核工业西南物理研究院
Southwestern Institute of Physics
中核集团 CNNC

Recent progress of US-PRC magnetic fusion collaborations on diagnostics development and plasma physics studies at SWIP

Wulyu Zhong

on behalf of HL-2A team and collaborators

Southwestern Institute of Physics, Chengdu, China

US-PRC Magnetic Fusion Collaboration Workshop

Mar 23-27, 2021

List of content

- Collaborations on advanced diagnostics
- Collaborations on plasma physics study
- Summary and collaboration opportunities

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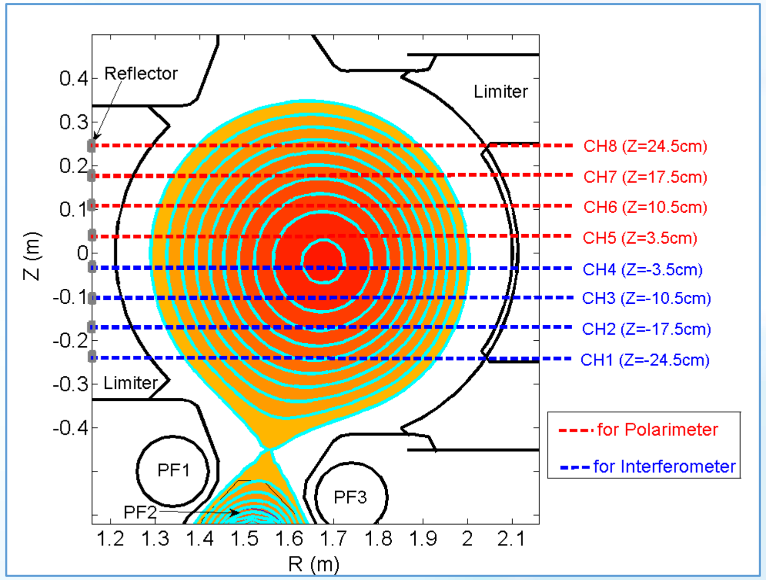
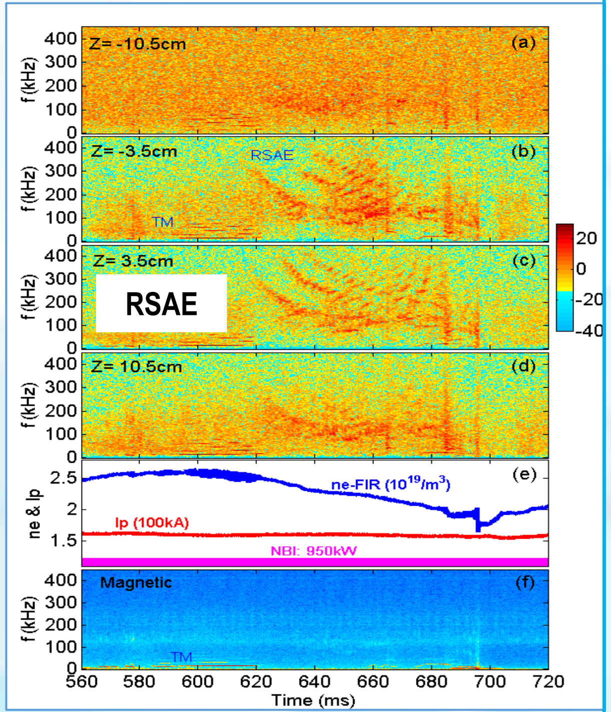
Far-forward collective scattering (FCS)

In collaboration with **Dr. W.X. Ding, UCLA**

- An eight-channel Far-forward Collective Scattering (**FCS**) diagnostic has been successfully developed from the formic-acid (HCOOH, λ=432.5μm) laser Polarimeter and Interferometer on HL-2A tokamak.
- FCS diagnostic played an important role in measuring the electron density fluctuations ($k<1.6cm^{-1}$).





Optical configuration of the FCS diagnostic and experimental result on HL-2A.

a) Y.G. Li et.al, High-sensitivity far-forward collective scattering diagnostic on HL-2A tokamak, ***Rev. Sci. Instrum***, 90(5): 053502, (**2019**).

b) Y. Li et.al, Progress of the synthetic HCOOH laser diagnostic system on HL-2A tokamak, ***Journal of Instrumentation***, 14: C120202, (**2019**) .

c) Y.G. Li et.al, Optical technologies towards improving the Far-infrared laser Polarimeter-Interferometer system on HL-2A tokamak, ***Fusion Engineering and Design***, 137(12): 137, (**2018**).

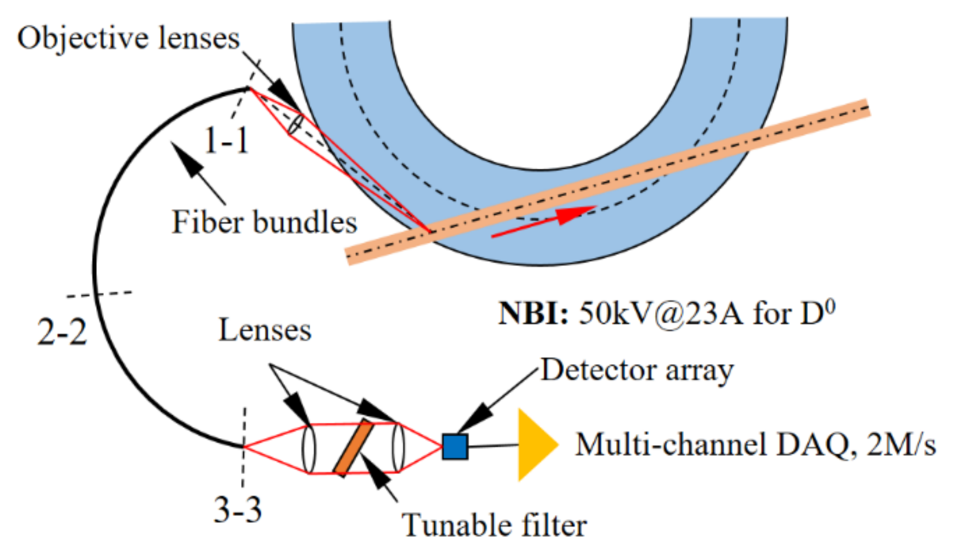
d) Y.G. Li et.al, First electron density fluctuation measurement via the HCOOH laser far-forward collective scattering on HL-2A tokamak, ***Journal of Instrumentation***, 11: C02002, (**2016**).

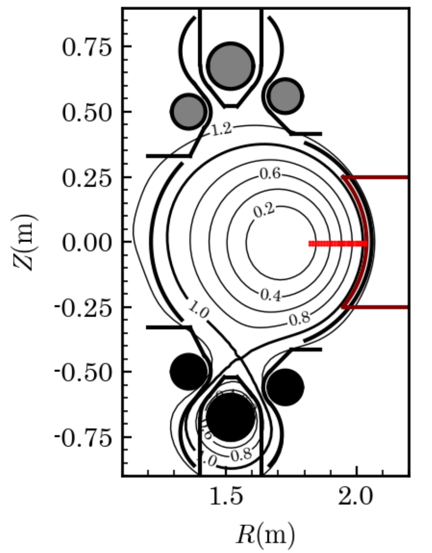
Future collaboration: Improvement of FIR laser Polarimeter/Interferometer on HL-2A tokamak.

Beam Emission Spectroscopy (BES)

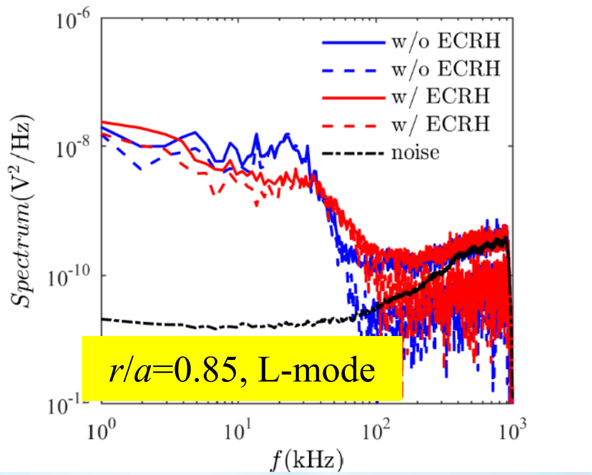
In collaboration with **Dr. George McKee, Dr. Z. Yan, UWM**

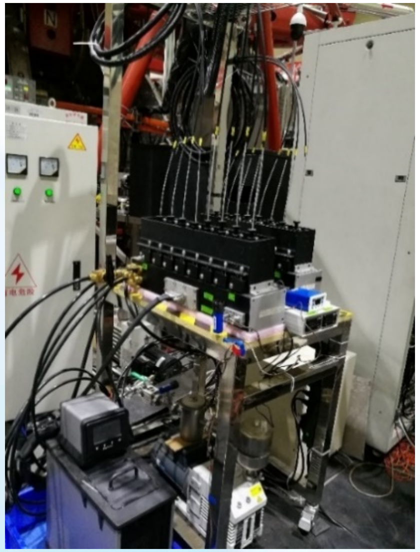
- High spatial (Δr = 0.7 (edge) ~ 1.2 (core) cm, ΔZ = 1.2 cm) and temporal resolution: Δt = 0.5 μs (2 M/s), measuring low-k density fluctuations.
- Extended from 16 channels (2018, Phase I) to 48 channels (2019, Phase II) , covering r/a = 0.43~1.03.





Good S/N rate for fluctuation measurement





- Newly developed integrated system in process (Phase III): 16-channel (2 modules) system upgraded to 64-channel system (1 module).

R. Ke, et al., RSI 89(10):10D122 (2018)

X. Qin, et al.,presented at HTPD2020

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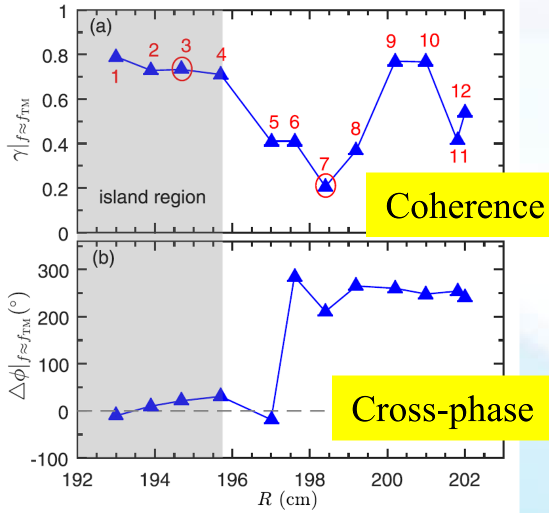
Beam Emission Spectroscopy (BES)

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

In collaboration with **Dr. George McKee, Dr. Z. Yan, UWM**

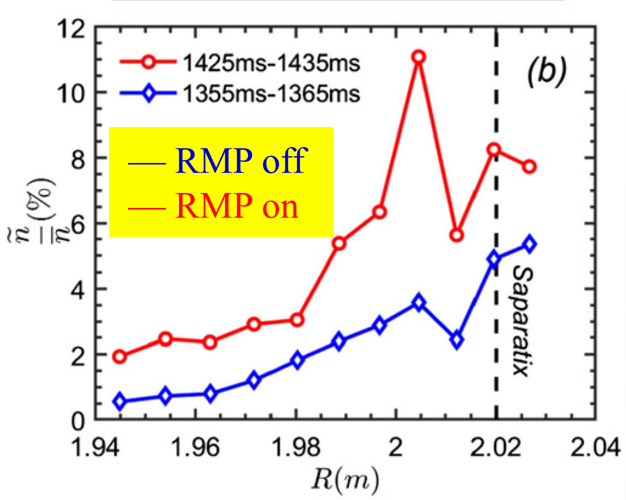
- BES system on HL-2A has good performance, and has been applied to a few scientific studies:
  - MHD instabilities, L-H transition, ρ* scaling, ELM mitigation with RMP, edge-SOL coupling, etc.

Turbulence amplitude modulated by TM: $(Env(n_e), T_e)|_{f=f\mathrm{TM}}$



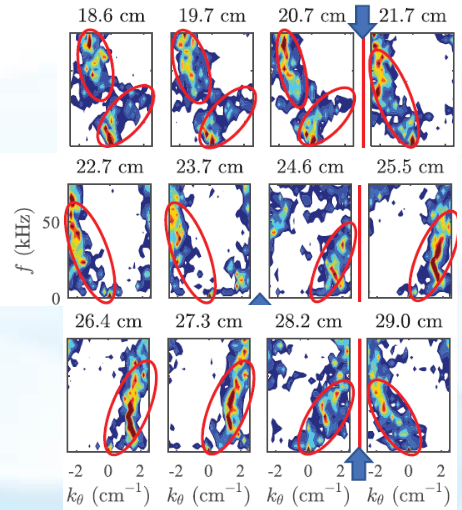
M. Jiang, et al., PST (2020)

ELM mitigation by RMP: enhanced turbulence



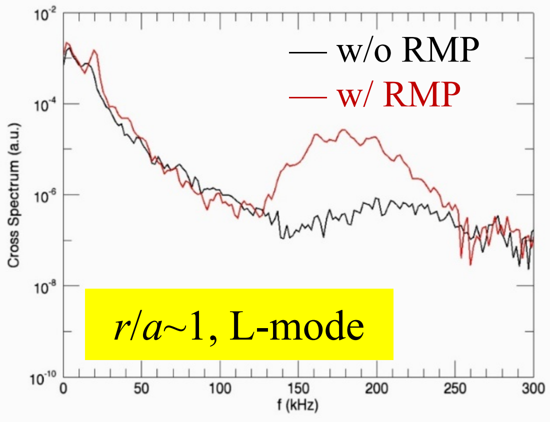
T. F. Sun, et al., NF (2021)

E×B staircase observed in HL-2A L-mode: $S(k_\theta, f)$



W. Liu, et al., PoP (2021)

Higher L-H transition power threshold with RMP: enhanced turbulence.



