The simulations of Grassy ELM characteristics and its impact on the divertor heat flux width for EAST

BOUT++
Boundary Plasma Turbulence Code

Nami Li[1]

X. Q. Xu[2]**, Ning Yan**[3]**, Yifeng Wang**[3]**, Yumin Wang**[3]**, Jinping Qian, J. Z. Sun**[1] **and D. Z. Wang**[1]

[1]*School of Physics, Dalian University of Technology, Dalian 116024, China*

[2]*Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

[3]*Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China*

10th US-PRC Magnetic Fusion Collaboration Virtual Workshop

March 23-27, 2021

This work was supported by the National Key R&D Program of China Nos. 2017YFE0301206 and China Postdoctoral Science Foundation under Grant No. 2020M670740. This work was also performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under DE-AC52-07NA27344

Outline

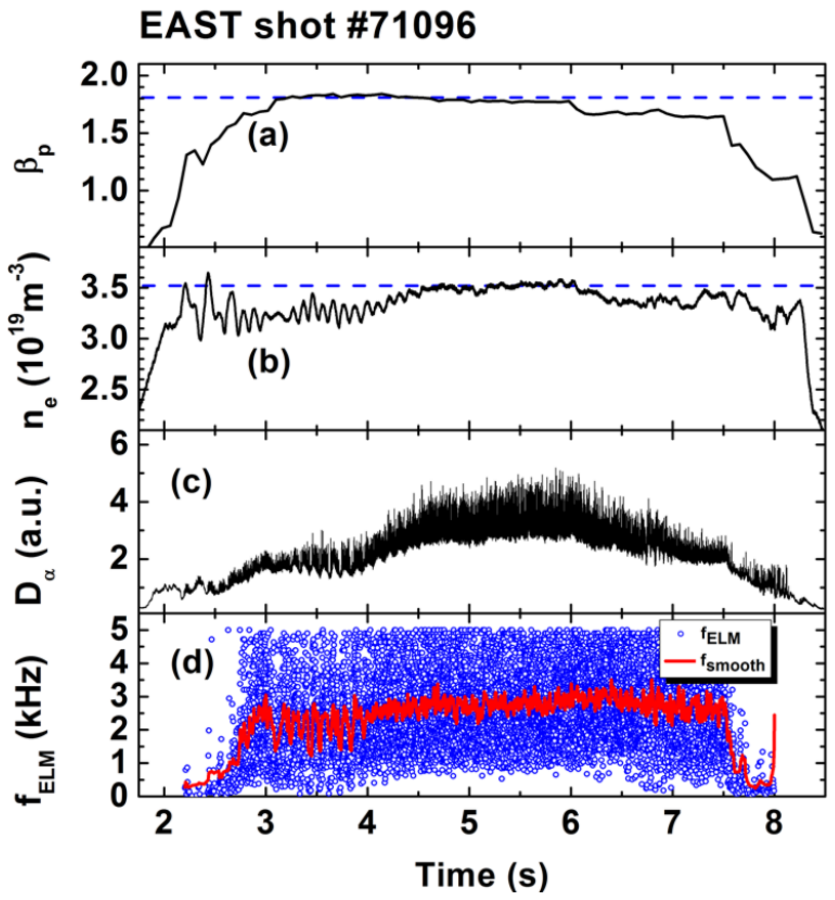
- ➢ Background and motivation
- ➢ Profiles and geometry for EAST Grassy ELM
- ➢ BOUT++ simulations of EAST trophy shot 90949 grassy ELM
  - ✓ Linear growth rate and turbulence dynamics
  - ✓ Heat flux across separatrix and divertor heat flux width
- ➢ Summary

