27th IAEA Fusion Energy Conference, Gujarat, India, Oct. 22-27, 2018

ASIPP

Recent advances in EAST experiments in support of steady-state operation for ITER and CFETR

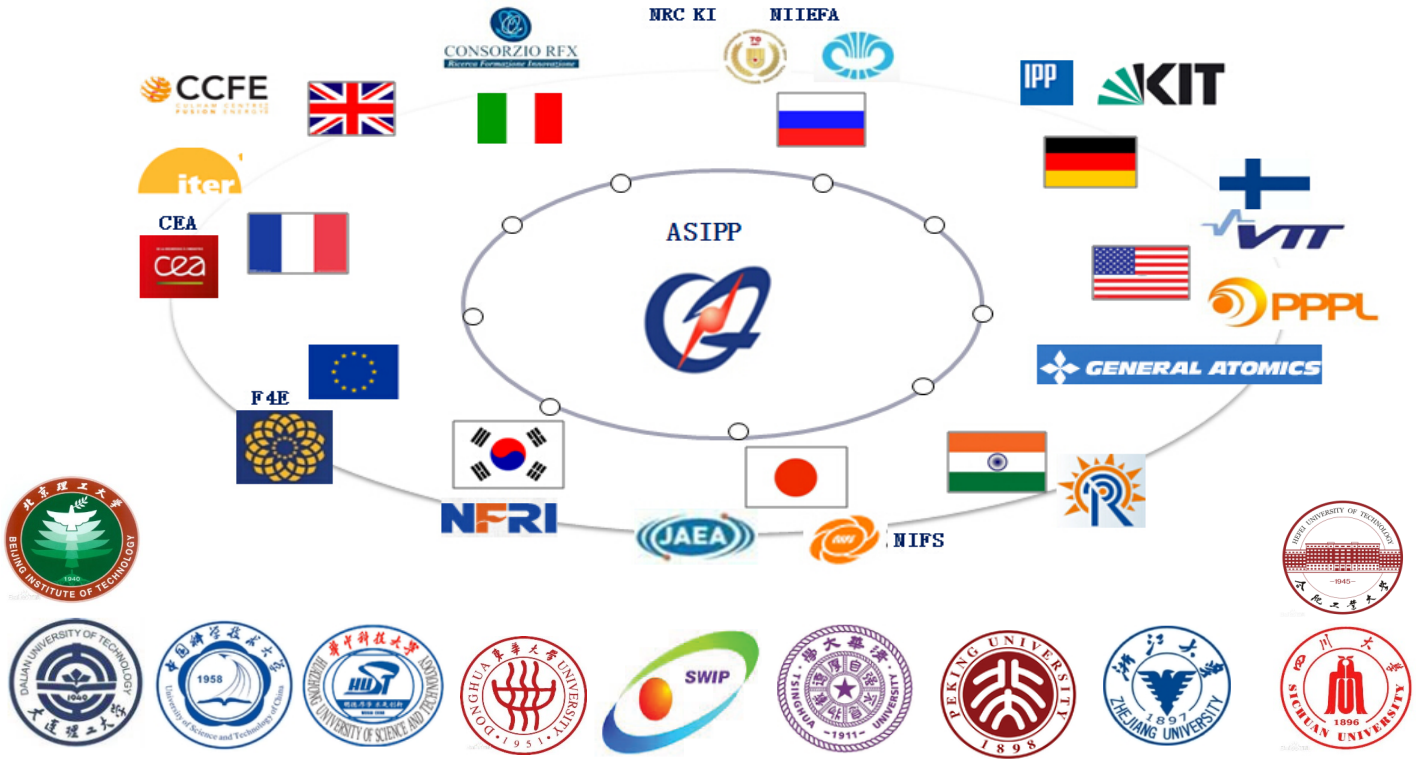
by

B. N. Wan

on behalf of EAST team & collaborators

Institute of Plasma Physics, Chinese Academy of Sciences

We acknowledge contributions from domestic and international partners to EAST research program



