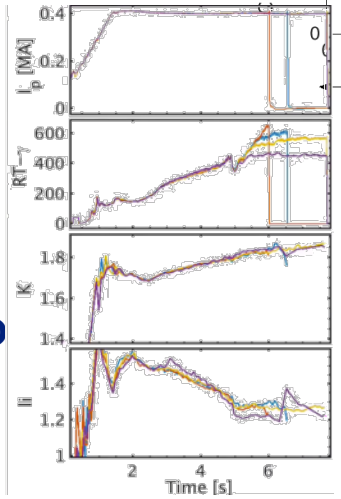
PSFC MIT Plasma Science & Fusion Center

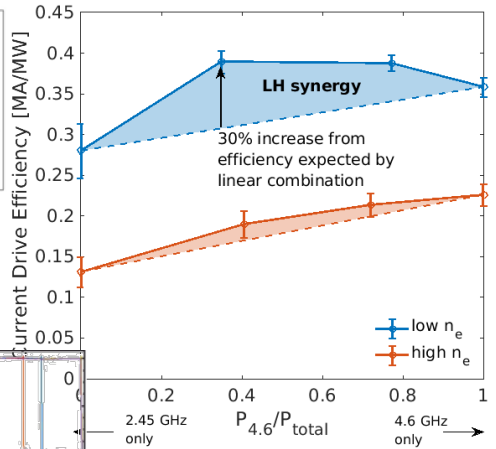
UCLA

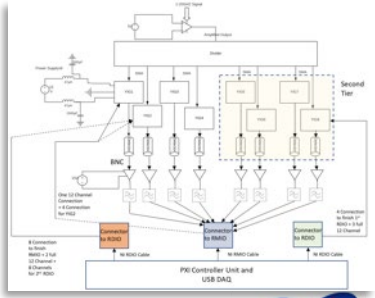
TEXAS The University of Texas at Austin











US-PRC Magnetic Fusion Collaboration Workshop March 2021

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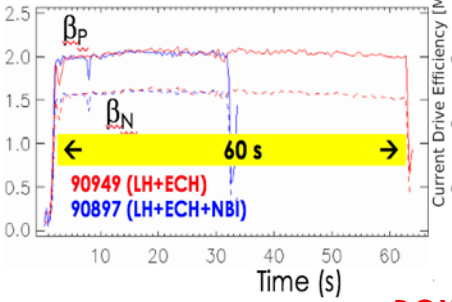
ASIPP

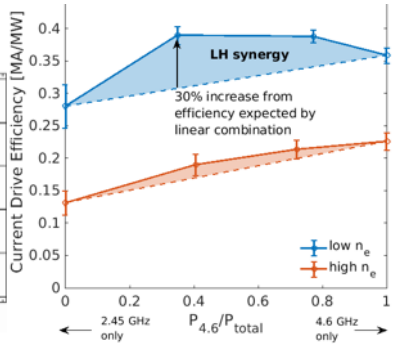
Long Pulse Tokamak Project Advanced Key EAST/CFETR Scenarios, Control Capabilities, Understanding, and Diagnostics in 2019-2020

- **Experimental progress in last EAST campaign (Fall 2019 – early 2020):**
  - Key contributions to extension of DIII-D High-β_P scenario to 60 sec on EAST → SS Q>5 in CFETR
  - Control of 3-point q-profile with Ip + two LH frequencies
  - DPRF disruption predictor demonstrated experimentally
  - Ar equally effective for detachment control as Ne
  - Maximum robust controllable growth rate quantified

60 s Hi β_P Q>5 CFETR

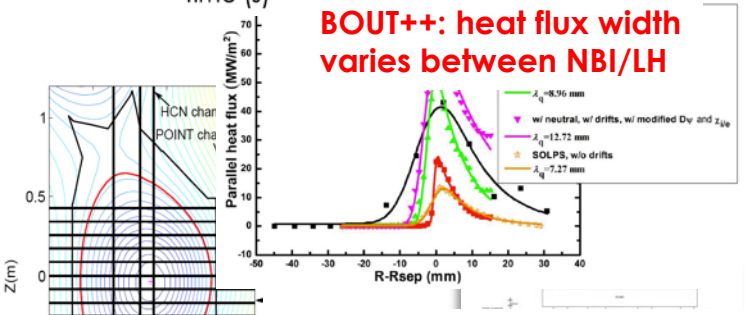


TRANSP: 30% Higher CD

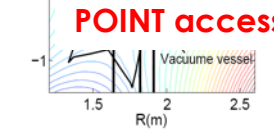


- **Analysis, simulation, and diagnostic advances:**
  - Major advance in usability of POINT constrained EFIT
  - TRANSP studies: 30% increase in CD efficiency from LH synergy
  - Advance in LH modeling + edge turbulence, wave scattering
  - BOUT++ simulations show different divertor heat flux widths between NBI/LHW, good agreement by including drifts
  - FMECE diagnostic tested at DIII-D, to deploy at EAST when travel possible

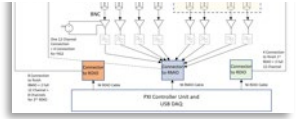
BOUT++: heat flux width varies between NBI/LH



POINT access in EFIT



FMECE ready for EAST



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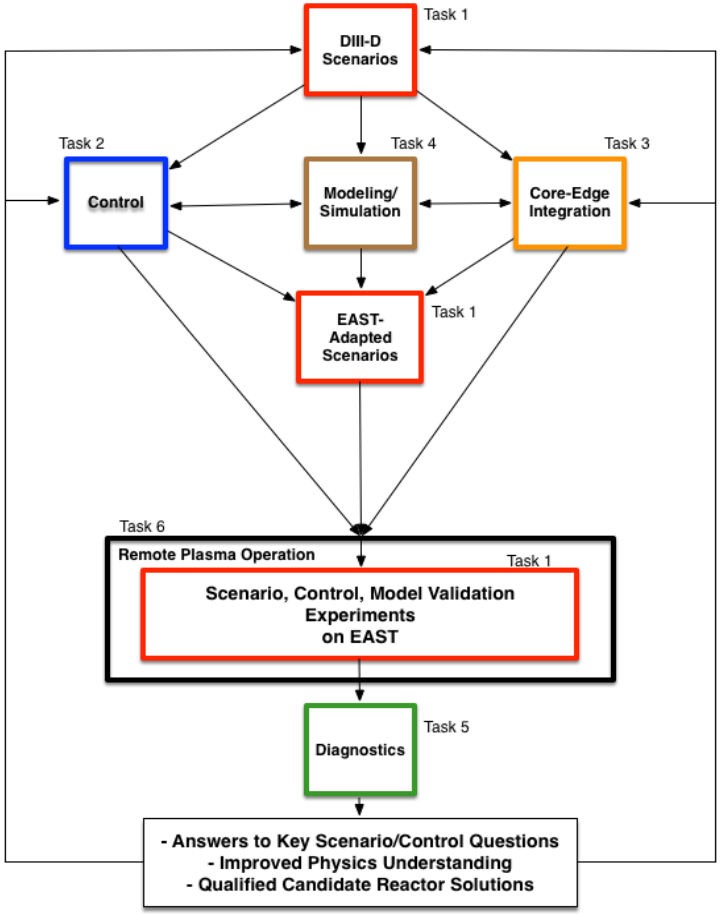
Scenarios and Control Project Consists of Interlocking Task Areas to Achieve Science Goals