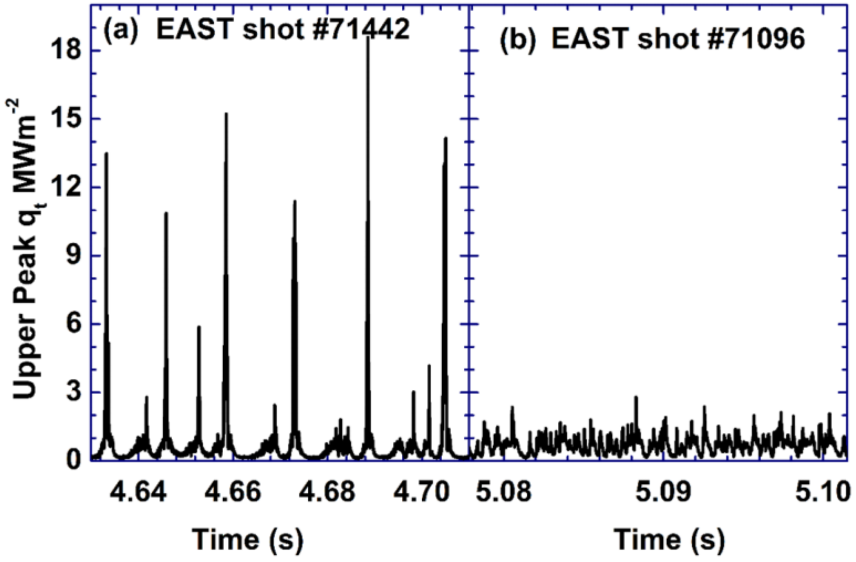
Background and motivation

- The heat flux distributions on divertor targets in H-mode plasmas are serious problems to the future devices
  - Based on Eich scalling[1-4] and HD mode[5] : $\lambda_q \propto 1/B_{pol}^{\gamma}$, which predicts $\lambda_q \sim 1.0$ mm for ITER
  - Both turbulence theory[6] , XGC[7] and BOUT++ simulations predict $\lambda_q \sim 5.0$ mm will not obey the scaling law for ITER due to the larger radial turbulence transport
- BOUT++ simulations predict that λ_q is broadened from ELM-free H-mode to small/grassy ELM regime (X.Q. Xu's talk at this workshop)
- Recently, both EAST and DIII-D grassy ELM experiments show a consistent divertor heat flux width broadening as BOUT++ simulations demonstrated in the grassy ELM regime
- Stationary small or no ELM H-mode regime with good confinement is a solution to large ELMs for ITER and is also one of the urgent tasks for next-step fusion development of CFETR

[1] T. Eich, 2013 Nucl. Fusion 53 093031. [2] R. Maingi, 2007 J. Nucl. Mater. 363–365, 196. [3] Makowski, 2012 Phys. Plasmas 19, 056122., [4] L. Wang. 2014 Nucl. Fusion 54 114002; [5] Goldston R.J. 2012 Nucl. Fusion 52 013009; [6] J. R. Myra, Physics of Plasmas 22, 042516 (2015); [7] C. S. Chang et al. Nucl. Fusion 57 116023 (2017)

A high confinement performance grassy-ELM H-mode regime has been achieved in EAST