Outline

- **Introduction**
- **Extension of steady-state operational regime with dominant RF H&CD**
- **Physics studies to resolve scientific and technical issues for EAST steady state operation**
  - LHW PI effect
  - ELM control
  - Particle/power exhaust control
- **Summary and future Plan**

ASIPP

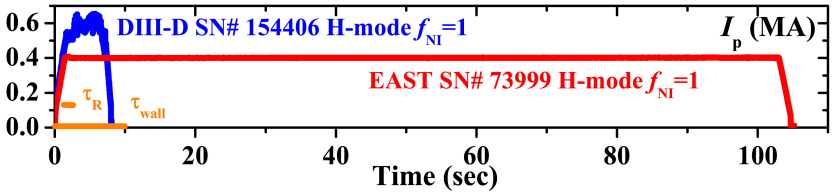
CFETR and ITER aim SS or hours operation

	Q_{pl}	β_N	f_{bs}	H_{98Y2}	$Ip(f_{oh})$	n_{bar}/n_{GR}	q_{95_iter}	R/a
CFETR SSO	~10	2.0	0.5	1.4	14	0.57	5.5~6	7.2/2.2~3.3
CFETR HB	>15	2	0.5	1.2	14(0.3)	0.85	5.5~6	7.2/2.2~3.3
ITER SSO	>5	>2.6	0.5	>1.3	9	0.85	5	6.2/2~3.1

$f_{bs} \sim \varepsilon^{1/2} * \beta_p \propto \beta_N * q_{95}$; large ε is favorable for confinement

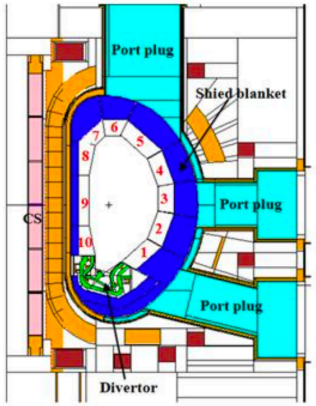
G. Zhuang OV/3-2

- **Develop physics basis for steady-state operation (ε, β_p)**
- **Extend integrated high performance results to true SSO**



J Qian, *Nucl. Fusion* 57 (2017)

DIIID; A~2.6
EAST; A~4.2

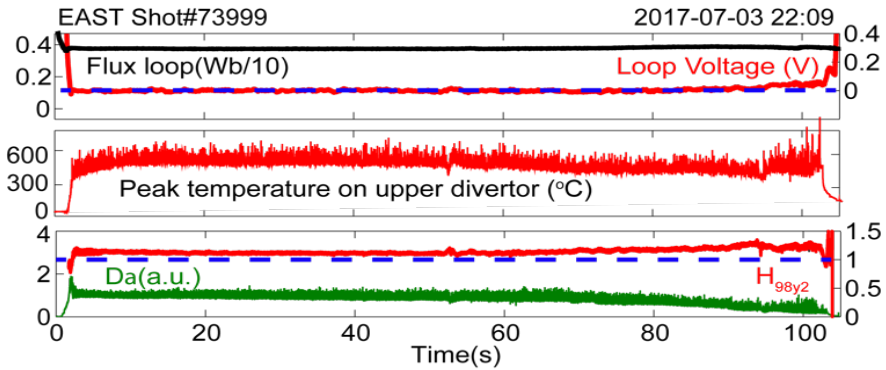


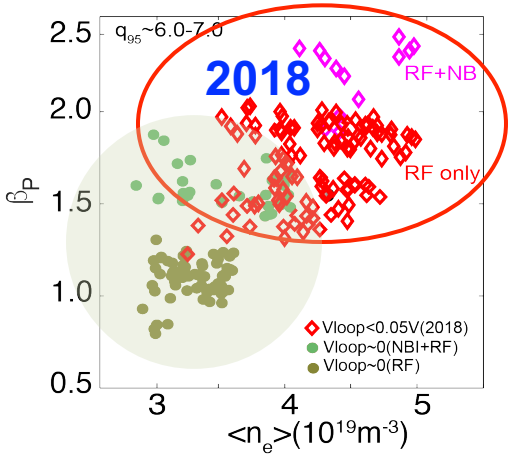
ASIPP

EAST demonstrated high β_P long pulse H-mode operation with high f_{bs} for ITER and CFETR