- **Scenarios and Control Project Goals:**
  - Develop long pulse steady state scenarios from DIII-D, simulations; extend to long pulse in EAST
  - Develop Control solutions to support other task areas; advance control research toward long pulse disruption-free operation
  - Study divertor physics and control; integrate core-edge solutions into scenarios
  - Advance diagnostics and remote capabilities to support scenarios/control development

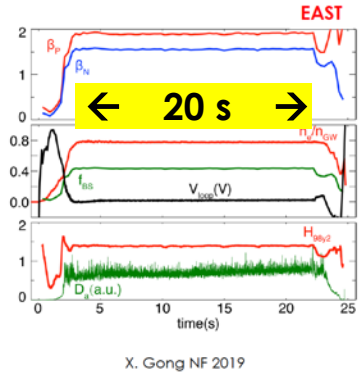
- **Tasks:**
  - T1: Scenarios
  - T2: Control
  - T3: Core-Edge Integration
  - T4: Modeling and Simulation
  - T5: Diagnostics
  - T6: Remote Operation



Task 1:
Scenario Development

Extension of DIII-D high β_P scenario to EAST achieves long-pulse performance for SS Q>5 in CFETR

Experiments on EAST Achieved Long-pulse Fully Non Inductive with RF Only-close to 1GW CFETR Performance



X. Gong NF 2019

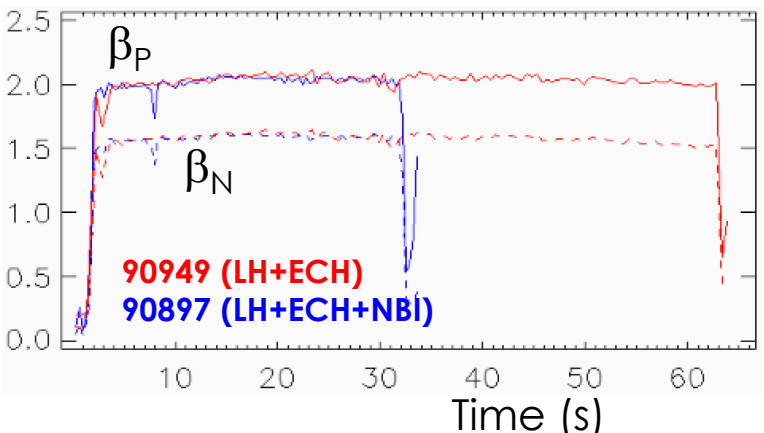
- Improved confinement (H_{98y2}~1.3) , zero torque with eITB
  - β_P ~2.0, β_N ~1.6, f_{BS} ~ 50%
- High LHCD efficiency at high density (n_e/n_{GW}~0.8) V_{loop}~0
- Metal wall with low tungsten concentration
- Small ELMs (f_{ELM}~1kHz)
- Challenges → T_e>>T_i, high ν^*

	CFETR A.3 SS	EAST SS
Fusion power	974	
β_N	2.0	1.6
f_{bs}	0.50	0.43
H factor	1.41	1.3
n_e/n_{GW}	0.57	0.8
q_{95} Iter	5.54	6.7

J. Qian, A. Garofalo, et al, **Invited talk, APS 2019**, "*Advances in Physics Understanding of High Poloidal Beta Regime Towards Steady-state Operation of CFETR*"

November 2019

- **High-β_P experiments achieved extension to 60 seconds of previous record duration of 20 seconds**
- **First approach achieved up to ~30 s making use of long-pulse NBI (Garofalo on-site)**
  - Limitation is the overheating, due to fast ion losses, of 4.6 GH LH antenna's tungsten limiter
- **Second approach achieved duration >60 s by removing NBI and reducing density**



EAST experiments follow up on first observation of QH-mode operating with tungsten divertor

Reference discharges from May 2019:

- **ELM were removed by counter-NBI in NBI heated plasmas, and by NRMP in RF-only plasmas**

J. Qian, A. Garofalo, et al, **synopsis, IAEA 2020,** "Development of Quiescent H-mode Scenario with ITER-like Tungsten Divertor in EAST"

November 2019 (Garofalo on-site):

- **Spurious Neon puff happening undetected → could not produce regular ELMs**
  - Edge recycling appears low

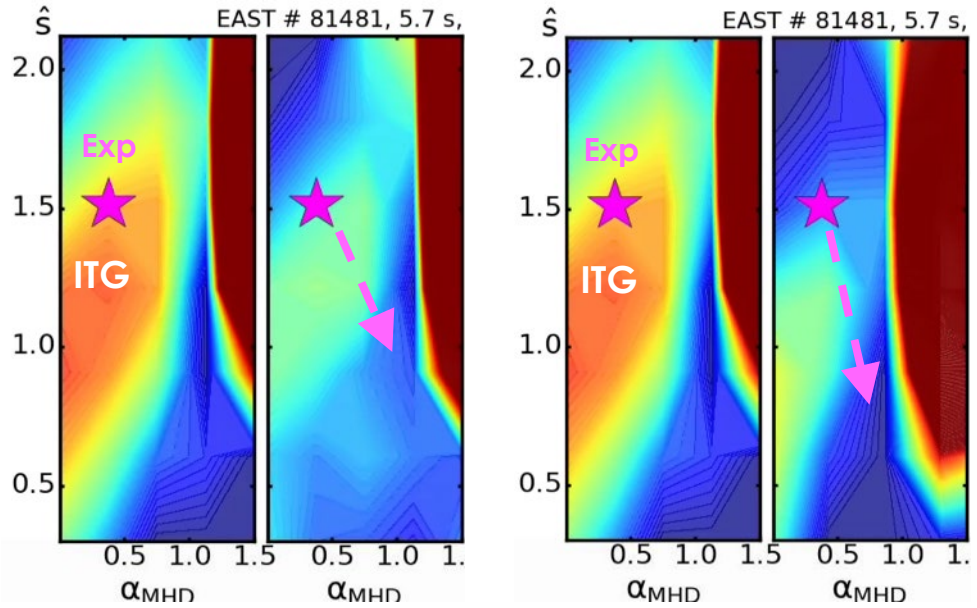
Remote experiment in December 2019:

- **Excellent machine conditions, very low impurities → could not get rid of ELMs, only reduce the amplitude**
  - Edge recycling appears high

→ Edge recycling differences may reconcile observations, showing a key role for access to QH-mode, similar to DIII-D

Comprehensive modeling shows possible paths to form large-radius ITBs in EAST high-β_P plasmas – Siye Ding

- **So far, EAST high β_P plasmas have comparable β_P to DIII-D cases, but no large radius ITB**
- **In spite of low ion heating, dominant low-k micro-turbulence at large radius of EAST high β_P plasma is ITG**
  - Exp. is trapped at low α by ITG mountain
- **Several paths could avoid ITG mountain**
  - Increase T_i by NBI or ICRF
  - Increase a/Ln_e by impurity injection at large radius, e.g. pellet injection
  - Reduce shear with strong OACD from external source
  - Initiate discharge with high shear at high q_{95}, then apply strong heating to achieve higher α, and ramp down q_{95} (similar to DIII-D recipe)



T_i/T_e*1.0 T_i/T_e*1.5 a/L_{ne}*1.0 a/L_{ne}*1.1

EAST

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Further Analysis and Planning Ongoing to Identify Experiments for Higher Confinement Long Pulse Plasmas

- Core scenario development and planning effort focused on:
  - Building a database of EAST shots to identify internal transport barrier(ITB) formation thresholds
  - Discussion with colleagues about how to do kinetic EFITs on EAST
  - Design of 1-day (remote) experiment to get higher radius ITBs by adjusting q-profile with open-loop and closed-loop (Lehigh U. controls)

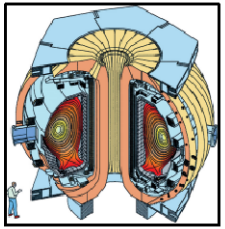
- Very limited new data this year due to Covid and EAST early shutdown

- New postdoc and staff begin contributing to these efforts this coming year

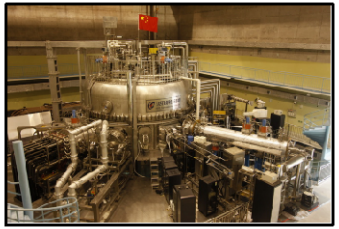
Task 2:
Control for Scenario Sustainment

Integrated Model-based Plasma Control for Long-Pulse High-Performance Scenario Development in EAST: *Mission, Recent Results and Future Plans*

- Adapt high-performance scenarios from DIII-D to EAST
- Develop control-physics understanding to enable adaptation
- Pioneer reactor-specific scenario and control solutions

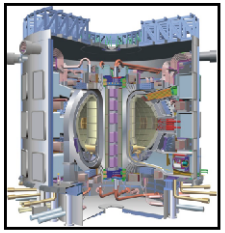


DIII-D

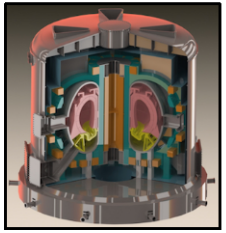


EAST

ITER

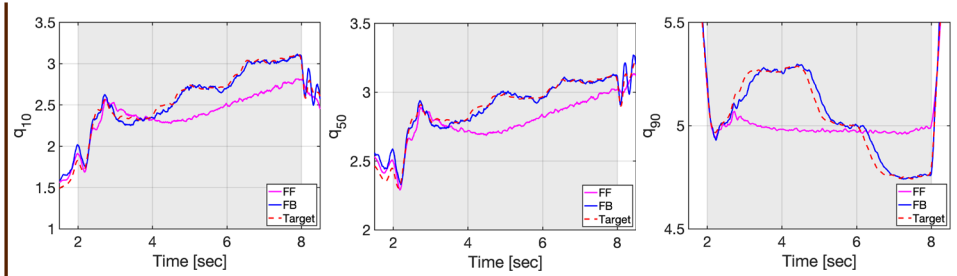


CFETR

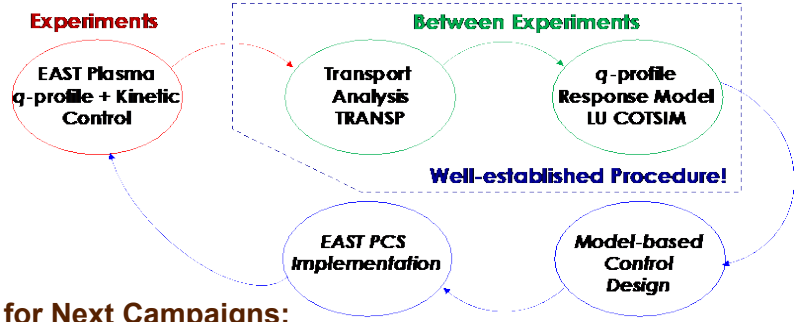


1. High-Performance Steady-State Scenarios
2. **Control for Long Pulse Sustainment**
3. Core-Edge Integration
4. **Simulations for Scenario Development and Control**
5. Diagnostics for Long Pulse Scenarios and Control
6. Remote Collaboration and Third Shift Operation of EAST

General Atomics
Lehigh University
Lawrence Livermore Nat Lab
Massachusetts Inst of Technology
Princeton Plasma Physics Lab
Univ of California Los Angeles
Univ of Texas Austin



Simultaneous feedback q-profile regulation at three spatial points was demonstrated for the first time in early 2020 by using two LH sources.



Development Needs to Enable High-performance Scenario Control:

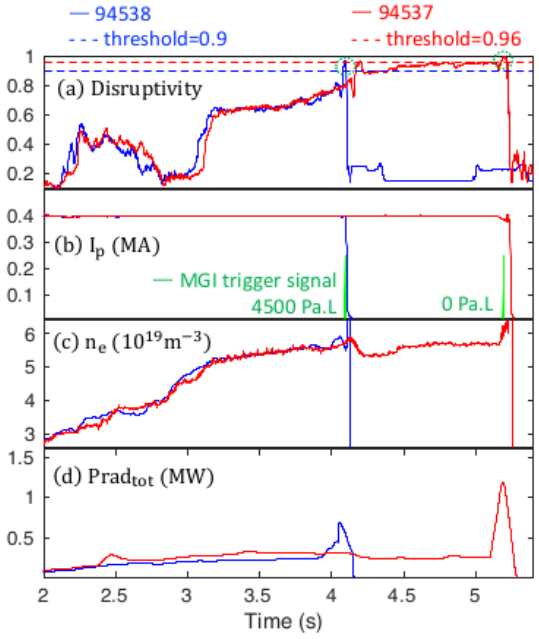
- Automatic POINT/MSE-constrained EFIT data for EAST experiments
- Enable routine use of real-time POINT/MSE-constrained pEFIT
- Develop new control capabilities for finer beam-power modulation
- Reliable command of all actuators (NBI/LWH/ECRF/ICRF) from PCS