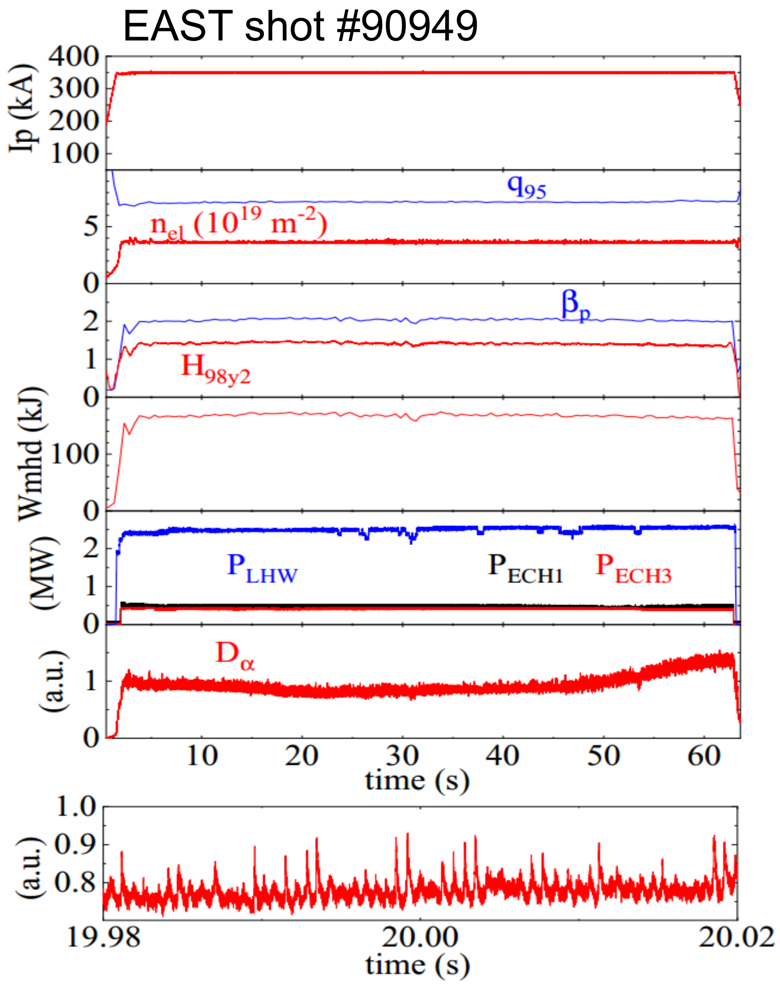


- ➢ **Heat fluxes of the grassy ELMs:**
  - ✓ **1/20-1/10 of large Type-I ELMs**
  - ✓ **Comparable with background level**

- ◆ **Presented here the characteristics of Grassy ELM and its effect on the divertor heat flux width for EAST trophy shot #90949 are performed using BOUT++**

G.S. Xu, et al., Phys. Rev. Lett. 122, 255001 (2019)

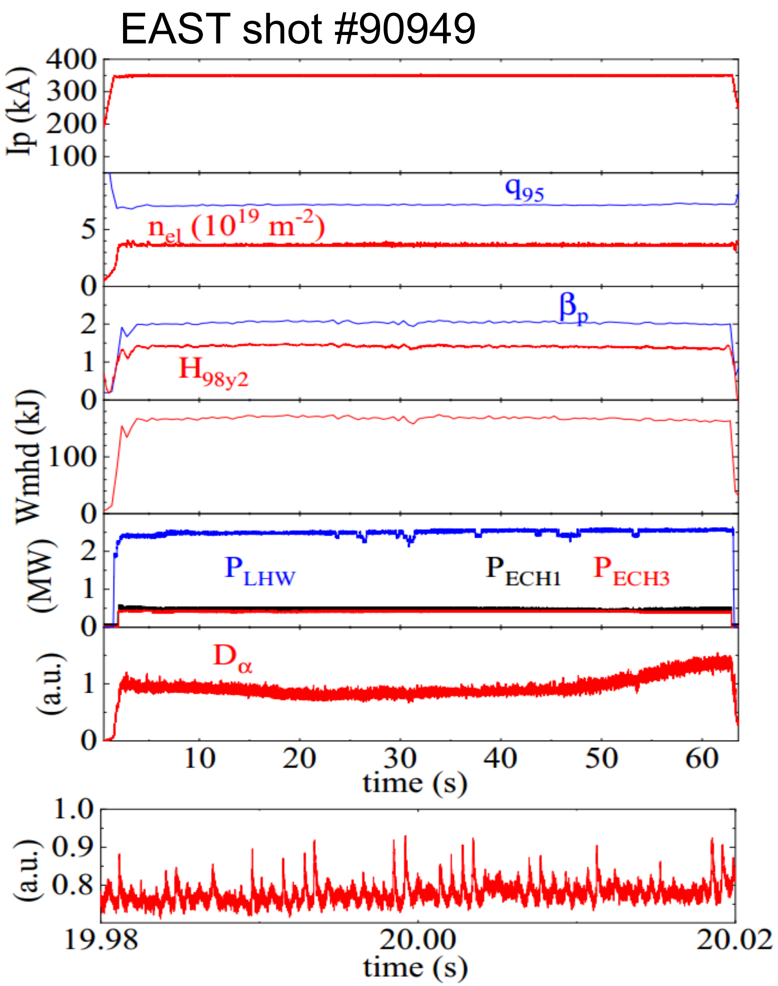
BOUT++ simulations for EAST High- β_p long-pulse experiments with grassy-ELM regime