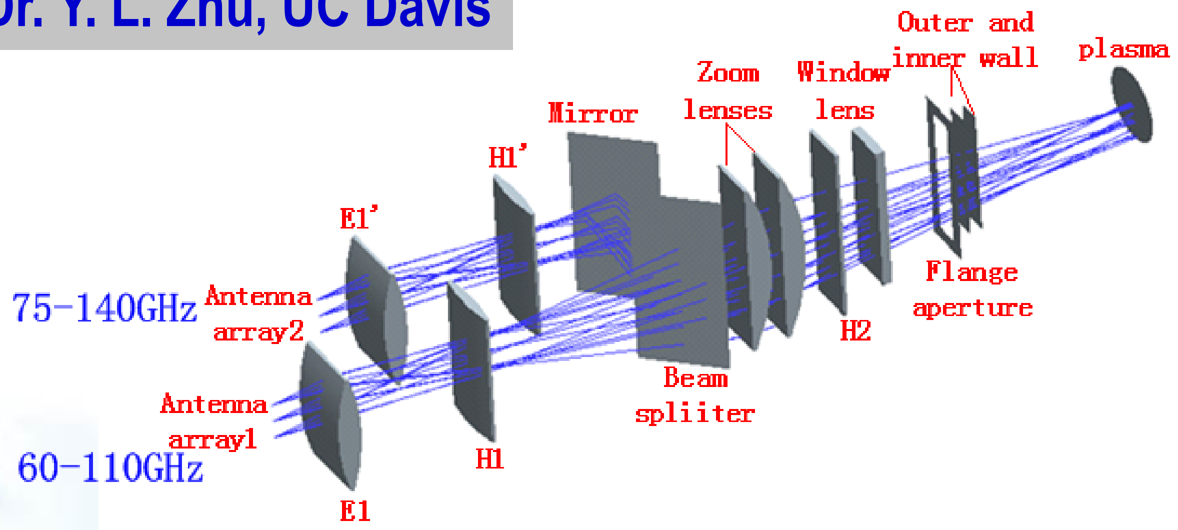
Y Zheng, et al., on progress

Future cooperation:

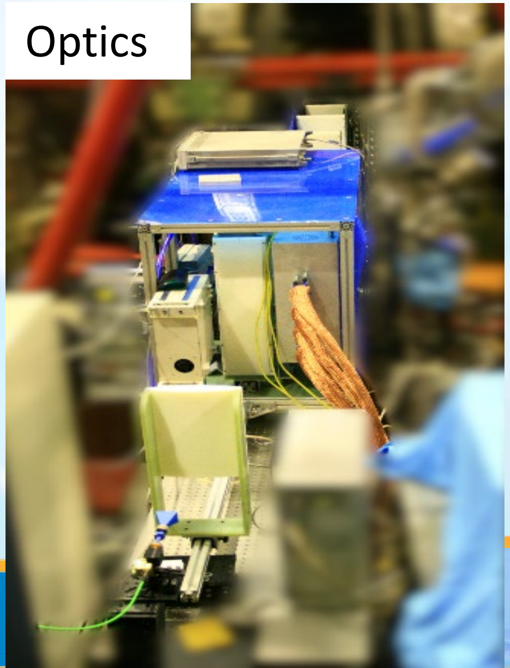
- Joint experiments on HL-2A/2M and DIII-D: L-H transition, ρ* scaling, etc.
- BES project on HL-2M tokamak.

Electron cyclotron emission imaging (ECEI)

In collaboration with **Dr. N. C. Luhmann, Jr. and Dr. Y. L. Zhu, UC Davis**



- 2D imaging for electron temperature fluctuations
- Two 24 (vert.)x8 (rad.) arrays, LFS and HFS imaging simultaneously
- Work frequency: 60-90 GHz (Bt>1.3T)
  75-140GHz (Bt>1.6T)
- View of field:53 cm in the vertical direction, and 35 cm in the radial direction.
- Wide zoom pattern (large scale MHD measurement) and narrow zoom pattern (fine structure measurement of small scale MHD, like ELMs)
- Resolution: 2.5 μs, 1-3 cm

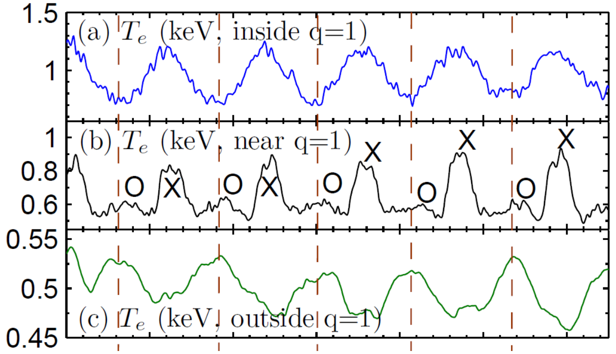


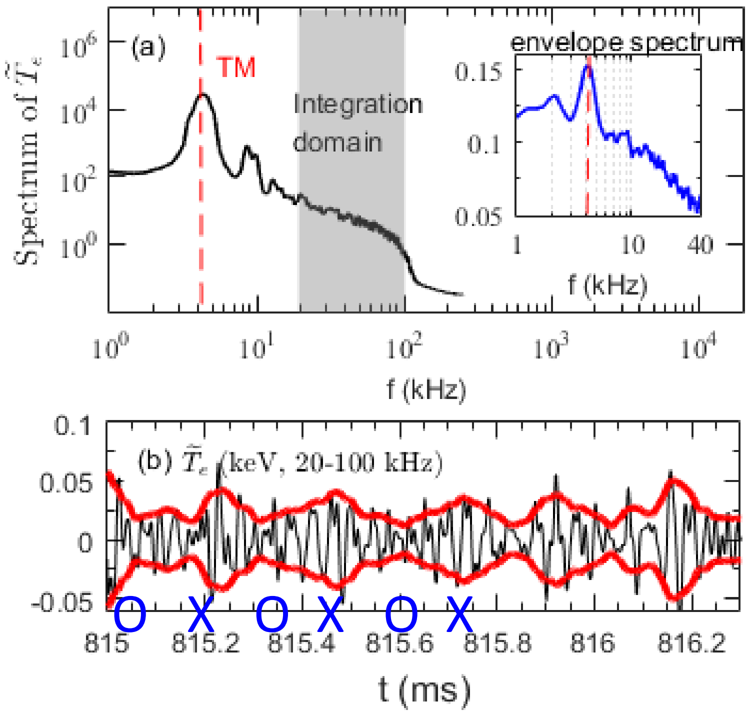
M. Jiang RSI 2013&2015
M. Jiang PST 2017

Electron cyclotron emission imaging (ECEI)

In collaboration with **Dr. N. C. Luhmann, Jr. and Dr. Y. L. Zhu, UC Davis**

Multi-scale interaction (M. Jiang, NF 2019)





Ongoing collaborations (2019-2021):

- ✓ Discussion about the improvements of ECEI data analysis with visual interface.
- ✓ Synthetic diagnostic application on HL-2M for ECE Imaging and Microwave Imaging Reflectometer.
- ✓ Design of the ECEI optics for HL-2M.

Proposals for future collaborations:

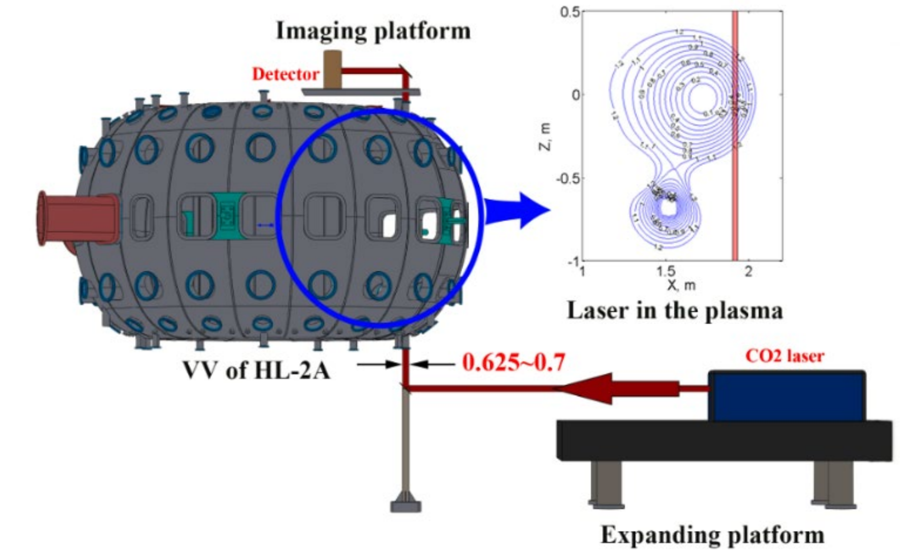
- ☐ System-on-Chip technology application on microwave imaging diagnostics on HL-2A (E-band and W-band).
- ☐ Joint experiments for pedestal transport studies on HL-2A/2M and DIII-D.

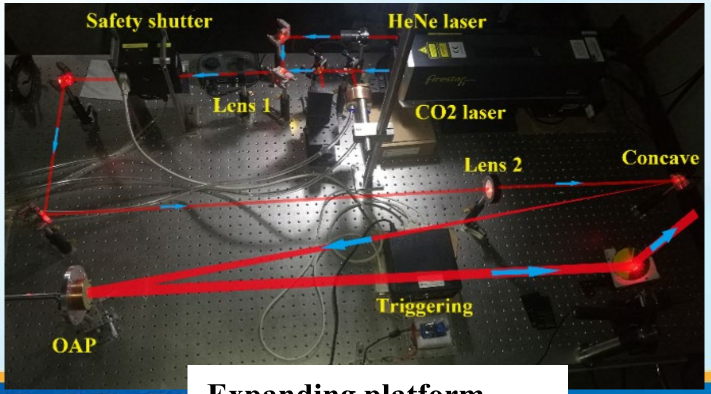
Phase Contrast Imaging (PCI)

In collaboration with **Dr. J.C. Rost, MIT**

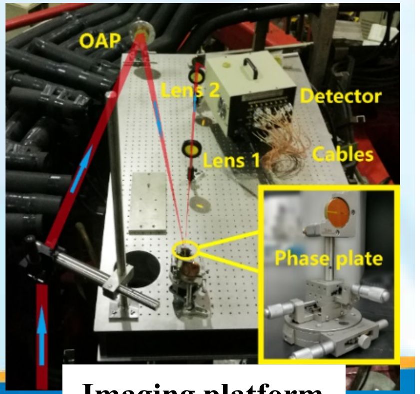
- 32-channel CO_2 laser-based PCI
- Line-integrated density fluctuations
- Covering r/a = 0.625-0.7
- Wavenumber: 2-15 cm^{-1}
- Time resolution: 2 μs

S. Gong, et al., PST, 21 084001 (2019).

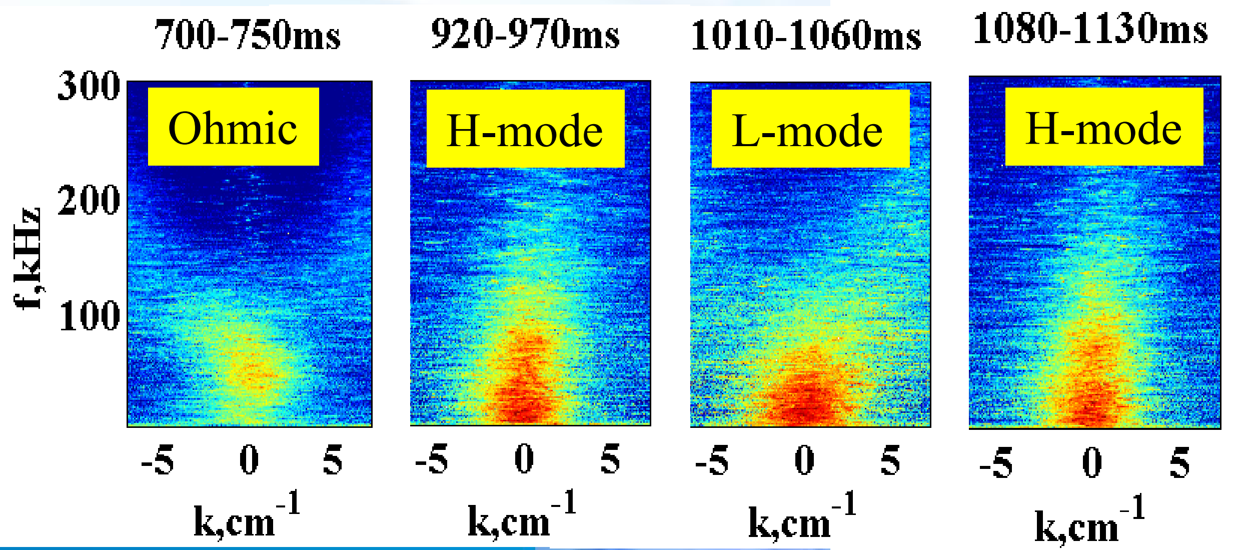




Expanding platform



Imaging platform



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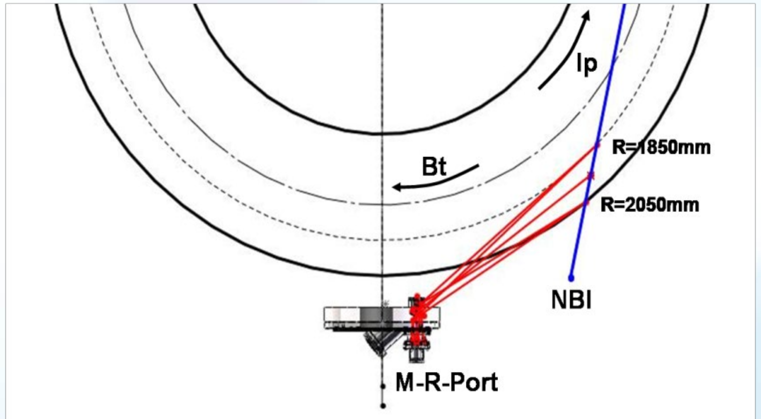
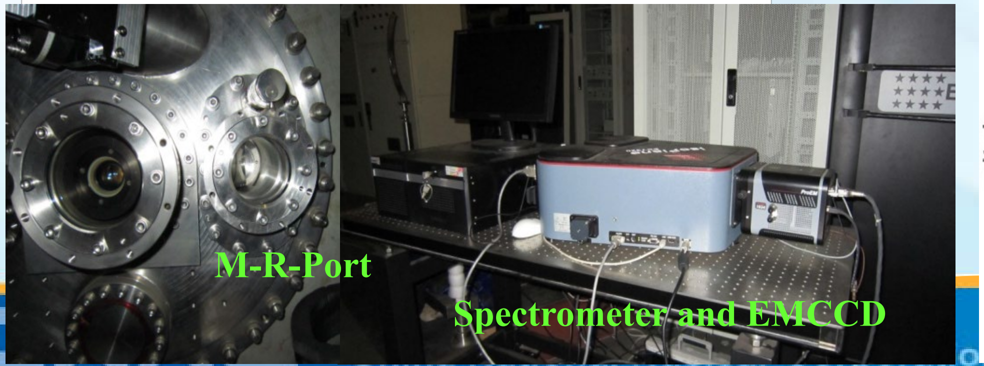
Fast ion D_α diagnostic (FIDA)