Goals for Next Campaigns:

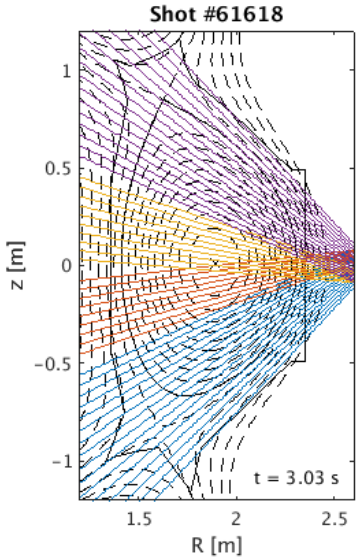
- POINT-constrained EFIT + TRANSP → Improved response models
- Redesign feedback controllers based on improved models
- Experimentally test model-based optimal current-profile controllers
- Make progress towards further control integration

Advances Made in Random Forest Prediction of Disruptions

- W. Hu, C. Rea et al., "Real-time prediction of high density EAST disruptions using Random Forest" Nucl. Fusion 2021 submitted.



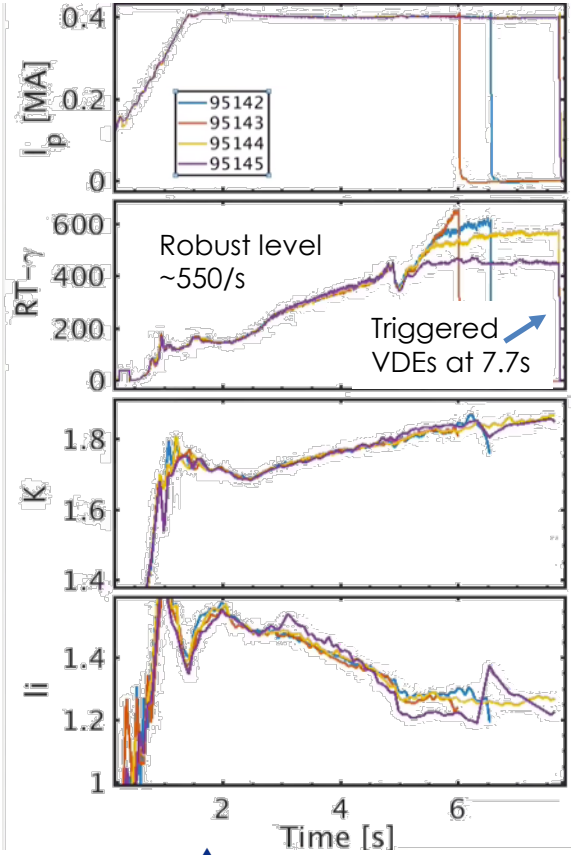
- Prad peaking factor -> calculated in real-time: a number of AXUV channels need to be digitized and sent to PCS:
  - Aid in real-time detection of density-limit disruptions;
  - Further upgrade of DPRF.



- Disruption_warning database is being repopulated with 2018-2020 experimental campaign data + new definition for Prad peaking factor.
- New real-time algorithm will focus on impurity-driven (W) disruptions [Gao et al. Fusion Engineering and Design **156** (2020) 111616] in view of restart of ops.

Vertical control *robustness* and RT-γ response Quantified in EAST

- **Finished the detailed K / γ scan**
  - Levels of 450 to 650/s
  - Robust control at ~550 /s for >= 2s
- **Triggered VDEs for open-loop-γ measurement at many levels**
  - Facilitates analysis comparing to PCS real-time calculation
- **Attempted increasing γ regulation**
  - Data collected to aid PID tuning
- **Artificial noise assessment begun**
  - Needed future development identified for detailed measurement



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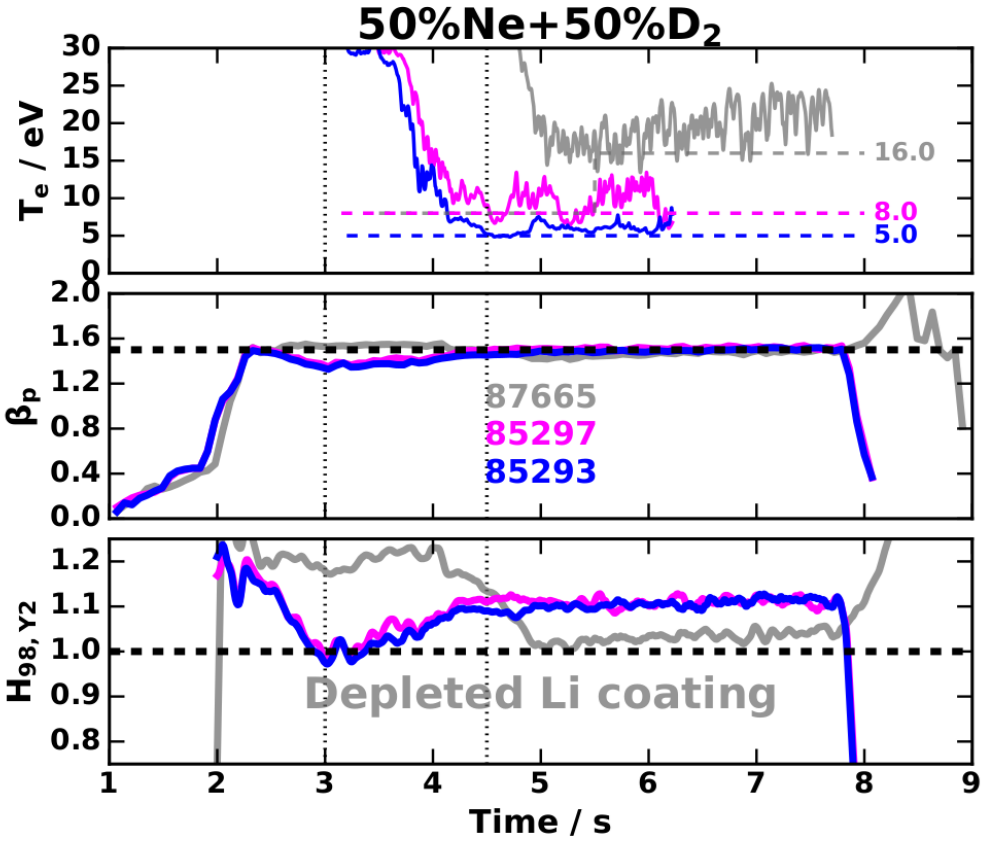
Task 3:
Core-Edge Integration