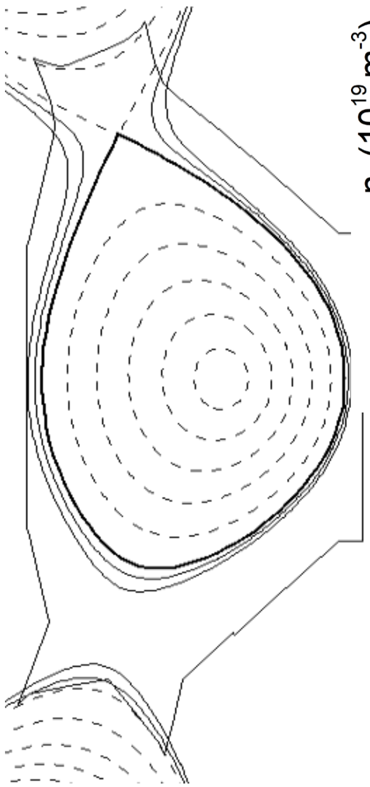


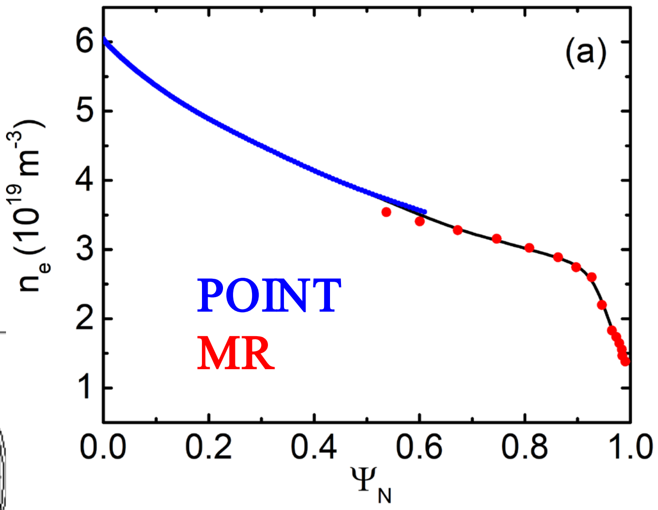
- **Close to SS Q>5 in CFETR Phase 2 Performance**
- **Develop long pulse steady state scenarios**
- **EAST trophy shot 90949 grassy ELM***
  - **Long pulse with small ELMs**
    - ✓ **duration >60s**
    - ✓ **f_{ELM}~1kHz**
  - **Improved confinement performance**
    - ✓ **H_{98y2} ~1.3, $\beta_p \sim 2.0$, $\beta_N \sim 1.6$, $f_{BS} \sim 45\%$, $q_{95} \sim 7.9$**
  - **RF-only fully non-inductive at high density: (n_e/n_{GW}~0.8)**
  - **Large density ratio: $n_{e,sep}/n_{e,ped}$~0.6**

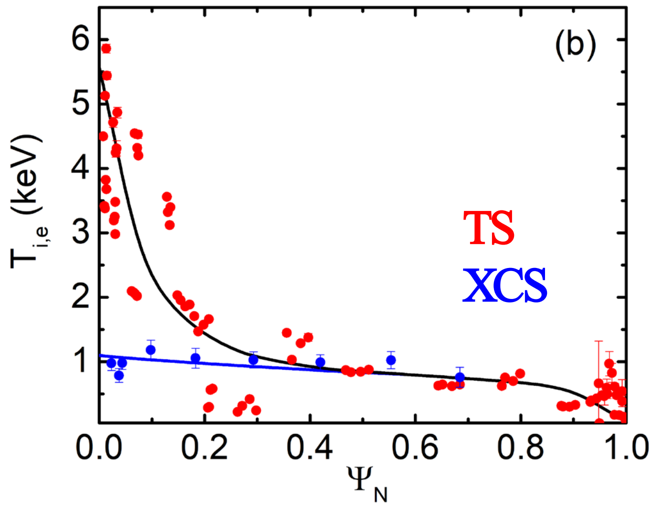
*B. Wan and David. Humphreys's talks at this workshop