In collaboration with **Prof. William W. Heidbrink, UCI**

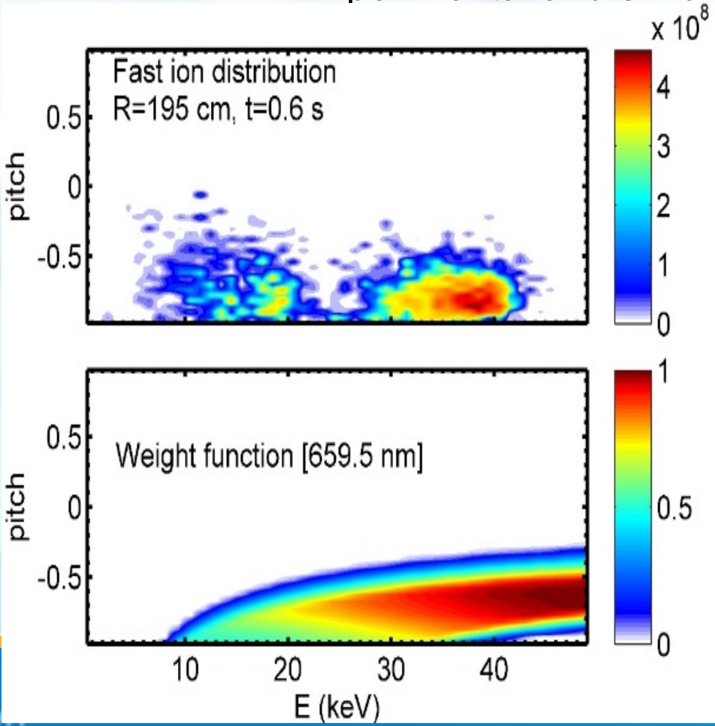
- Fast ion D_α diagnostic (FIDA) with tangential viewing is developed on HL-2A to measure spectra produced by neutralized fast ions.
- Viewing area covers from R=1.85 m to R=2.05 m along the radial direction.
- FIDASIM code is applied to obtain FIDA spectra and weight function (2019-2021).

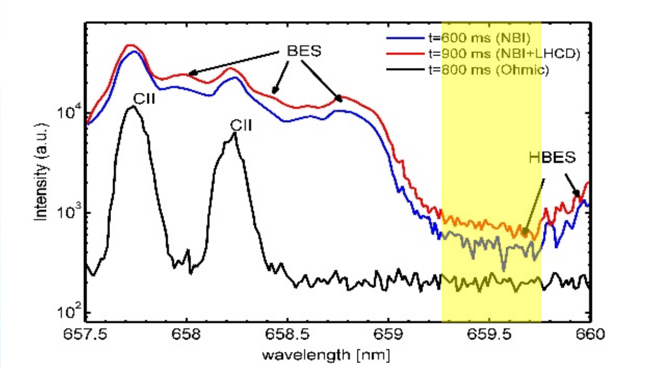
*H. Y. Zhou et.al, **RSI** submitted, (2021).*
*Y.M. Hou, et al., **GF-A2019036***

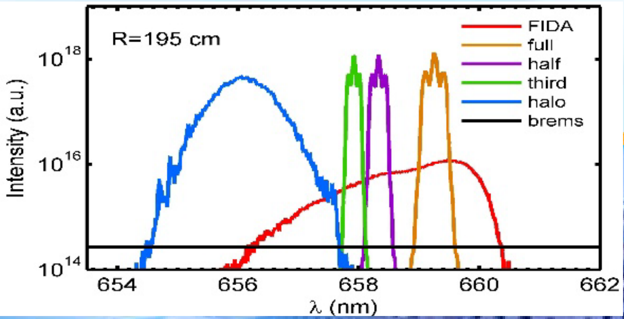




Experimental and simulation results of FIDA spectra on







List of content

- Collaborations on advanced diagnostics
- **Collaborations on plasma physics study**
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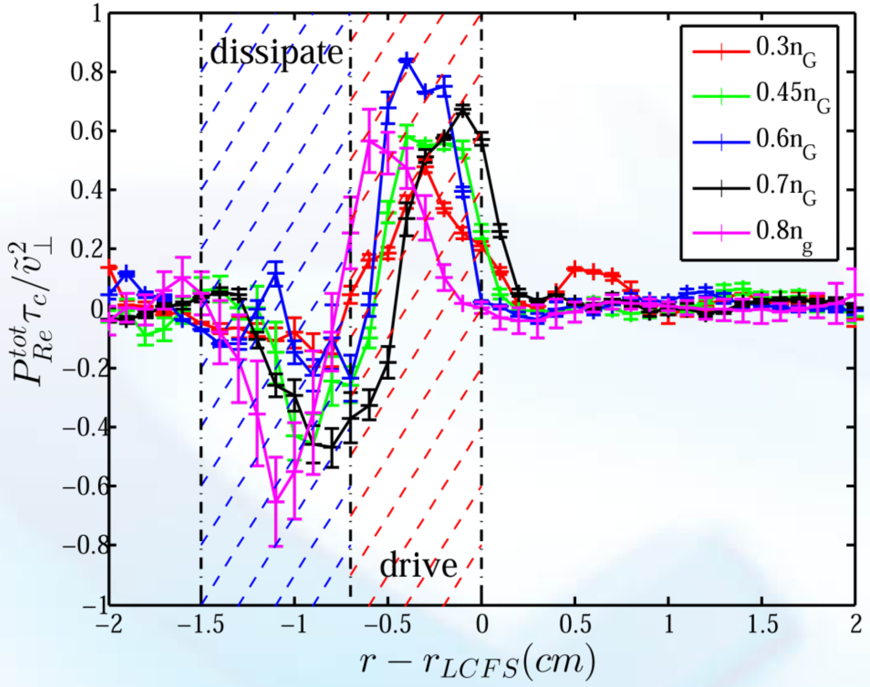
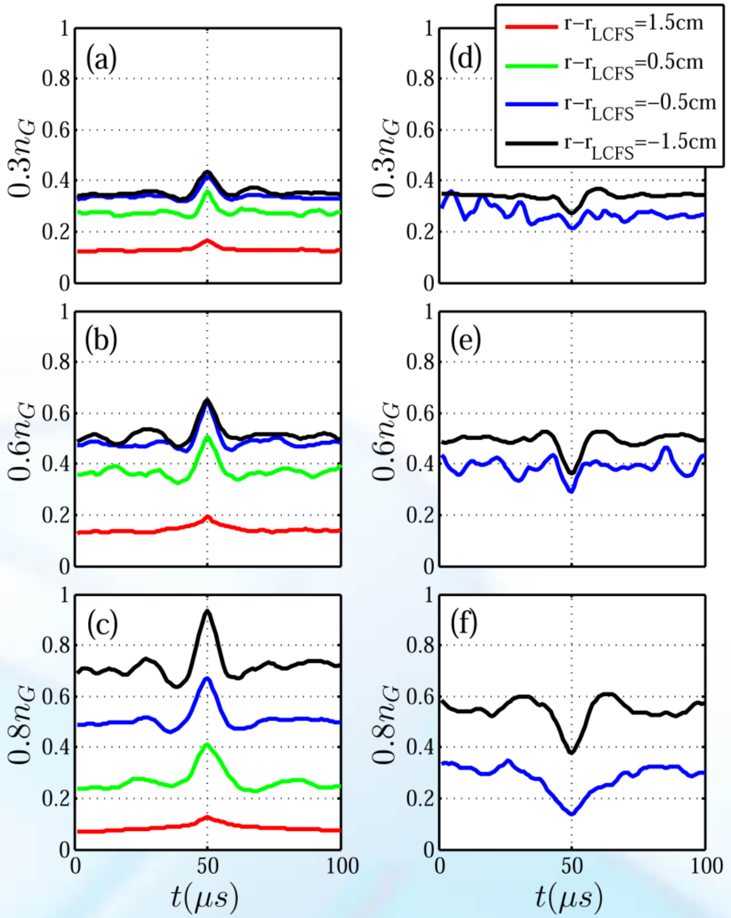
Shear flow, intermittency and density limit

In collaboration with **Prof. George Tynan, UCSD**





L. Wang *et al* Phys. Plasmas 26 (2019) 092303

- It was found that higher burst rate of intermittency as well as stronger dissapation effects from diffusive stress to the shear flow under high plasma densities in the SOL and edge of HL-2A.
- These reults provided new evidence for the explanation of the density limit phenomenon.

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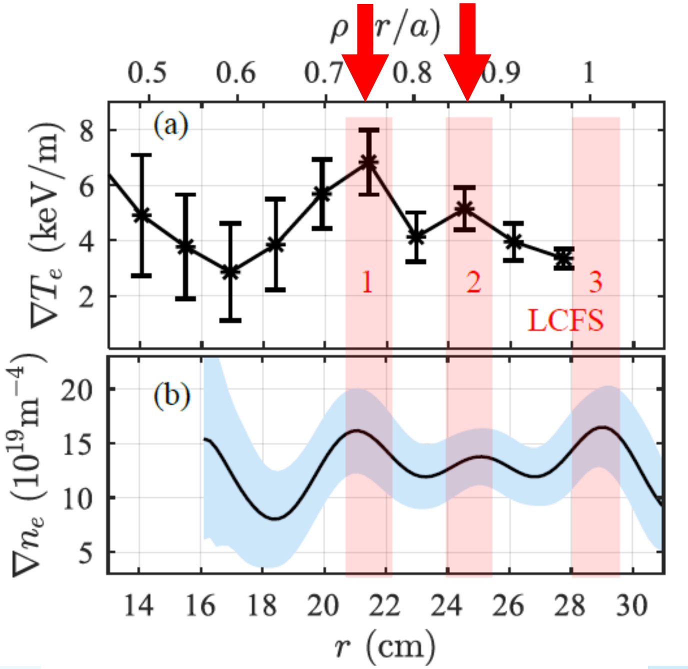
Evidence of $\boldsymbol{E}\times\boldsymbol{B}$ staircase in L-mode plasmas

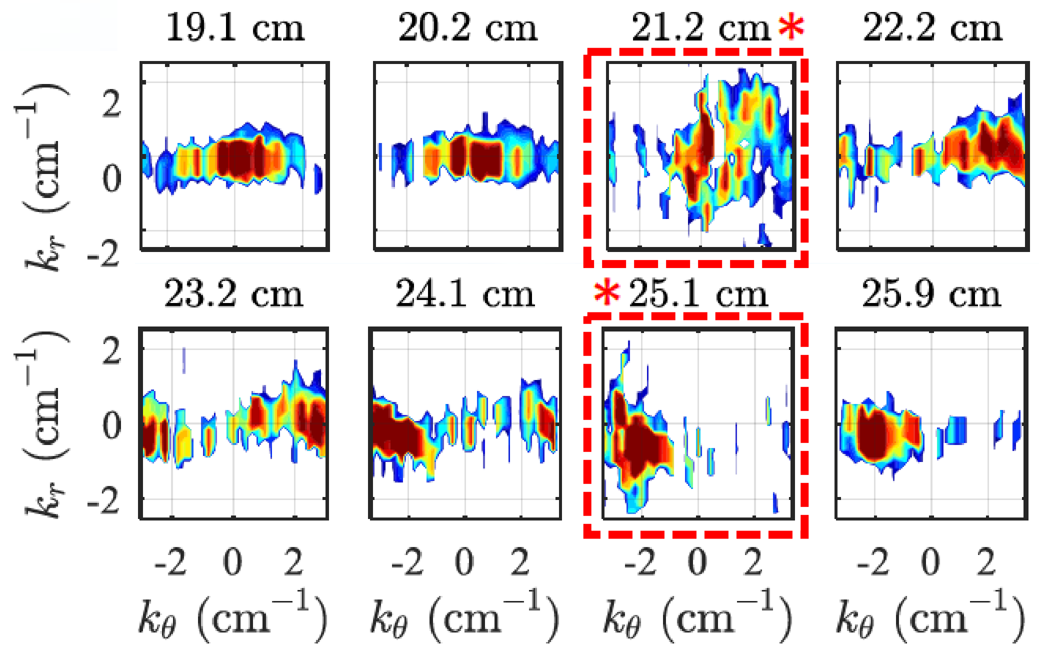
In collaboration with **Prof. George Tynan, UCSD**

Evidence 1:
$\nabla n_e, \nabla T_e$ profile corrugations



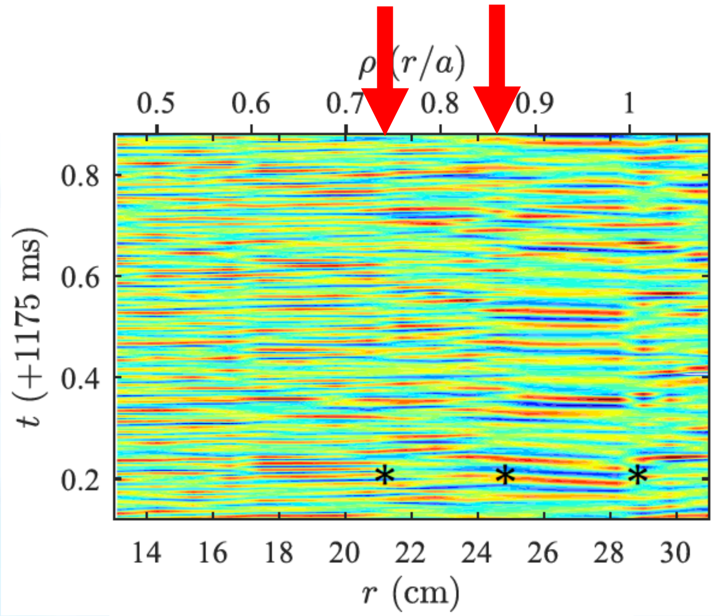
*From ECE and FMCW Reflectometry data

Evidence 2:
Change of eddy tilting, implying ExB shear layers



k_r/k_θ from BES data

Evidence 3:
Block of long-range transport events



$\tilde{n}_e(r,t)$ measured by BES

W. Liu et al Phys. Plasmas 28(2021) 012512

Evidence of ExB staircase was found in HL-2A L-mode discharges by studying multiple plasma behaviors together.