Advances in Core-edge Integration with Divertor T_e Control

- Feedback control LP T_e with impurity seeding
- Controller can manage T_e scan
- High β_p scenario retains confinement in detachment with Neon
- Relies on Li wall conditioning



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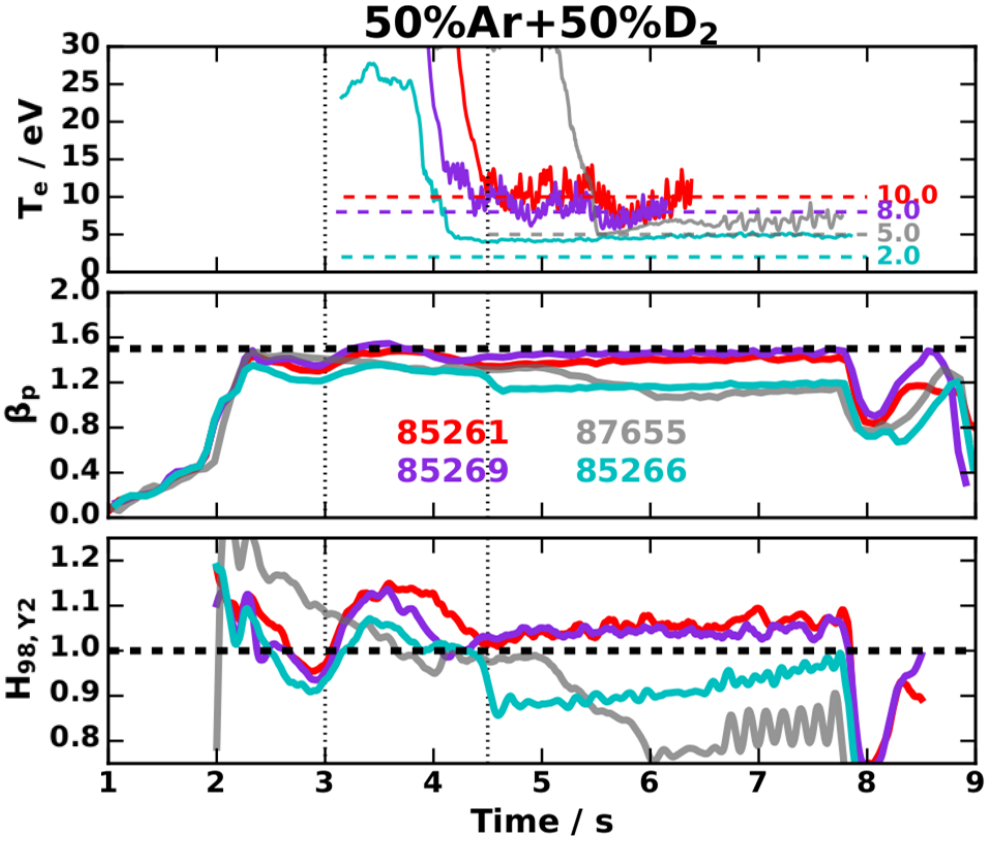
EAST T_e control works with Ar as well as Ne

- Previously, significant confinement loss from open-loop Ar injection
- Only 10% drop in H_{98} with feedback control in Ar-detached high β_p
- Confinement retained with marginal detachment

Eldon, 24th PSI invited, submitted to NME



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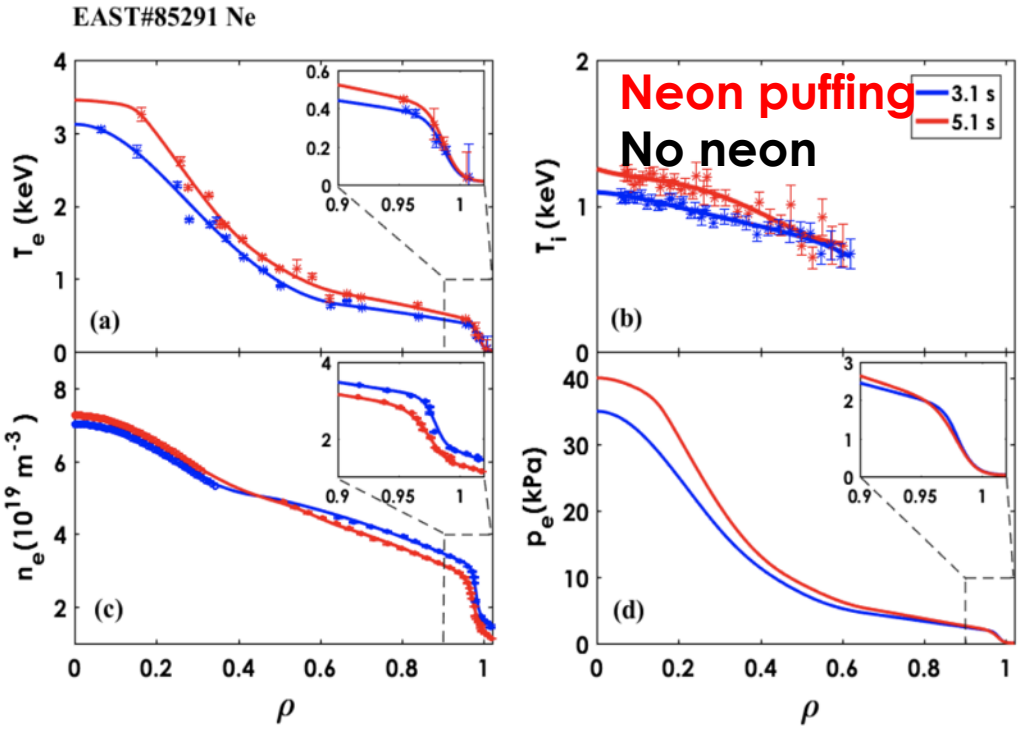
Neon improves global confinement integrating with a partially detached divertor

- Energy and beta increase by 10% after neon injection
- Pedestal improves
- Core temperatures increase
- Good core edge integration