Plasma profiles and magnetic configuration for EAST Grassy ELM shot #090949 @20s







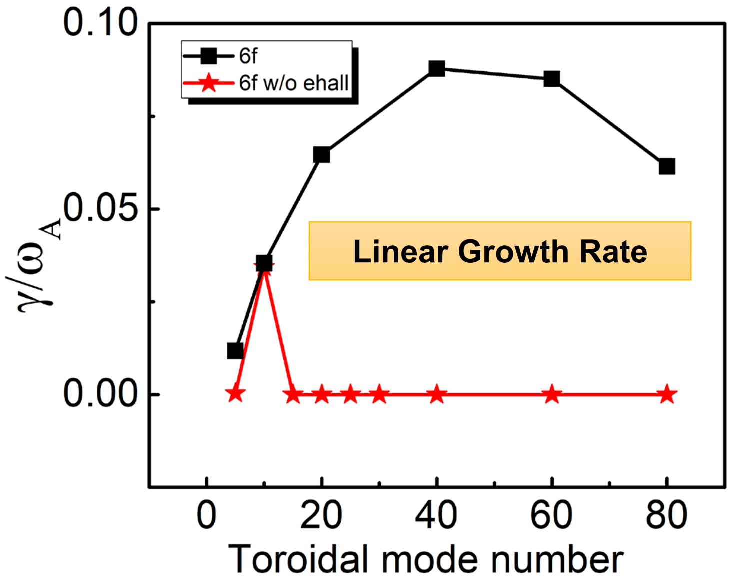


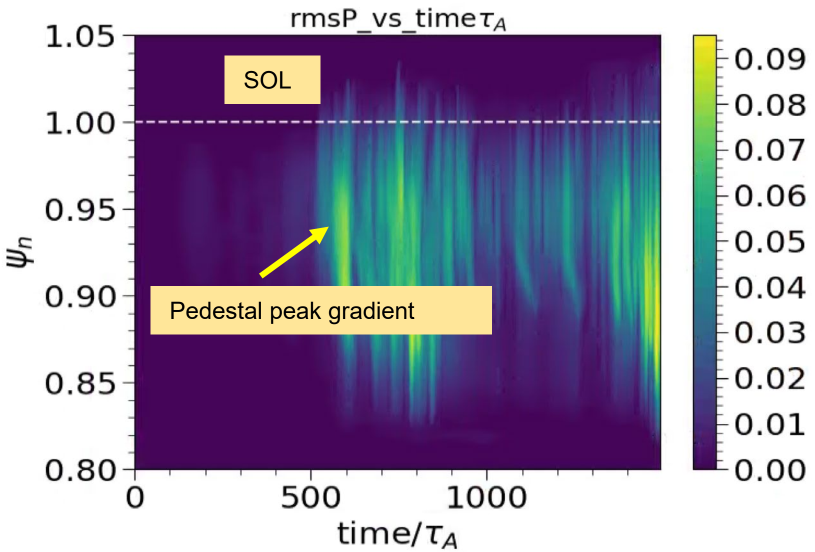
- The equilibria is reconstructed using the kinetic EFIT code with the constraints of experimentally measured total pressure profile and flux surface averaged toroidal current density profile dominated by j_{BS} in the pedestal region
  - g-file, p-file are used to generate the grid for the BOUT++ simulations
- Main diagnostics: TS, XCS, MR, POINT

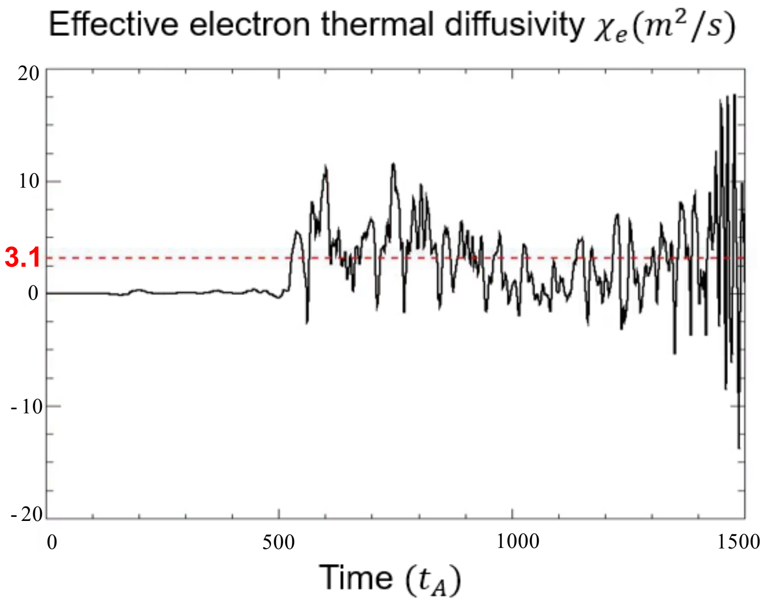
Outline

- ➢ Background and motivation
- ➢ Profiles and geometry for EAST Grassy ELM
- ➢ **BOUT++ simulations of EAST trophy shot 90949 grassy ELM**
  - ✓ Linear growth rate and turbulence dynamics
  - ✓ Heat flux across separatrix and divertor heat flux width
- ➢ Summary