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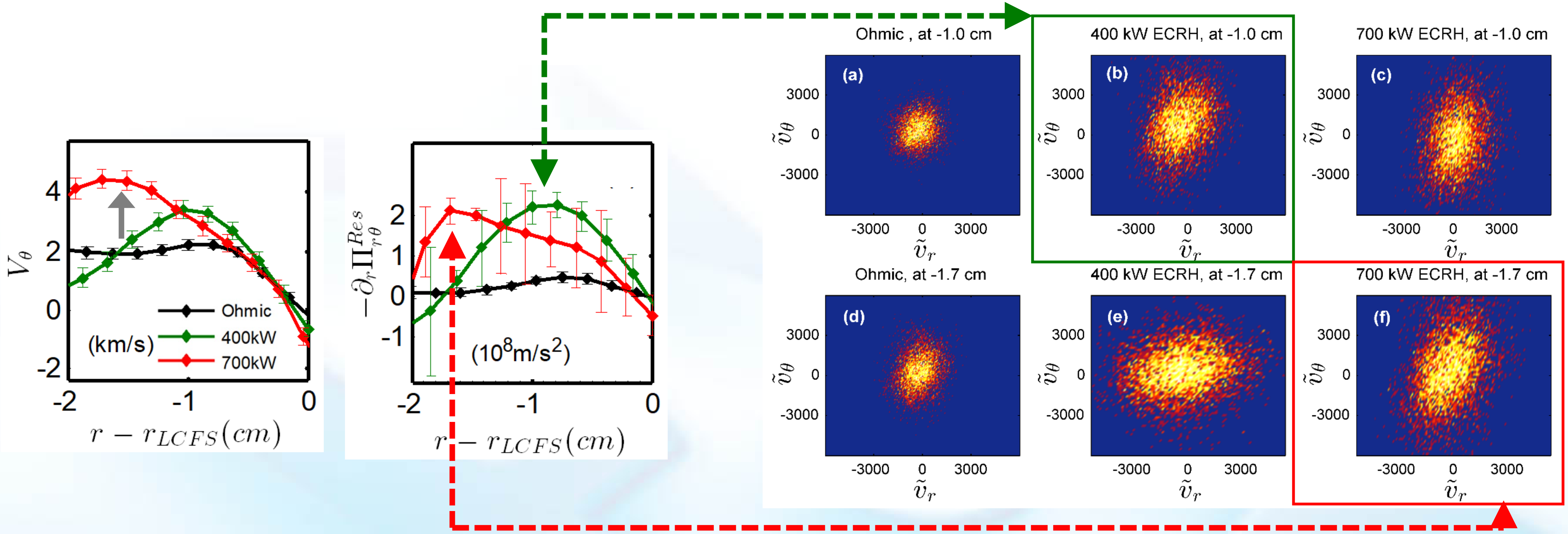
Turbulent generation of edge poloidal flows

In collaboration with **Prof. Patrick. H. Diamond, UCSD**

T. Long, Patrick. H. Diamond et al NF 59 106010 (2019)



- The physics linking edge poloidal flows to turbulent momentum transport were studied.
- As ECRH power increases, the intrinsic poloidal torque increases significantly, thus driving an increasing plasma poloidal flow. The dynamics of spectral symmetry breaking in turbulence is consistent with the development of this torque.

Turbulence Spreading and Explicit Nonlocality

In collaboration with **Prof. Patrick H. Diamond, UCSD**

A model for turbulence spreading was derived from a simplified kinetic equation:

$$\frac{\partial}{\partial \hat{t}}\hat{I} = \mathcal{G}\otimes\frac{\partial}{\partial \hat{r}}\left[2\hat{D}_0\hat{I}\frac{\partial}{\partial \hat{r}}\left(\hat{I}-\frac{\delta_{b*}^2}{2}\frac{\partial}{\partial \hat{r}^2}\hat{I}\right)\right]+\mathcal{G}\otimes\hat{I}-\hat{I}^2$$

$$t\to\hat{t}/\gamma_L,\qquad r\to\hat{r}L_T,\qquad \langle\tilde{\phi}^2\rangle\to\hat{I}\,\gamma_L/\gamma_{NL}$$

It contains the nonlocal effects, which are in the form of the convolution with nonlocal kernel:

$$\mathcal{G}(x)\propto\exp(-|x|/\delta_{b*})$$

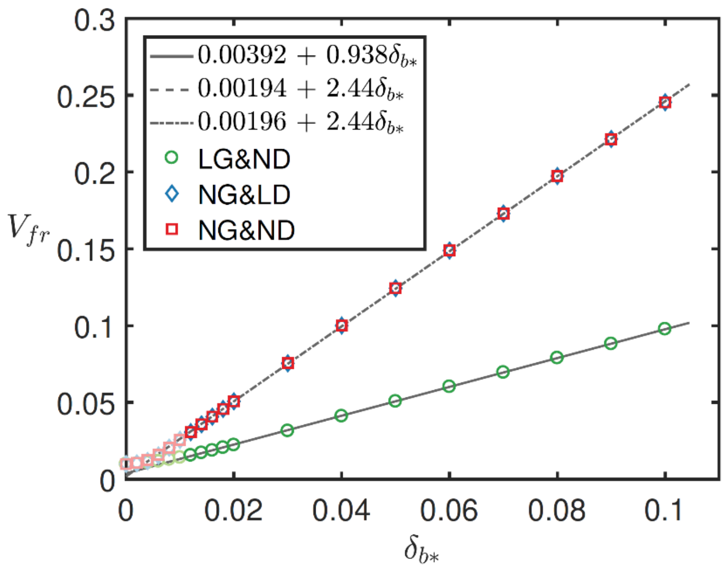
Nonlocal effects thicken the turbulence spreading front and increase the speed of front propagation.

Qinghao Yan and P H Diamond, to be submitted.

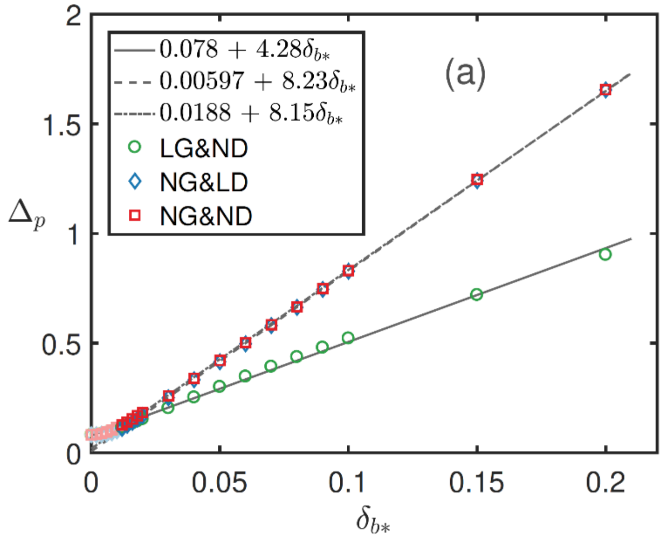
The remaining fraction of turbulence in the unstable region, when summed up, follows a simple linear relation:

$$\bar{\hat{I}}=\bar{I}/(\rho_*^2)=1-\delta_{b*}$$

The transport coefficient scales in the same way



Leading edge propagation speed V_{fr} for different δ_{b*} (the banana orbit width)

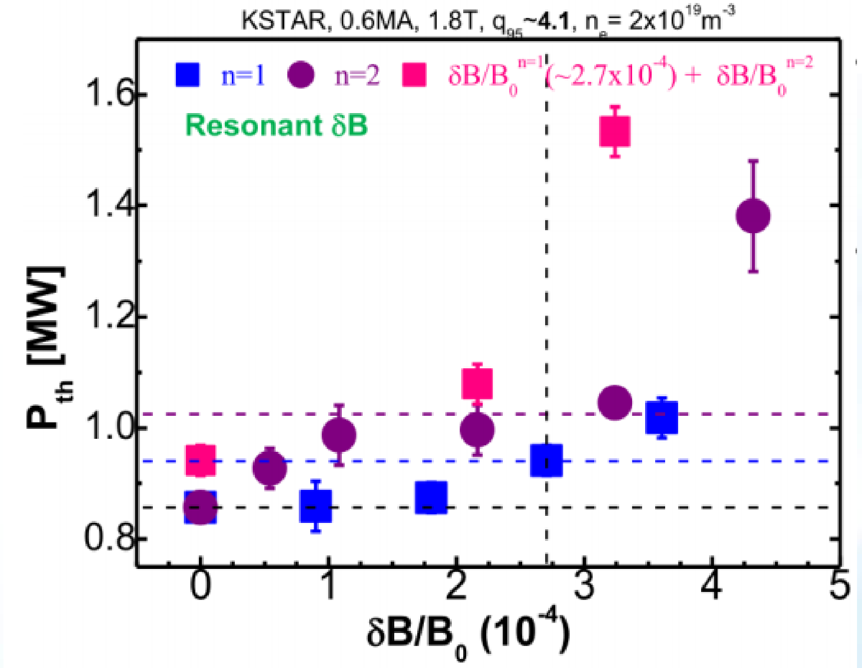


Turbulence front penetration depth Δ_p against δ_{b*}.

A Mean Field Model in a stochastic B-field

In collaboration with **Prof. Patrick H. Diamond, UCSD**

M. Jiang, W.X. Guo and P H Diamond, in Progress



Experiments show the RMP increases P_{th} of L→H transition.

Need model to elucidate the physical mechanism.

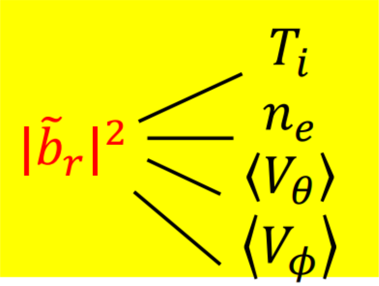
How stochastic B-field affects EXB shear?

Five field model:

① $$\frac{\partial}{\partial t}I = \frac{\gamma_L}{(1+\alpha V_E'^2)^\sigma}I - \beta I^2$$ Turbulence intensity

② $$n\frac{\partial T_i}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(rQ_i) = S_H$$ Ion temperature

③ $$\frac{\partial n_e}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_e) = S_p$$ Electron density



④ $$\langle V_\theta \rangle = V_{\theta,neo} + \frac{1}{\mu}\frac{\partial}{\partial r}\left(\frac{1}{B^2}\tau_c V_E' \frac{I}{1+\alpha V_E'^2} - \frac{B^2}{4\pi\rho}\tau_c' V_E' |\tilde{b}_r|^2\right)$$ Poloidal flow

⑤ $$\frac{\partial}{\partial r}\langle V_\phi \rangle|_{r_{sep}} = -\frac{1}{\chi_\phi}\int_0^{r_{sep}} S_M dr - \frac{V_{Ti}^2}{\beta \chi_\phi}\frac{B_\theta}{B}\langle \tilde{b}_r \tilde{b}_\theta \rangle|_{r_{sep}}$$ Toroidal flow

Jr induced by stochastic field (due to ambipolarity breaking) directly related to particle flux and Maxwell stress in flows.