KD Li, submitted to NF

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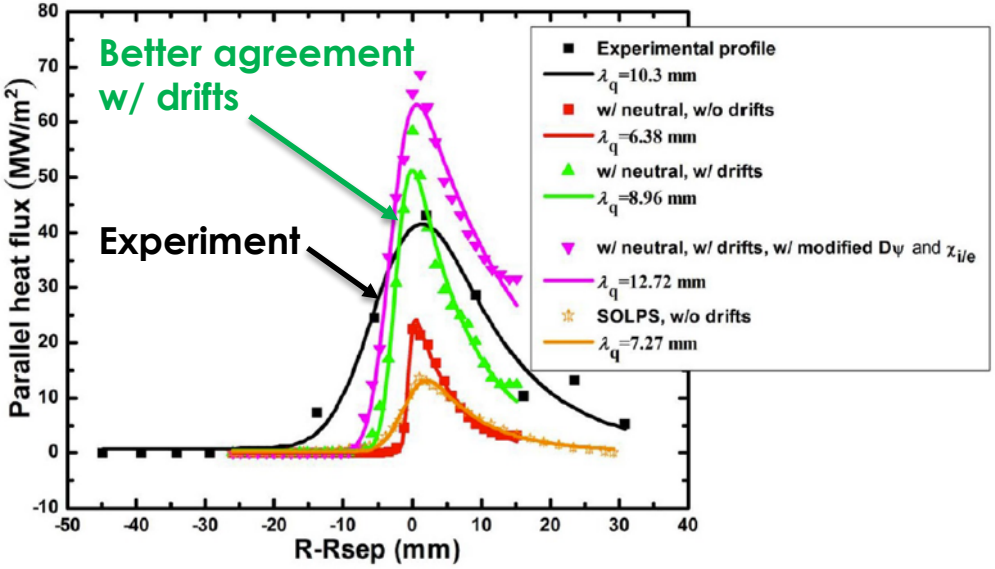
BOUT++ Modeling of Divertor Heating Showed Better Agreement with Experiment by Including Drifts

- BOUT++ edge code to simulate divertor heat flux in high performance EAST shots
  - Better agreement with drifts
  - Simulations & experiment both show heat flux width changes between NBI and LHW heating
  - Similar simulation efforts have been applied to predict CFETR ELM heat flux



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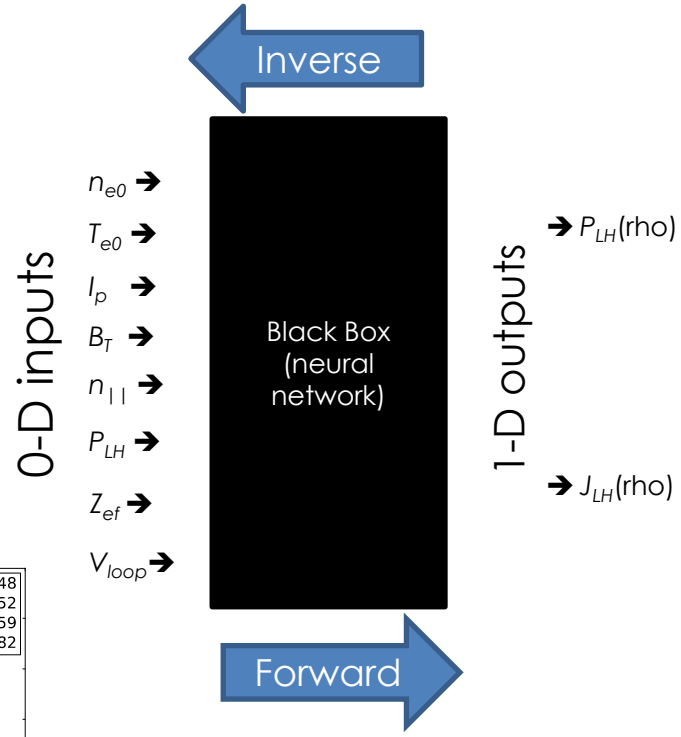
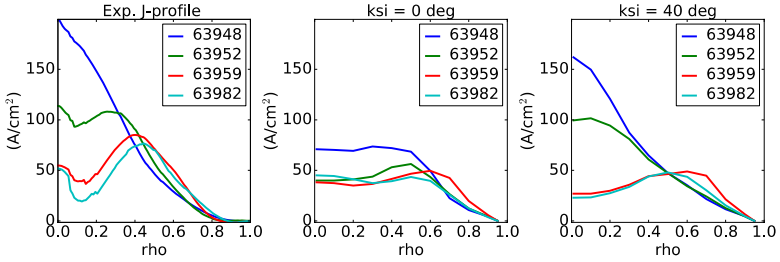
Task 4:
Modeling and Simulation

Development of a Machine Learning Surrogate Sodel for LHCD on EAST Enabling Faster Execution in Simulations

- **Simulation database consisting of**
  - 4374 simulations on structured grid of input parameters
    - f_0, Z_{eff}, n_{e0}, T_{e0}, $n_{||}$, P_{LHRF}, B_T, I_p
  - 3800 random simulations with subset of input parameters
    - n_{e0}, T_{e0}, $n_{||}$, P_{LHRF}, B_T, I_p
  - Collaboration with AI experts at LBNL to train fast surrogate model (neural network)
    - Preliminary results show that approach is successful within range of parameters scanned so far

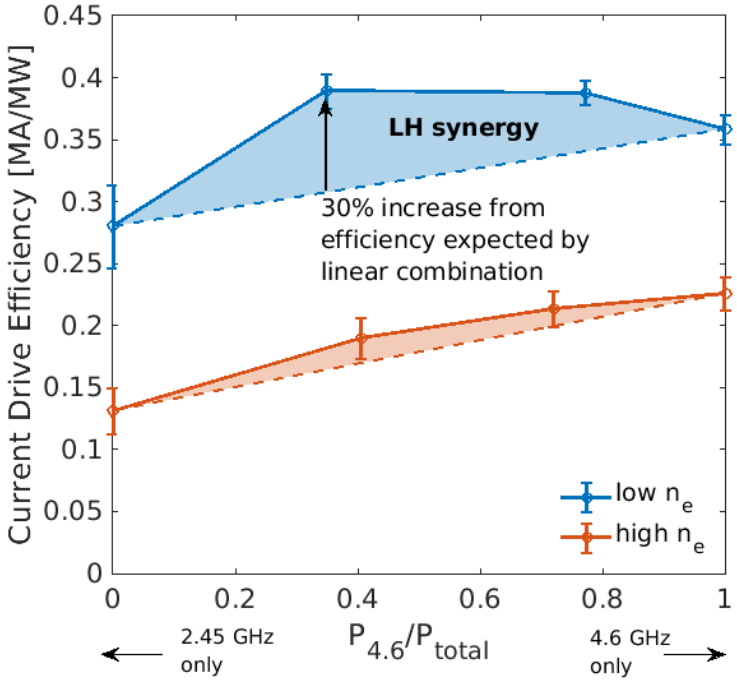


Future work will incorporate +30° $k_\perp$ rotation in second simulation database