BOUT++ 6-field turbulence simulations show turbulence is generated inside pedestal & spread into the SOL







- **Unstable for peeling ballooning mode at low-n**
  - **Most unstable mode n=30-50**
  - **Significant drift-Alfvén turbulence contribution at high-n**
- $\chi_{e,ave} = 3.1\ \mathrm{m}^2/s$ **>** $\chi_{\perp,critical} = 1.02\ \mathrm{m}^2/s$ **indicates grassy elm falls into turbulence dominated regime**

Divertor heat flux width is broadened in the grassy ELM regime due to the large turbulence transport

Shot	East #90949
$B_{p,omp}(T)$	0.162
$T_{e,sep}(eV)$	91
$\nu^*_{e,SOL}$	6.87
Eich: λ_q(mm)	5.5
HD: λ_q(mm)	5.7
λ_q^{BC}(mm)	5.11
$\lambda_q^{eich,tur}$(mm)	10.01
BOUT++ transport: $\lambda_q^{transport}$(mm)	13.64
BOUT++ turbulence: λ_q^{turb}(mm)	10.67

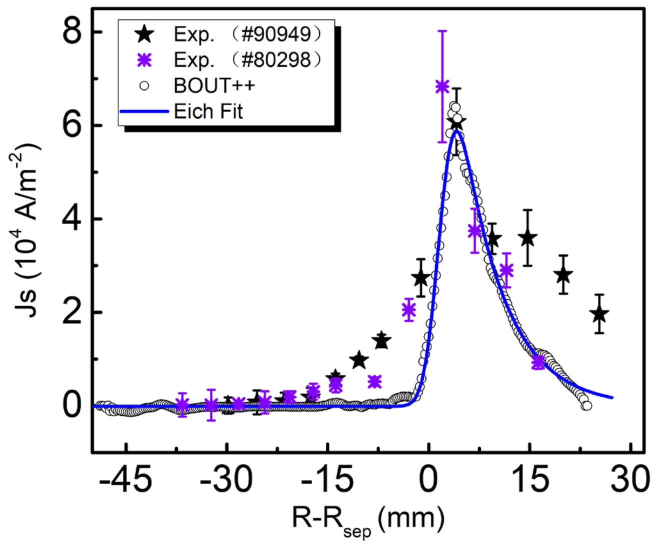
Collisionality:

$$\nu^*_{e,SOL} = \frac{\pi \hat{q}_{cyl} R}{1.03 \cdot 10^{16}} \frac{n_e}{T_e^2} Z_{eff}$$

Near-Separatrix Ballooning criticality

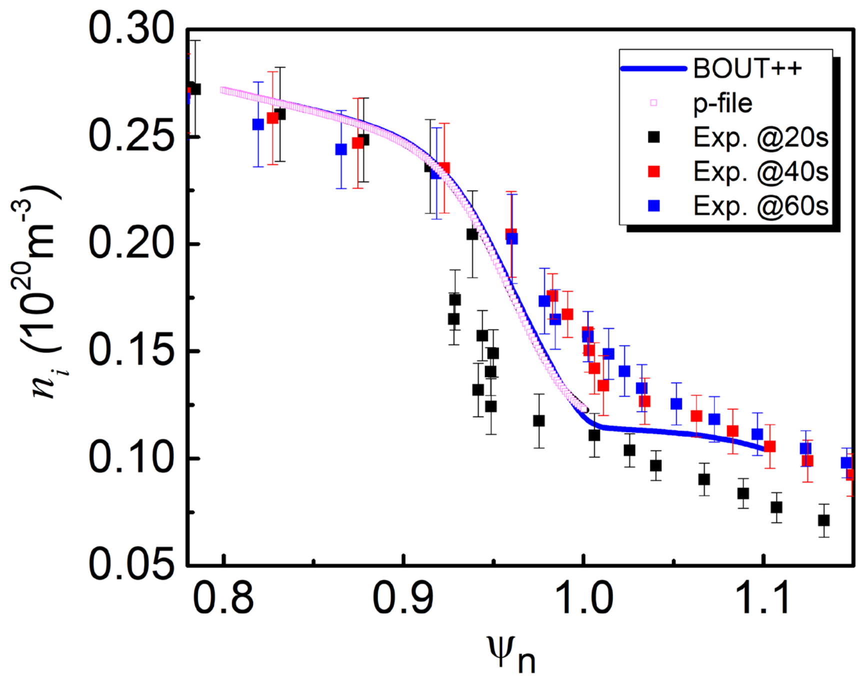
For DIIID and EAST :