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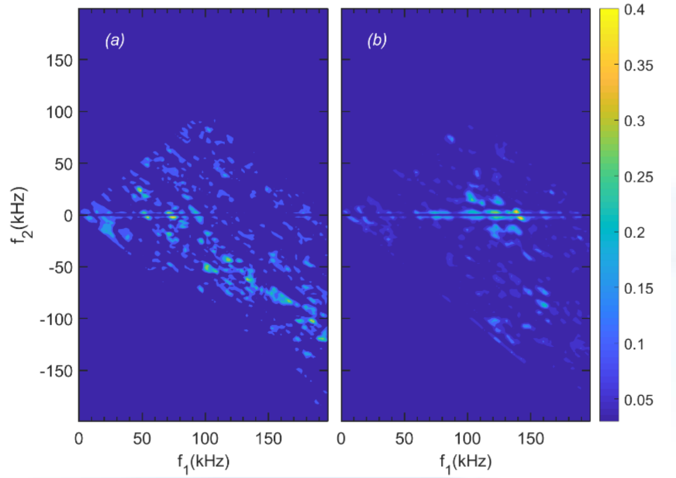
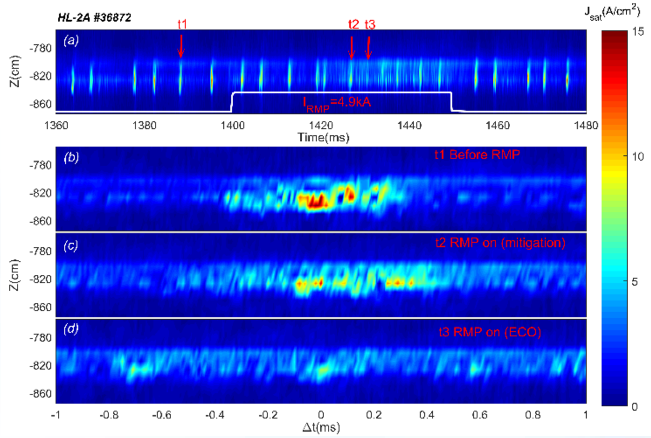
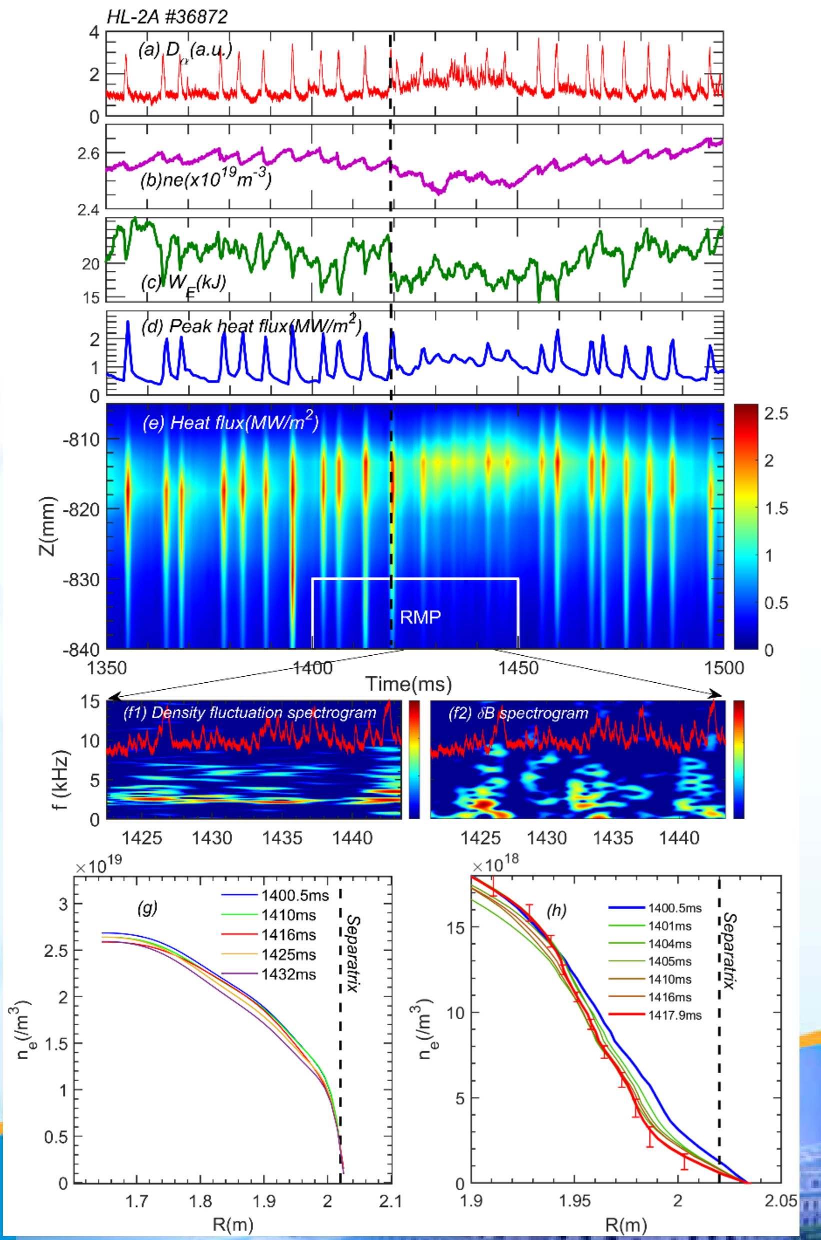
Edge coherent oscillation providing continuous particle transport during ELM mitigation by n = 1 RMP

In collaboration with **Prof. Yueqiang Liu, GA**





T. F. Sun et al Nucl. Fusion 61 (2021) 036020



- An edge-coherent oscillation (ECO) with a bursting feature was observed in the steep-gradient pedestal region during the ELM mitigation by RMP.
- ECO is excited by three-wave interaction of turbulence enhanced by the RMP field because of pump-out effect.
- ECO drives a significant outflow of particles, providing a channel for a nearly continuous extra particle transport across pedestal during ELM mitigation by RMP.

The dependence of turbulence characteristics on ρ*

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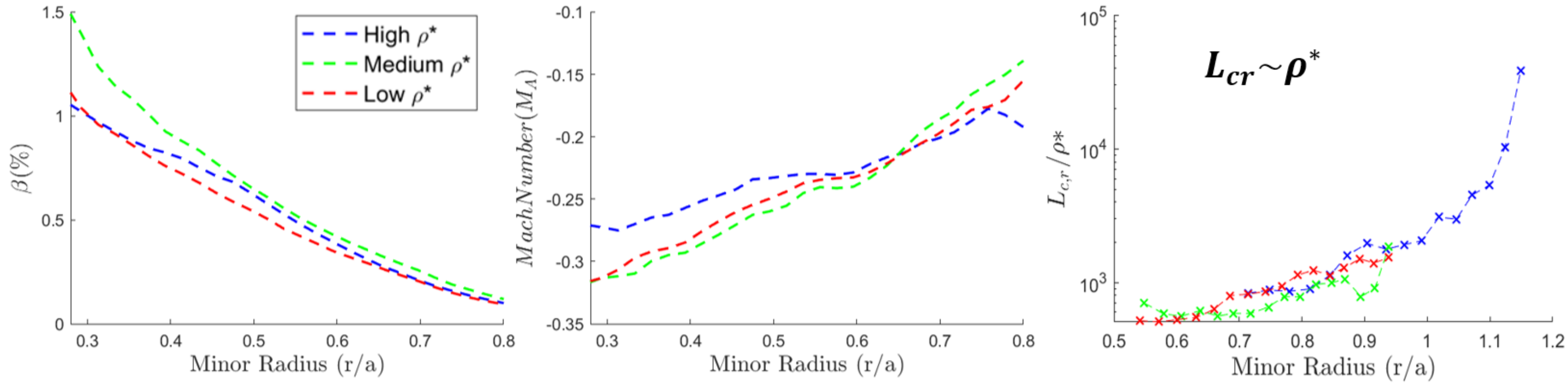
In collaboration with **George McKee, UW-Madison**



Presented at the 61st APS-DPP meeting by X. Qin, experiments conducted by R. Ke

- The variation of turbulence characteristics with ρ* are measured with BES in HL-2A plasmas while other dimensionless quantities (β, M_A) are held nearly fixed.
- The scaling obtained from HL-2A experimental results agrees well with the prediction from the Gyro-Bohm like model and is consistent with the results obtained from other tokamaks like DIII-D.
- The dependence of turbulent transport on ρ* will be analyzed in the future.

Physics of turbulence and impurity transport

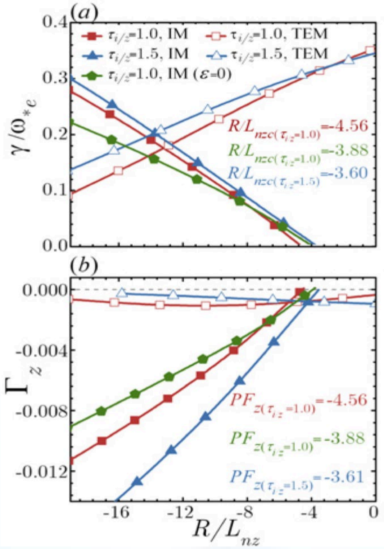
In collaboration with **Prof. Horton, Univ. of Texas, Austin**

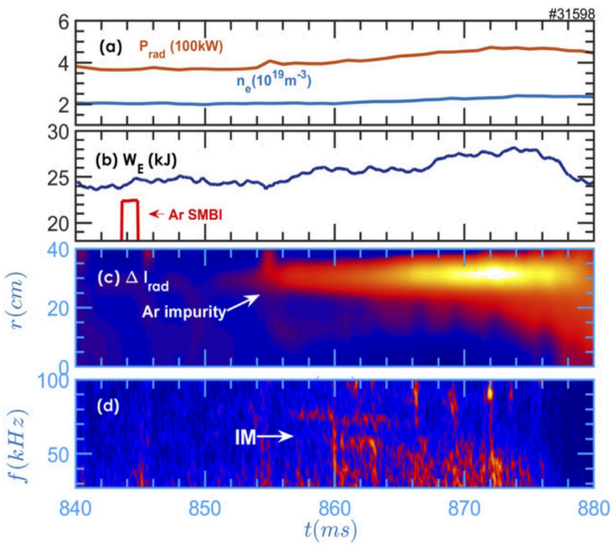
Integrated theoretical simulation with experiment:

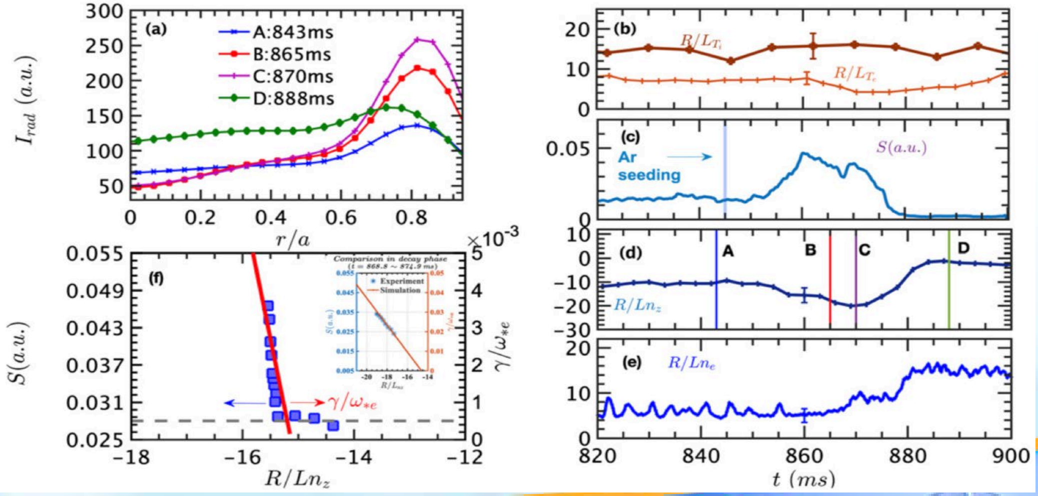
- the impurity mode is excited by an edge peaking impurity density profile.
- The impurity ion flux induced by IMs is shown to be approximately one order of magnitude higher than that induced by TEMs when both kinds of modes coexist.
- The simulation results such as PF and main ITG effects are found in coincidence with the evidence observed in argon injection experiment on HL-2A tokamak.
- IM turbulence is demonstrated to be a plausible mechanism for the transport of impurity ions with edge peaking impurity density profiles.

$$\Gamma_s = \frac{n_{0s}}{R}\left(D_{ns}\frac{R}{L_{n_s}} + D_{Ts}\frac{R}{L_{T_s}} + RV_{ps}\right)$$ **Particle flux**

$$q_s = \frac{T_{0s}}{R}\left(\chi_{ns}\frac{R}{L_{n_s}} + \chi_{Ts}\frac{R}{L_{T_s}} + Rv_{qs}\right)$$ **Heat flux**







M. K. Han et al., NF, 61 (2021) 046010

Academic exchange in theory and experiment

In collaboration with **Prof. Horton, Univ. of Texas, Austin**

Academic lectures and discussions:

- Seminars: turbulent transport in magnetized plasma, turbulent electron and impurity transport in fusion plasmas, RF current drive and ECRH heating.
- Discussion with theory and simulation group.
- Discussions with experimental colleagues on turbulence experiments and current drive.