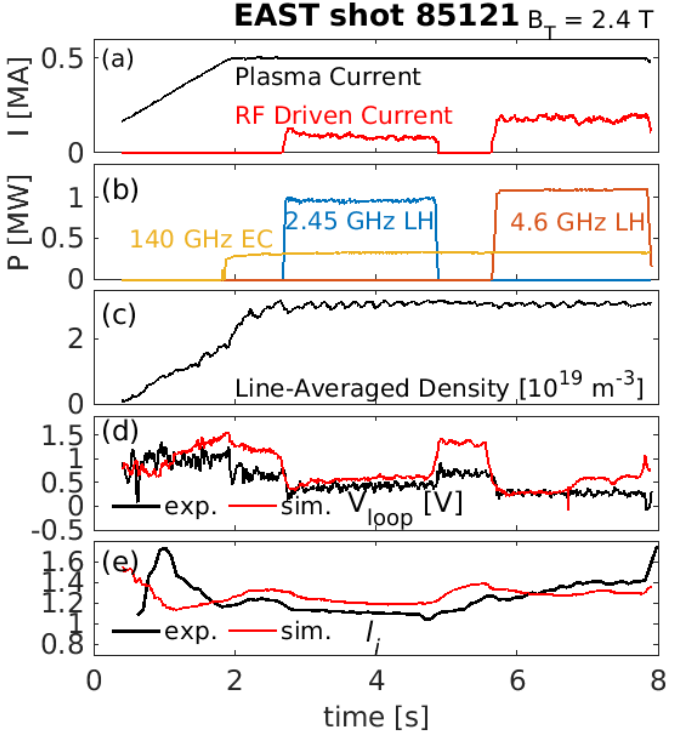
Observation of current drive synergy between two different frequencies of lower hybrid

- Simultaneous injection of 2.45 GHz and 4.6 GHz wave gives higher current drive efficiency than either wave alone, for $n_{e,lin} \approx 2.0 \times 10^{19}$ m^{-3}
- Synergy was not observed in the high density case ($n_{e,lin} \approx 3.3 \times 10^{19}$ m^{-3})
- Results presented in an invited talk at the 2020 APS and accompanying *Physics of Plasmas* paper

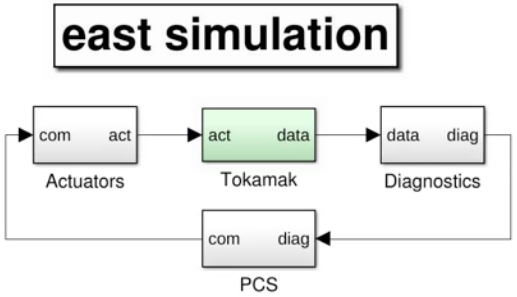


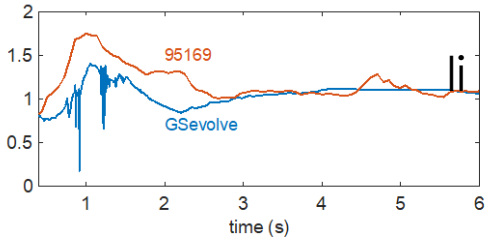
Simulation of LH + EC discharges required updates to the TRANSP/GENRAY/CQL3D interface

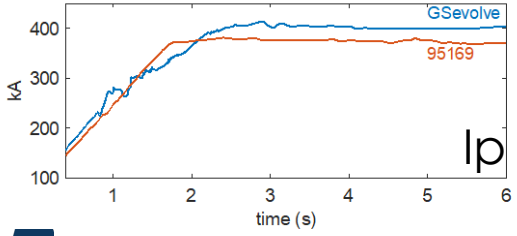
- Work has started on simulating a set of EAST discharges with simultaneous injection of LH + EC power
- Updates were made to the interface to include interactions between fast electrons from different RF sources
- Gaussian process regression was again used to improve time resolution on input electron temperature and density profiles
- This work will more accurately quantify the known synergy between LH + EC sources

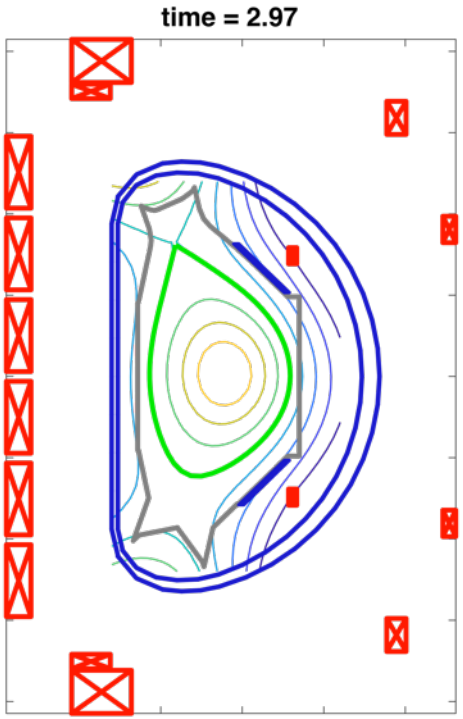


GSevolve Profile Evolution Validated with EAST Data









#95169

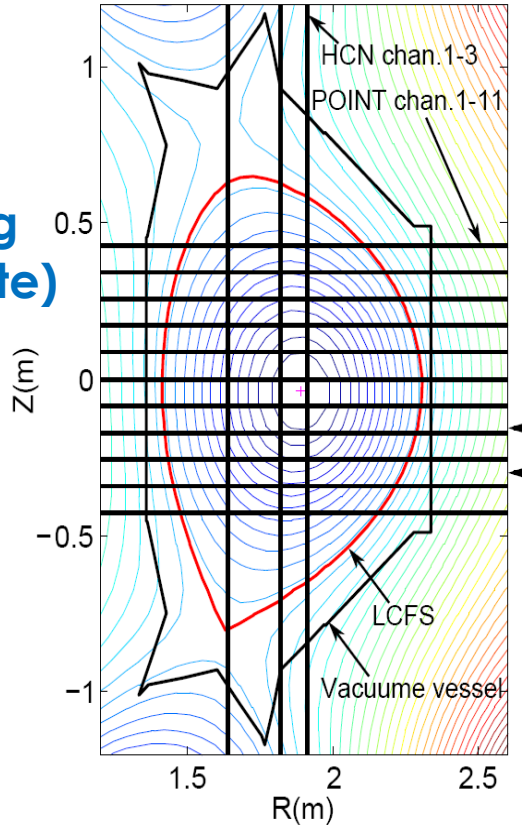
- East simulation including current profile evolution
- Simulation controlled by EAST PCS
- Supports verification, testing, design of PCS algorithms
- Simulation validated by li evolution