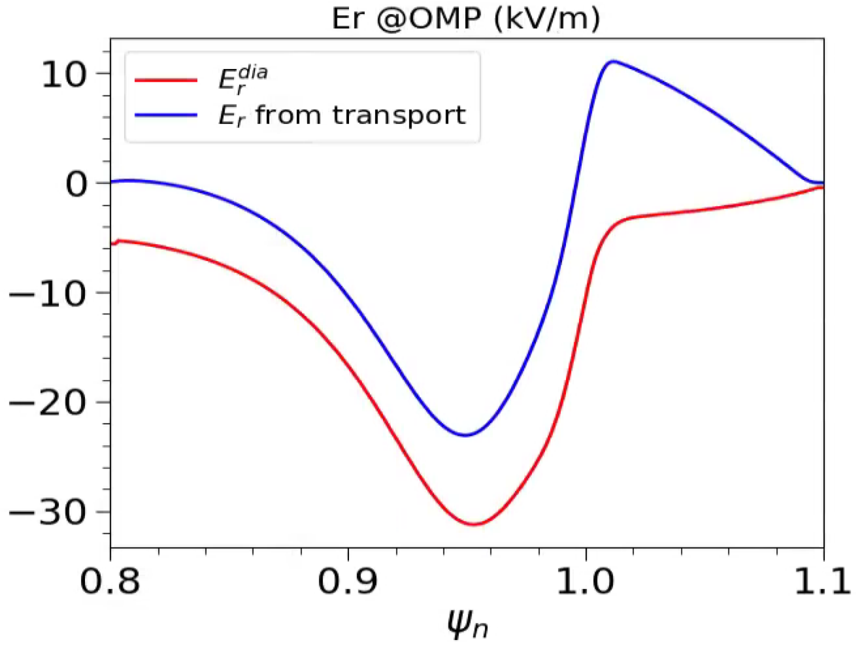
$$\lambda_q^{BC} = 0.43 \times B_{pol,MP}^{-1.36}$$



- Divertor heat flux width is broadened due to the larger radial turbulence and the SOL collisionality
  - Turbulence dominated radial transport in the grassy ELM regime
- The magnitude of the particle flux calculated by BOUT++ is comparable with experimental data while the width is ~1-3 times smaller than the Exp.
  - Experimental data: probe
  - Need more experimental data to establish a statistical average

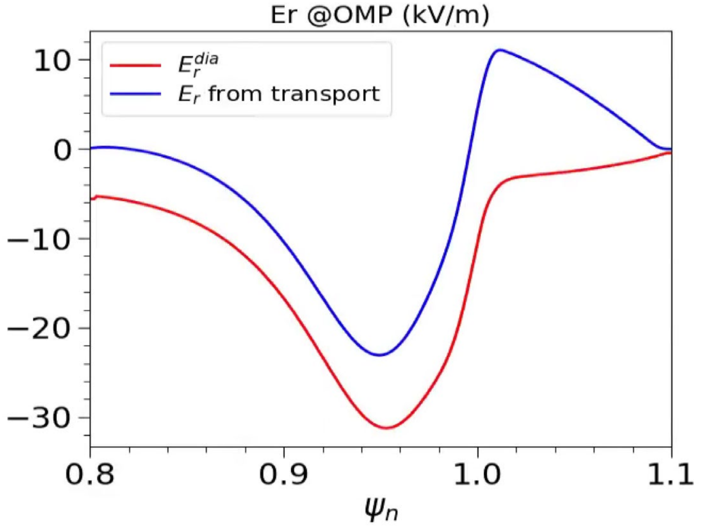
The simulated plasma profiles compared well with the experiment data