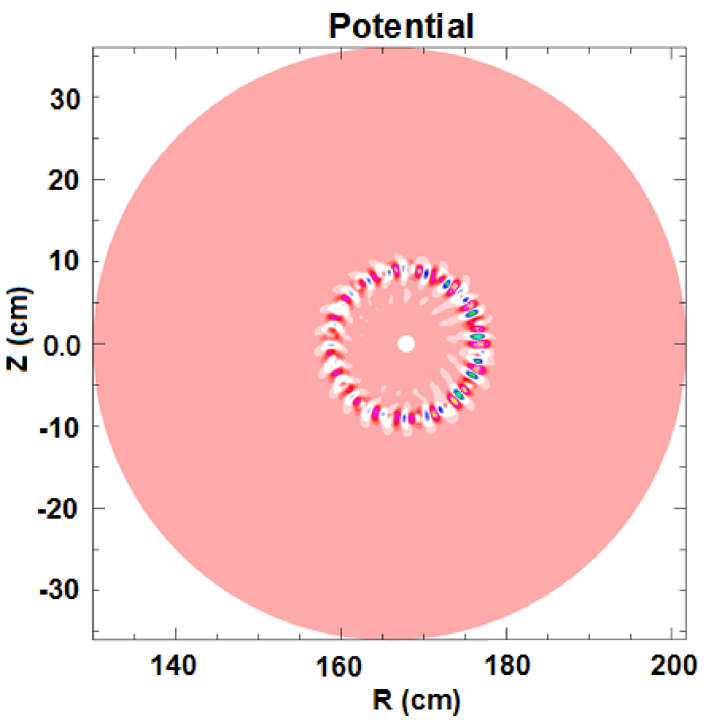
Future plan:

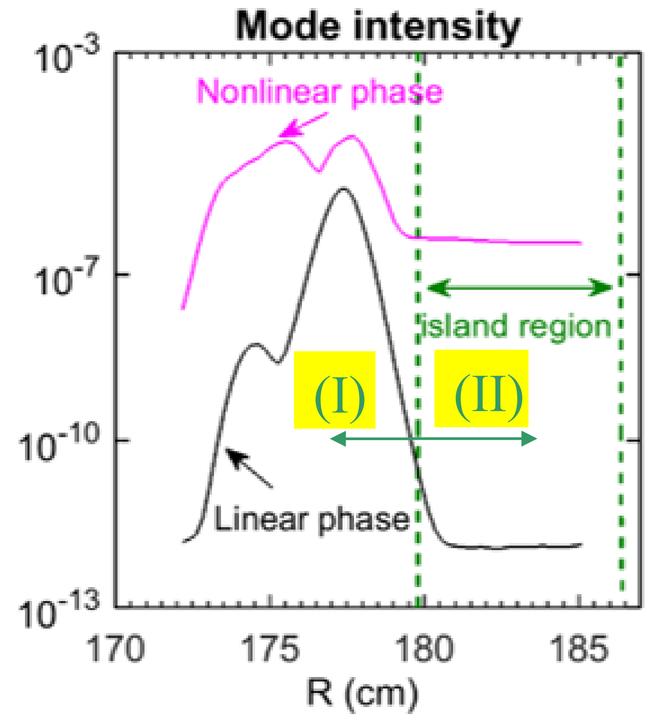
1. Joint study on turbulence transport and improving confinement.
2. Exchange students or younger researchers.

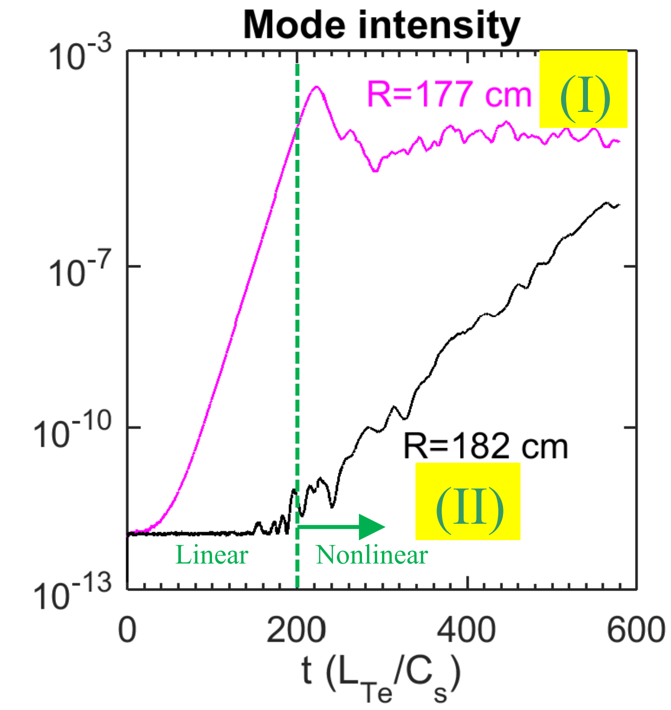
Turbulence spreading across magnetic island

In collaboration with **Prof. W.X. Wang, PPPL**

M. Jiang et al., NF 59 066019 (2019)





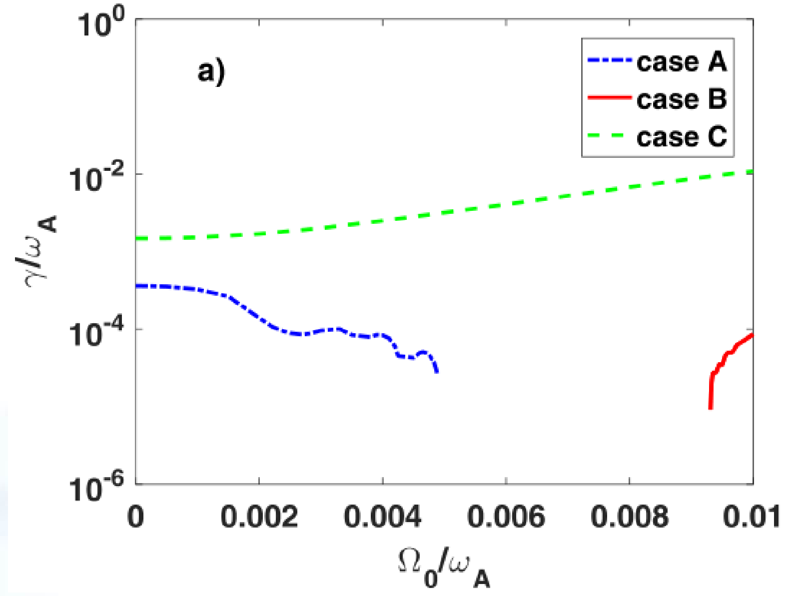


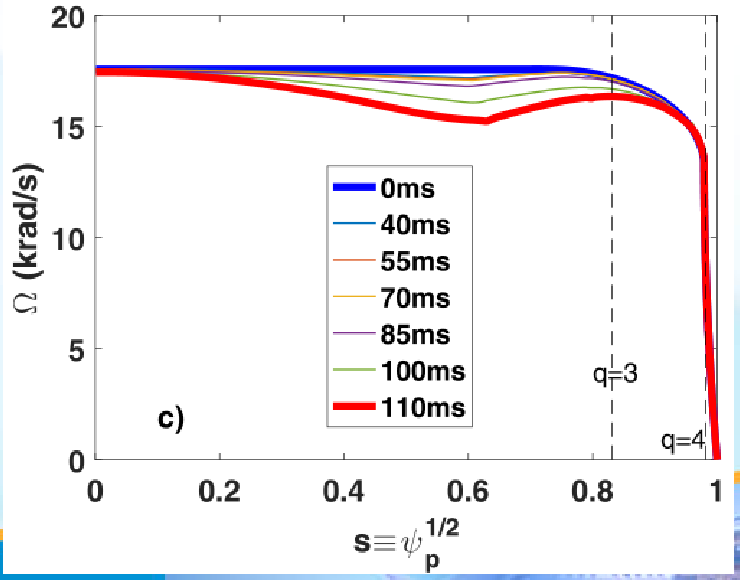
- GTS simulation shows that the turbulent mode outside the island (close to the core) rotates in electron diamagnetic drift direction (TEM)
- In linear phase, the turbulence level inside island is very low, whereas in the nonlinear phase it largely increases, consistent with the turbulence spreading observed from the ECEI data.

An explanation for EHO accompanied with QH-mode

In collaboration with **Prof. Yueqiang Liu, GA**

- The wall stabilization (case A & case B) opens a stable window for the linear ELIM (Edge localized infernal mode).
- MARS-Q quasi-linear simulations show that the mode can either damp or accelerate the plasma flow. However, the common tendency is that the mode always modifies the flow in such a way, that in turn helps to push the mode to a more stable domain.





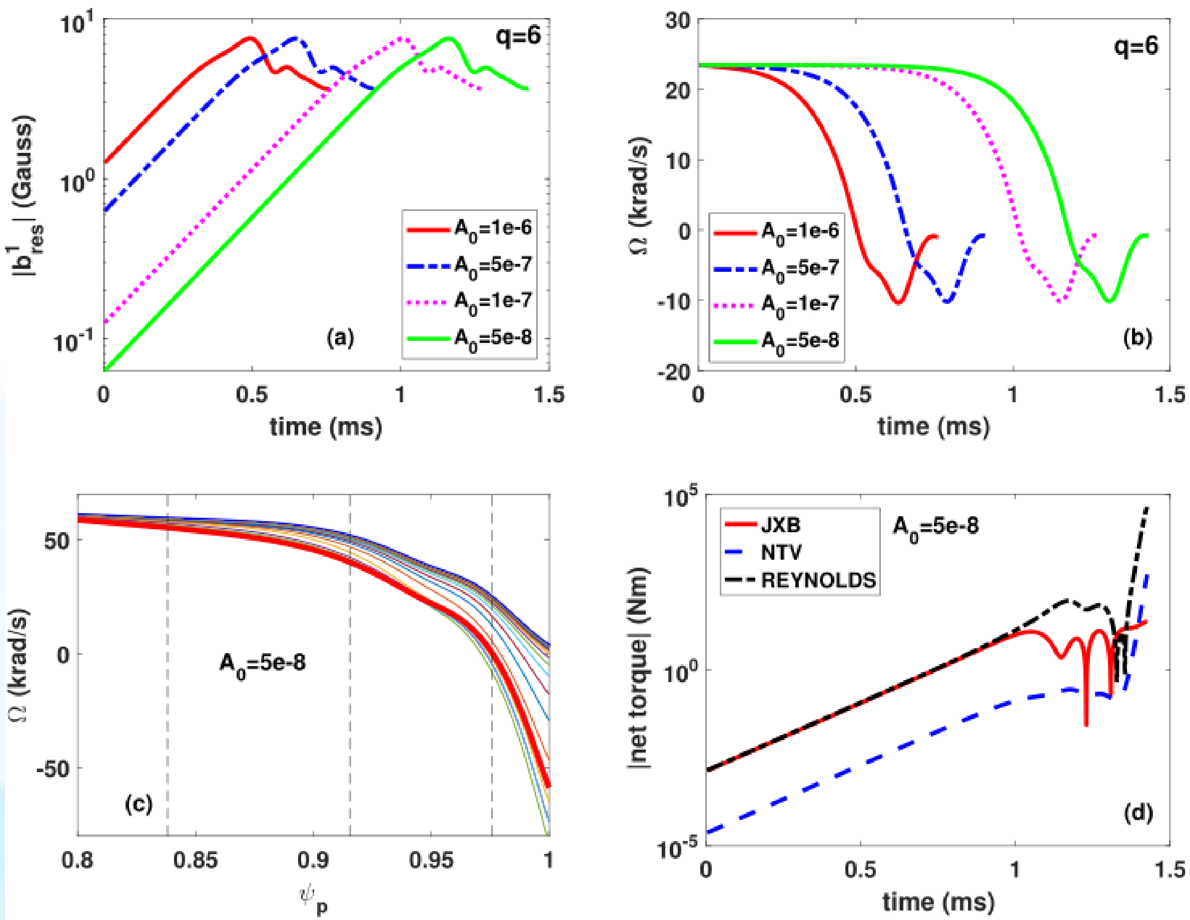
G.Q. Dong, Y.Q. Liu et al, NF 59 (2019) 066011

MARS-Q modeling of kink-peeling instabilities in DIII-D QH-mode plasma

In collaboration with **Prof. Yueqiang Liu, GA**

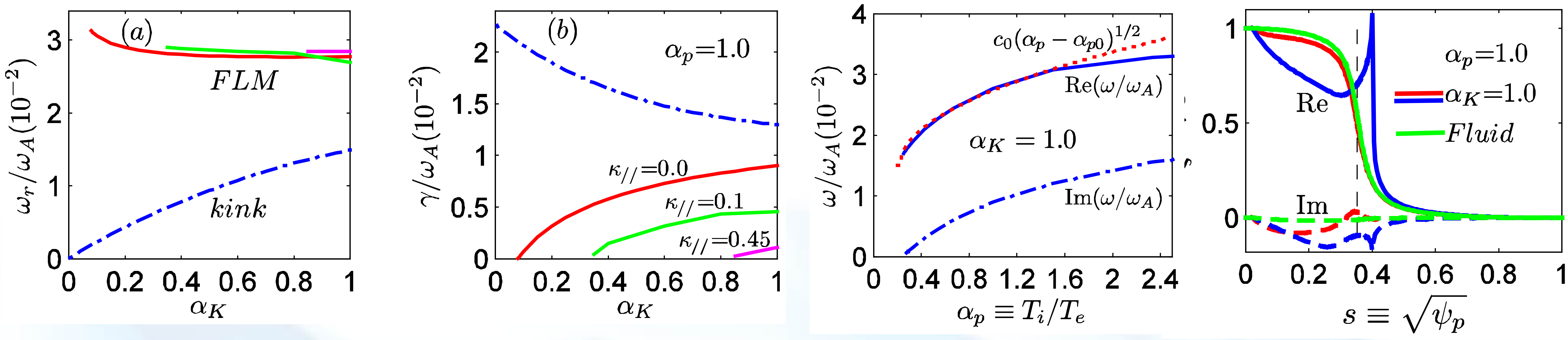
- MARS-Q quasi-linear simulation finds that the stabilization and saturation of the kink-peeling mode are due to the combination of both the flow amplitude damping and the slight increase of the flow shear.
- The Reynolds stress torque is found to generally play a major role in the flow damping, though the NTV torque can also play a dominant role in certain cases.