Task 5:
Diagnostics

UCLA Results: LPT Scenarios and Control in East

UCLA team: D.L. Brower, W.X. Ding, J. Chen, H. Lian

POINT System and Profile Reflectometers



Primary results for 2020:

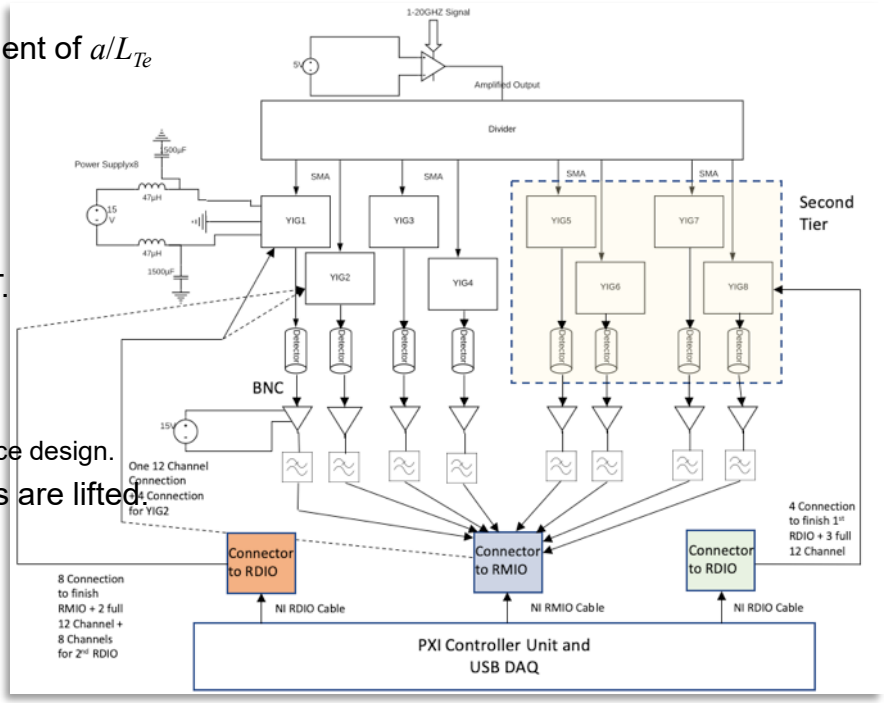
1. Supported EAST-POINT operations for DOE team during remote 3rd shift and onsite experiments (postdoc onsite)
2. Improved POINT performance by reducing optical feedback effects
3. Supported development of POINT constrained EFIT reconstructions
   - good fit to 11 chord POINT density data
   - fit to Faraday measurements being improved
   - EFIT reconstructions more readily available to US team members

Fast Modulated ECE (FMECE) Diagnostic Qualified at DIII-D and Ready for Install at EAST

- **Status of research and progress:**
  - Design and development FMECE (year 1) ✅
  - Demonstrate variable location ECE channels via measurement of a/L_{Te} (year 2) ✅
  - Diagnostic tested at DIII-D; ready for install at EAST ✅

- **Impacts of perturbational events:**
  - LTO and COVID delayed the diagnostic installation at EAST.
  - Restrictions at the University level:
    - Travel restrictions.
    - Hiring freeze.
    - Lab work at UT was/is restricted – affecting hot calibration source design.
  - Ready to deploy the diagnostic as soon as travel restrictions are lifted.

- **2021 plans (Year 2):**
  - Integrating the FMECE into EAST ECE diagnostic.
  - Real-time clustering of the ECE channels.
  - Continue collaboration with EAST on the hot calibration source design.



Task 6:
Remote Operation and Experiment Execution

Long Pulse Tokamak Project Continued to Pioneer Remote Operation on EAST and Helped Enable DIII-D to Operate Campaign in Pandemic

- **Remote 3rd Shift Experiments in EAST 2019-20 Campaign:**
  - Detachment control experiments
  - Extension of DIII-D High-β_P scenario to longer pulse in EAST
  - Current profile control experiments
  - Disruption prediction, prevention, avoidance experiments

- **EAST Remote Operation methods helped enable DIII-D to operate in pandemic conditions:**
  - DIII-D remote functions exploit procedures pioneered in EAST remote operation
  - Remote monitoring facilities imported from GA Remote Control Room (machine status, realtime traces, realtime boundary reconstruction, …)
  - Remote Physics Operations (plasma control system access and operation) modeled on EAST remote 3rd shift
  - Discord video gaming software use for EAST 3rd shift enables operations-physics team communication in DIII-D campaign

GA Remote Control Room Supports EAST 3rd Shift Experimental Operations

Discord Video Gaming Software for Remote Ops in 2020-21 DIII-D Campaign

DIII-D NATIONAL FUSION FACILITY

Plans for Year 2 (~FY2021)

- **EAST experiments:**
  - EAST shutdown scheduled to end, experiments resume ~ mid-2021
  - Participation in Spring (May-July), Fall (Nov-Dec) campaigns
  - Advance High-β_P scenario duration, performance with new machine resources (co-NBI, improved ICRF & LHW coupling, lower W divertor, more ECRH)
  - Initial integration of optimized trajectories, profile control, proximity ctrl
  - Implement methods for large radius ITB scenario in EAST
  - Test EAST new divertor and optimize detachment control
- **Simulations, Analysis, Implementations:**
  - Determine if LH synergy compatible with high density
  - Optimized integrated scenarios
  - Complete commissioning of proximity control, experimental quantification of performance
  - Install FMECE and obtain experimental data, begin use in proximity control
- **Management/Planning:**
  - Complete acquisition of post-docs
  - Renew/revise experimental proposals for EAST startup ~Spring-Summer 2021…

"We Are Connected" EAST 3-Shift Joint Experiments – Several proposals granted run time in 2020

- Extension of QH-mode on EAST tokamak (Andrea Garofalo - GA)
- Integration of High β_P scenario on EAST (Andrea Garofalo - GA)
- Improve high-beta steady-state performance by raising ITB-radius via magnetic shear and MHD control (Chris Holcomb LLNL)
- Impact of impurity on detachment stability in high poloidal β_P plasmas (Huiqian Wang - GA)
- Robust vertical control metric quantification + real-time growth-rate prediction piggyback (Jayson Barr - GA)
- Expanding operation regimes with LH synergy for current drive (Wilkie Choi - PPPL)
- Advancing towards fully non-inductive plasma at high current (Greg Wallace - MIT)
- Investigation of the DC electric field nonlinearity effect on LHCD (Seung-Gyou Baek - MIT)
- Further Development of Advanced Scenario Control Capabilities in EAST (Eugenio Schuster - Lehigh University)

Cancelled due to cryo fault and early EAST shutdown – Plan to renew requests for 2021 campaign…