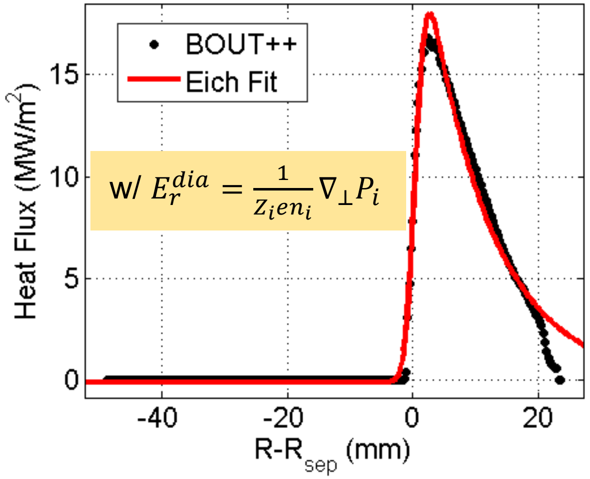


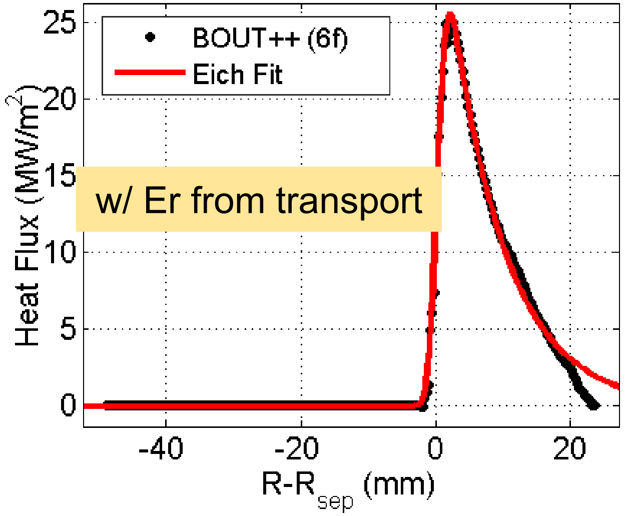


- ✓ **2D plasma profiles and radial electric field are calculated using BOUT++ transport code**
- ✓ **Experimental data: microwave reflectometry (MR)**

Radial electric field has strong effects on the turbulence behavior and the heat flux







	With diamagnetic Er	With Er from transport
S (mm)	1.84	1.52
$\lambda_q^{eich,fit}$(mm)	10.39	8.18
λ_{int}(mm)	13.41	10.67

From diamagnetic Er to Er from 2D transport simulations:

- ✓ **Turbulence increases as the Er-well gets shallower due to the stabilization weakened**
  - **Energy lose increased and pedestal crash delayed**
- ✓ **Radial transport is suppressed while the poloidal flow increased with a positive SOL Er**
  - **Peak heat flux increases while the width decreases**

Summary

- BOUT++ turbulence simulations are conducted to capture the physics of the Grassy-ELM characteristics and its impact on the divertor heat flux width for EAST trophy shot #90949 @20s
  - Long pulse with small ELM
  - High energy confinement performance H_{98y2} ~1.3, High β_p~2 and q_{95}~7.9
  - Larger density ratio $n_{e,sep}/n_{e,ped}$
- The turbulence is generated from the peak gradient of pedestal and transport to the SOL
  - Unstable for peeling ballooning mode (n=30-50) with drift-Alfvén instability at high-n
  - Turbulence increases as the Er-well gets shallower due to the stabilization weakened
- Divertor heat flux width is broadened due to the larger radial turbulence and SOL collisionality
  - BOUT++ simulated: λ_q~10-14 mm
  - HD and Eich scaling: λ_q~5-6 mm
  - Turbulence dominated radial transport in the grassy ELM regime
  - The width is inversely proportional to Er
    - ✓ Radial transport is suppressed while the poloidal flow increased with a large positive SOL Er

The simulations of Grassy ELM characteristics and its impact on the divertor heat flux width for EAST

BOUT++
Boundary Plasma Turbulence Code

Thanks for your attention!

10th US-PRC Magnetic Fusion Collaboration Virtual Workshop

March 23-27, 2021

This work was supported by the National Key R&D Program of China Nos. 2017YFE0301206 and China Postdoctoral Science Foundation under Grant No. 2020M670740. This work was also performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under DE-AC52-07NA27344