G.Q. Dong, Y.Q. Liu et al, accepted by NF (2021)



Fishbone-like mode (FLM) excitation by trapped thermal ions (TTIs)

In collaboration with **Prof. Yueqiang Liu, GA**

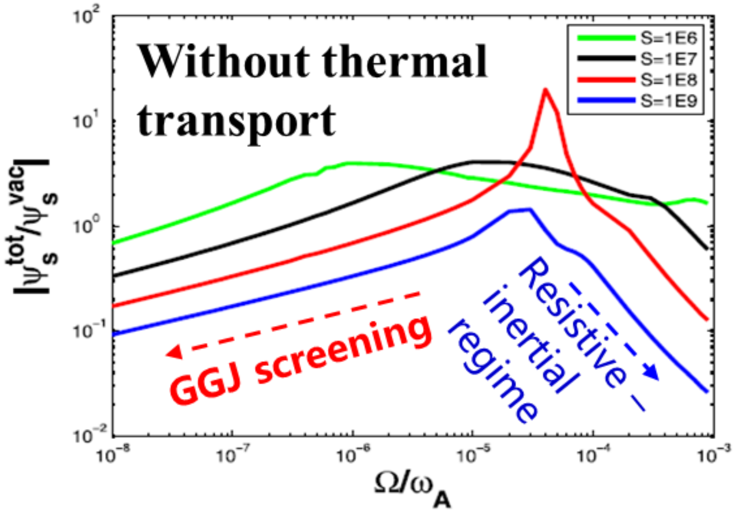


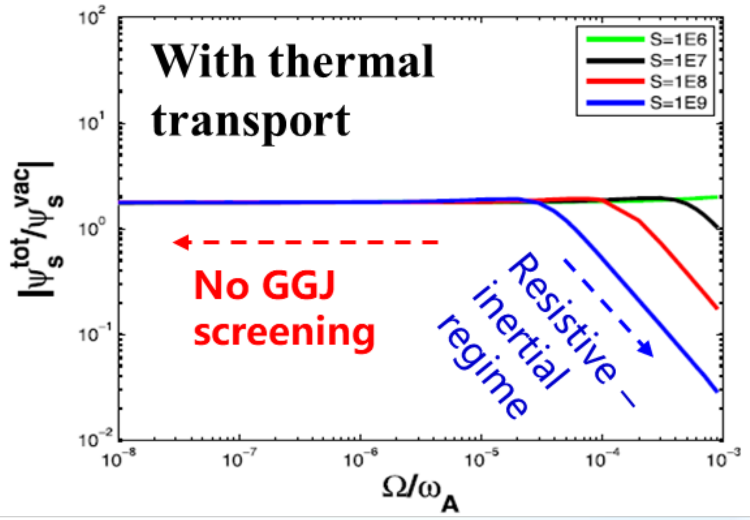
- ➢When the drift kinetic effect of thermal ions is taken into account, FLM can be driven by TTIs by using MARS-K code.
- ➢The real frequency of the FLM is comparable to the bounce frequency of trapped thermal ions.
- ➢The FLM can only be triggered by TTIs at sufficiently high thermal temperature.

W. Xie, Y. Q. Liu, G. Z. Hao et al., AIP-Advances, in press

Effects of anisotropic thermal transport on plasma response and MHD instabilities

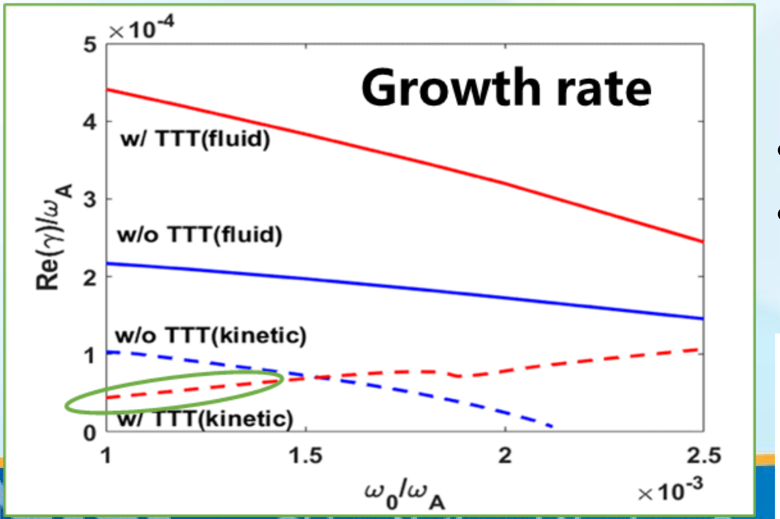
In collaboration with **Prof. Yueqiang Liu, GA**





- Comparison of the computed plasma response amplitude with varied toroidal rotation W and Lundquist number S
  $\Omega/\omega_A < 10^{-5}$, GGJ screening ; $\Omega/\omega_A < 10^{-5}$, Resistive-Inertial (RI) regime
  GGJ screening at slow rotation is removed by anisotropic thermal transport

Xue Bai,Yueqiang Liu*, PoP, 2020, 27(12): 124502.*
Xue Bai, Yueqiang Liu*, PoP 2020, 27(7): 072502.*
Xue Bai, Yueqiang Liu*, PoP, 2018, 25(9): 090701.*
Xue Bai, Yueqiang Liu, PoP, 2017, 24(10): 102505.*



- In fluid theory, anisotropic thermal transport destabilize RWM
- **Taking kinetic effect of trapped EPs into account, anisotropic thermal transport can stabilize RWM together with EPs**

□ Future cooperation

Numerical investigation of effects of **anisotropic thermal transport** and **energetic particles** on **MHD instabilities** in HL-2A/M

Investigating physical mechanism of detachment Cliff in DIII-D by SOLPS

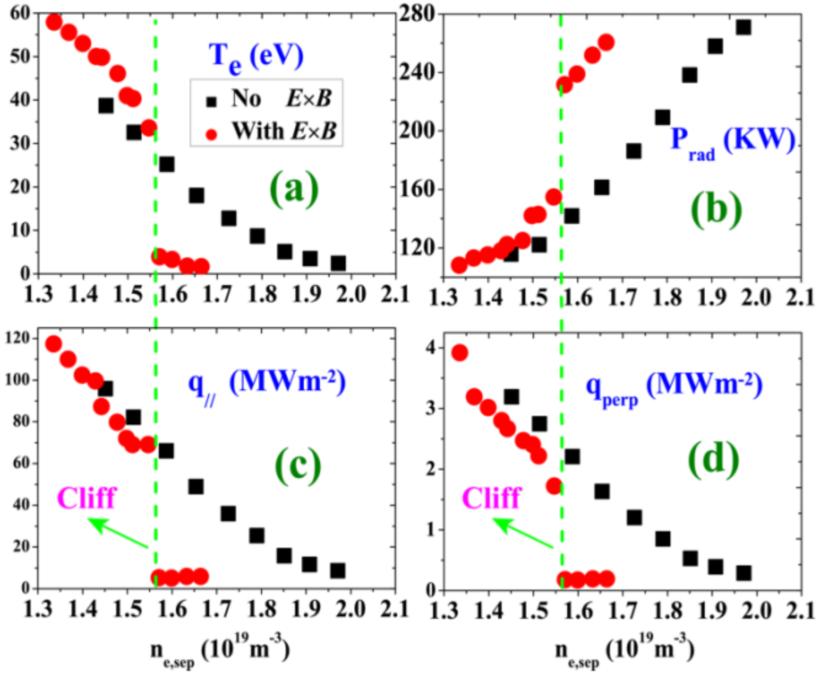
In collaboration with **Prof. Houyang Guo, GA**

Detachment Cliff : the target heat flux and target electron temperature rapidly drop from ~20eV to 2eV, called detachment cliff.

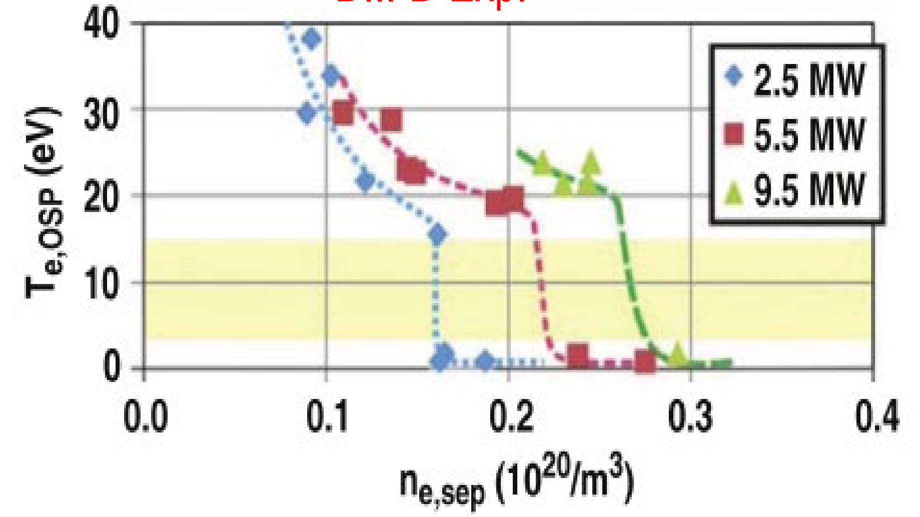
Detachment Cliff will affect the achievement of partial detachment.

- Studying production necessary condition of Detachment Cliff.
- Investigating the root reason for detachment cliff.

SOLPS modeling DIII-D



DIII-D Exp.



- By modeling DIII-D experiment, the detachment cliff phenomena was well explained, and the necessary conditions and its produced root reason were also found .
- Necessary conditions including: E× B drift, relative small radial transport, carbon impurity, Favarable $B\times\nabla B$.

H.L. Du, Nucl. Fusion 60 046028 (2020).

核工业西南物理研究院
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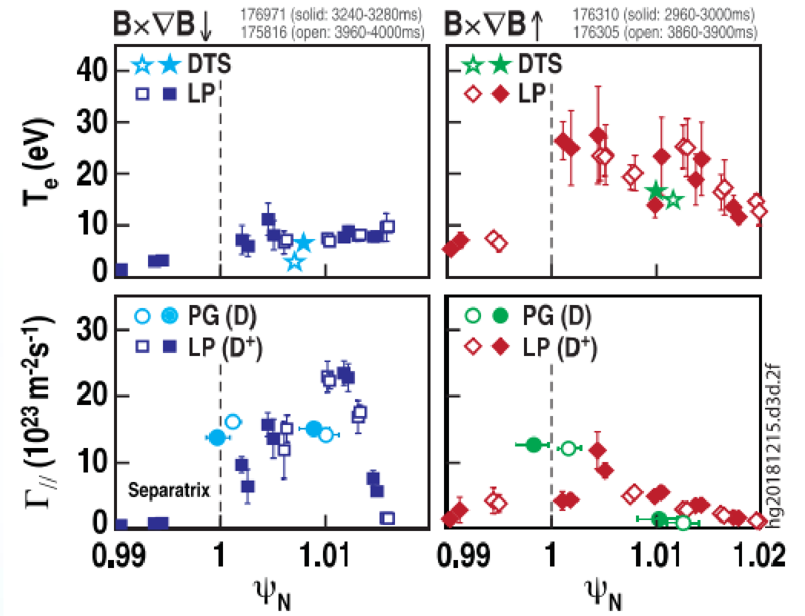
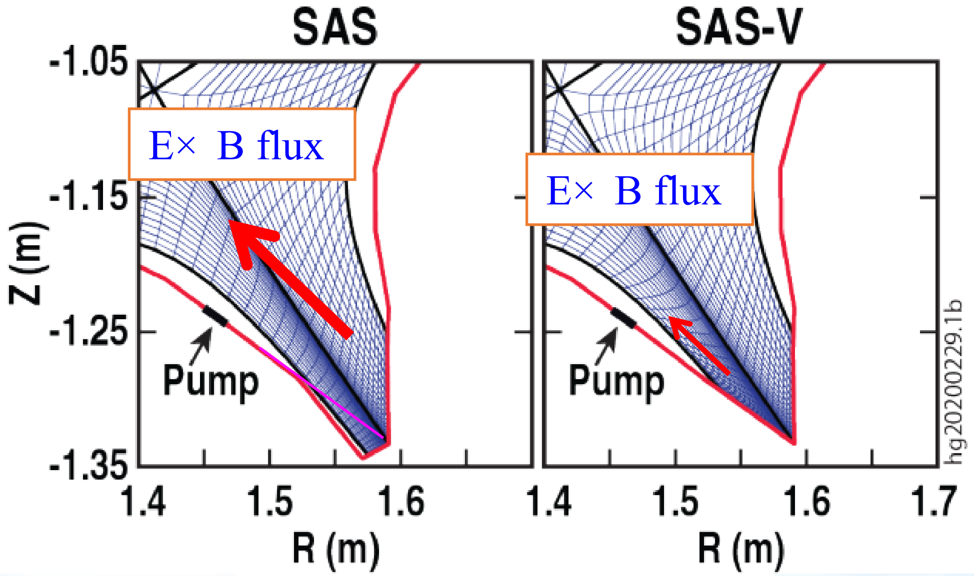
Adding extra particle reflecting baffle in PFR mitigating E×B to improve detachment

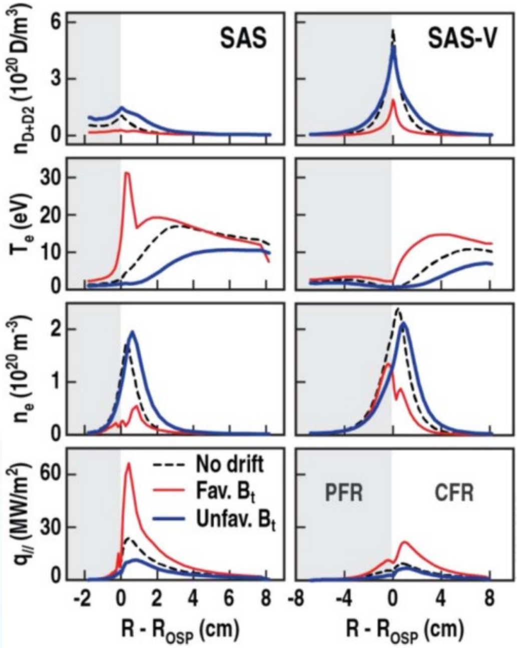
In collaboration with **Prof. Houyang Guo, GA**

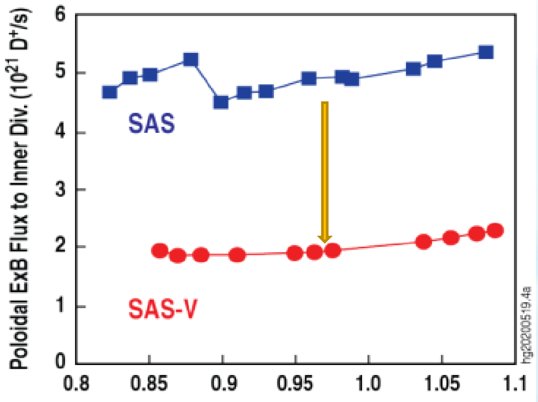
DIII-D SAS Exp.dat



SOLPS-ITER modeling







- DIII-D experiment showed the impact of E× B drift on SAS closed divertor detachment is very strong.
- A method to reduce the effect of E× B drift on detachment was found.

The E× B drift effect on detachment can be mitigated by adding extra reflecting baffle in PFR region. As a result, the detachment can be achieved easily with relative low upstream density.

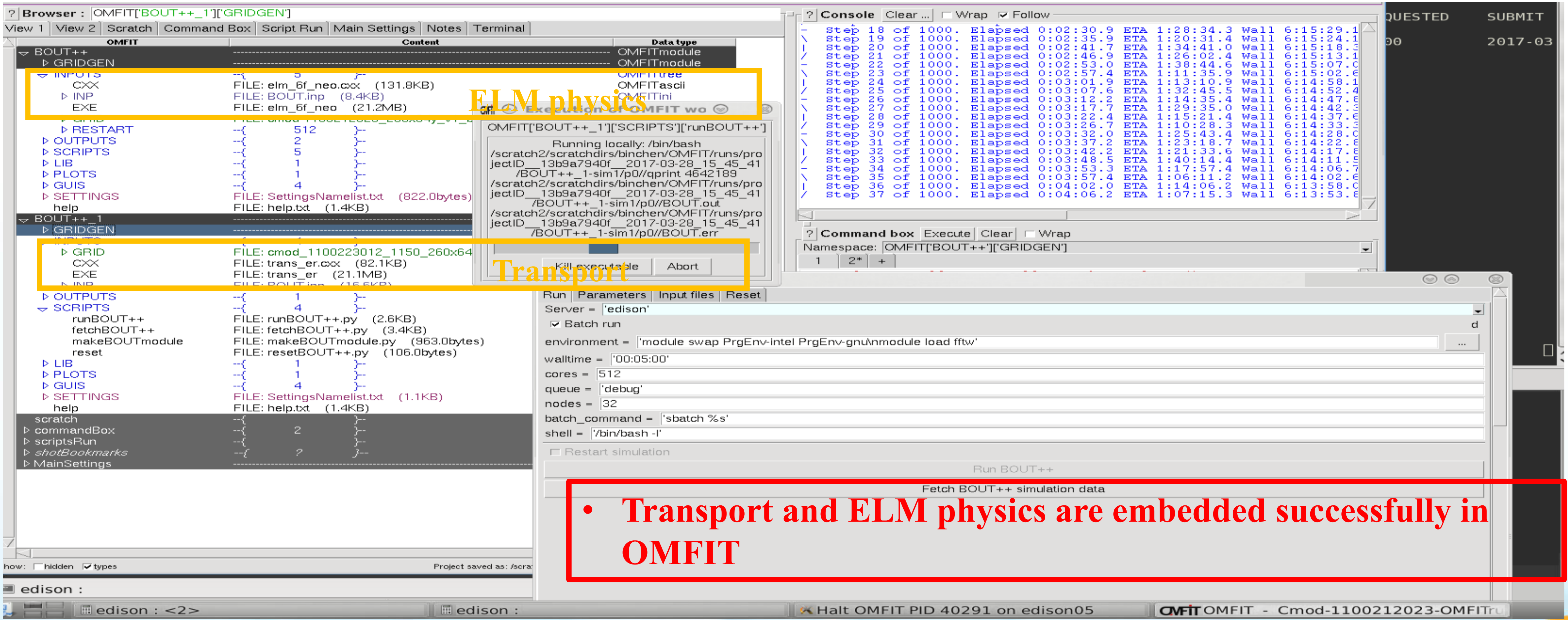
Houyang Guo et al. Nucl. Fusion 59 (2019) 086054

H.L. Du, H.Y. Guo, et al. Nucl. Fusion 60 (2020) 126030

Integrated simulation of ELM and transport on OMFIT platform

核工业西南物理研究院
Southwestern Institute of Physics
中核集团 CNNC

In collaboration with **Prof. X Q Xu, LLNL**



- **Transport and ELM physics are embedded successfully in OMFIT**

Z H Wang et al. the 3rd AAPPS-DPP 2019 (invited talk)

Scenario development for HL-2M

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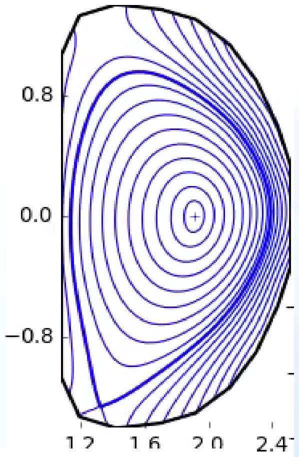
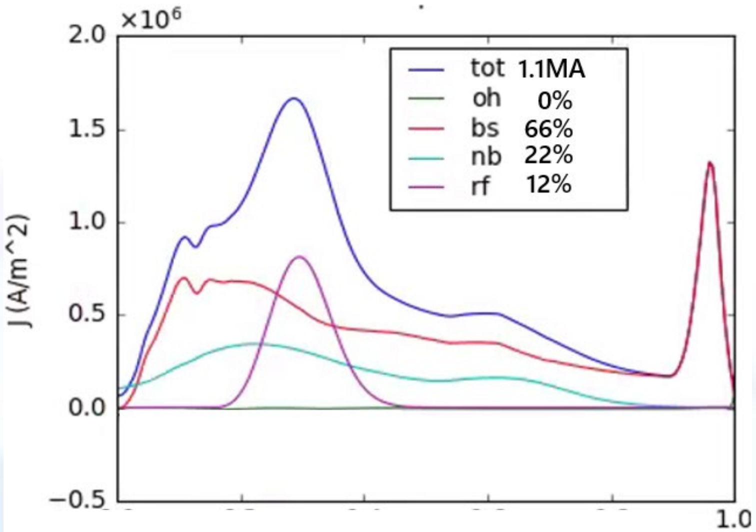
Southwestern Institute of Physics
中核集团 CNNC

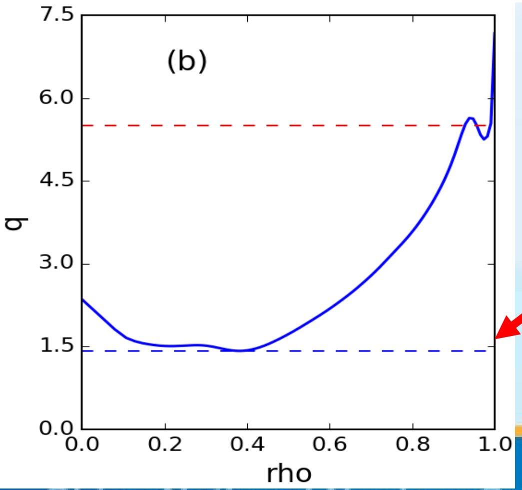
In collaboration with **Prof. Orso Meneghini, GA**



Equilibrium



Different current distributions



q_{min}>1.5

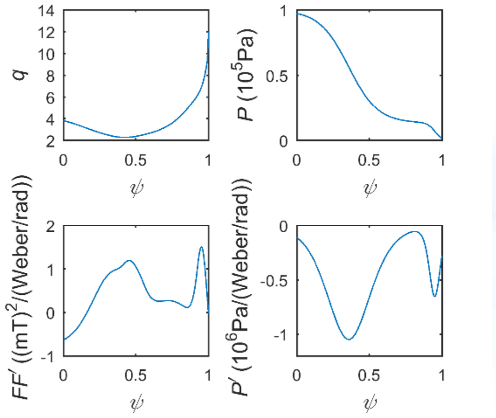
HL-2M parameter list

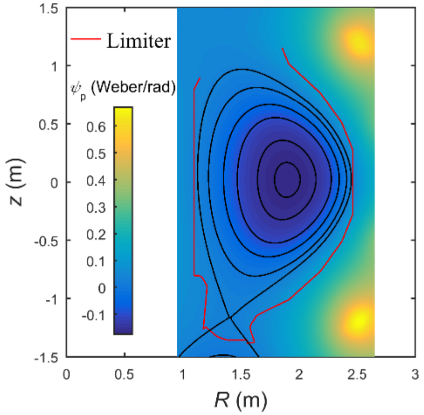
Plasma Current Ip (MA)	1.1
Central magnetic field B_T/T	2.0
Electron temperature Te(0) (keV)	6.8
Ion temperature Ti(0) (keV)	13.0
Electron density $n_e/10^{19}m^{-3}$	4.4
Poloidal beta βp	1.75
Normalized beta β_N	3.1
Power of NBI / MW	10.0
Power of ECW / MW	3.0
Bootstrap current fraction	66%
Non-induction current fraction	100%
Pedestal density $n_{e\_ped}/10^{19}m^{-3}$	2.0
Zeff(0)	2.2
l_i	0.86
$H_{ITER98y2}$	1.57

Construction of DTB equilibria of HL-2M by EFIT

In collaboration with **Prof. Orso Meneghini, GA**

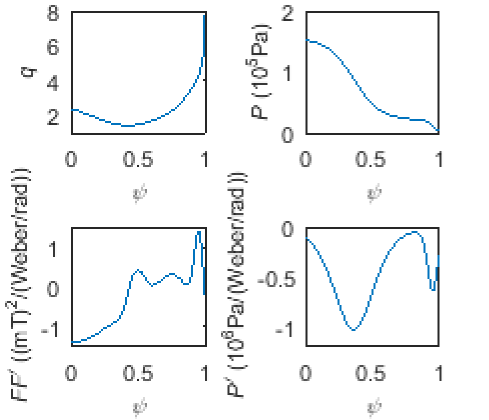
I_p: 1.0MA□ B_{T0}: 2.2T□ β_N: 3.1782

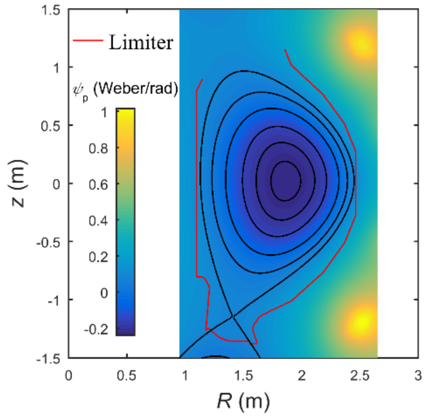




Coils	Threshold (A)	Demand (A)
PF1□ upper□	0.145E+5	0.145302E+04
PF2□ upper□	0.145E+5	0.249962E+04
PF3□ upper□	0.145E+5	0.432542E+04
PF4□ upper□	0.145E+5	0.630062E+04
PF5□ upper□	0.38E+5	-0.348155E+04
PF6□ upper□	0.3941E+5	0.570459E+04
PF7□ upper□	0.39E+5	-0.135268E+05
PF8□ upper□	0.3529E+5	-0.497716E+04
PF1□ lower□	0.145E+5	0.132313E+04
PF2□ lower□	0.145E+5	0.131930E+04
PF3□ lower□	0.145E+5	0.352215E+04
PF4□ lower□	0.145E+5	0.252373E+04
PF5□ lower□	0.38E+5	0.464277E+04
PF6□ lower□	0.3941E+5	0.715098E+04
PF7□ lower□	0.39E+5	-0.146265E+05
PF8□ lower□	0.3529E+5	-0.565452E+04
CS□ upper□	0.11E+6	-0.252789E+05
CS□ lower□	0.11E+6	-0.252789E+05

I_p: 1.5MA□ B_{T0}: 2.2T□ β_N: 3.2384





Coils	Threshold (A)	Demand (A)
PF1□ upper□	0.145E+5	0.102412E+04
PF2□ upper□	0.145E+5	0.318260E+04
PF3□ upper□	0.145E+5	0.740729E+04
PF4□ upper□	0.145E+5	0.355371E+04
PF5□ upper□	0.38E+5	0.641957E+04
PF6□ upper□	0.3941E+5	0.201320E+04
PF7□ upper□	0.39E+5	-0.196755E+05
PF8□ upper□	0.3529E+5	-0.631512E+04
PF1□ lower□	0.145E+5	0.946001E+03
PF2□ lower□	0.145E+5	0.103508E+04
PF3□ lower□	0.145E+5	0.648705E+04
PF4□ lower□	0.145E+5	0.330164E+03
PF5□ lower□	0.38E+5	0.132841E+05
PF6□ lower□	0.3941E+5	0.688900E+04
PF7□ lower□	0.39E+5	-0.215444E+05
PF8□ lower□	0.3529E+5	-0.726806E+04
CS□ upper□	0.11E+6	-0.432976E+05
CS□ lower□	0.11E+6	-0.432976E+05

List of content

- Collaborations on advanced diagnostics
- Collaborations on plasma physics study
- **Summary and collaboration opportunities**

Summary and future cooperation opportunities

Collaborated area:

- ✓ Diagnostics: BES, ECEI, FIDA, FIR, PCI, ……
- ✓ Plasma physics: turbulent transport, boundary plasmas, turbulence scaling, turbulence spreading, ELM mitigation, divertor detachment, impurity transport, QH-mode, energetic particle
- ✓ Integrated simulation: OMFIT platform, EFIT, Scenario development for HL-2M

Future cooperation opportunities:

- ◆ Joint experiments and diagnostics development (advanced scenarios, MHD control, advanced divertor,......)
- ◆ Theory and modeling (key physics related to high performance plasmas, scenarios development,......)
- ◆ Graduate students education and young staff training

Thank you !