EAST aims to find integrated solutions of tokamak steady-state operation

- Long pulse operation with metal wall
- Bootstrap current fraction f_{bs} ~ 50%



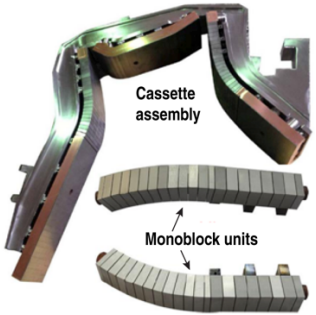


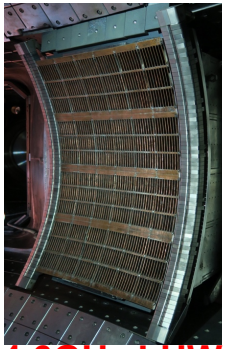
World record long pulse steady-state H-mode operation with tungsten divertor

Extension of β_P operational regime with f_{bs}~50% at CFETR relevant q_{95}

ASIPP

EAST capabilities facilitate to extend high performance to true steady-state operation



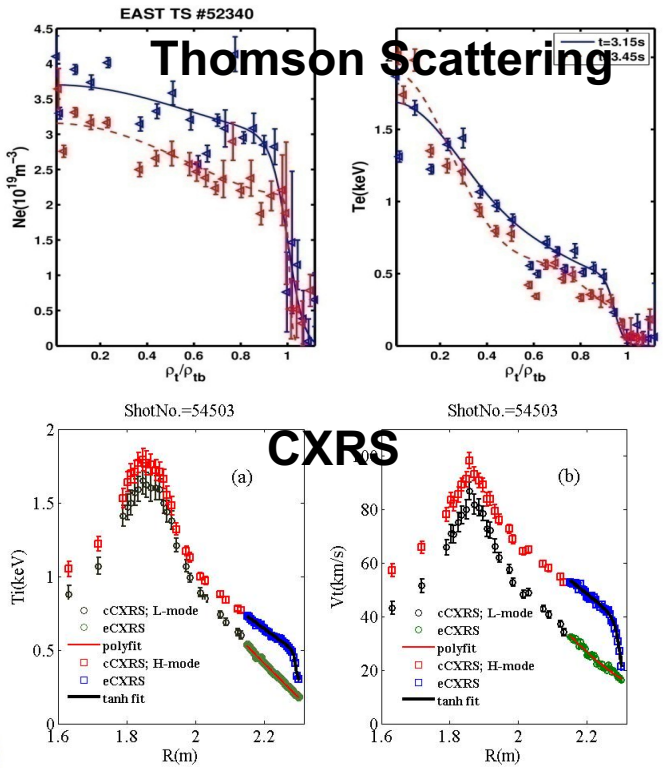


New 4.6GHz LHW W guide limiter
$P_{in\text{-}Max}$~3.5MW

- **LHCD 4+6 MW (2.45/4.6GHz)**
  - Fast Electron Source/Edge Current Drive /Profile
- **ICRH 6+6 MW (25-75MHz)**
  - Ion and Electron Heating Central Current Drive
- **ECRH 1+1(4) MW (140GHz)**
  - Electron heating/Steering mirror, j_ϕ tailoring
- **NBI 4+4 MW (co/counter, 80kV)**
  - Ion heating/Variable rotation/ rot-shear
- **Fueling (gas puffing, SMBI, pellet)**
- **In-vessel cryopump**
- **Wall conditioning**
- **Active water cooling (PFC)**

ASIPP

Diagnostic systems in support of steady-state long pulse operation and physics study



- **Plasma operation**
  - Magnetic measurement, visible/IR camera, thermocouples, LP, pressure gauges, RGA
- **Profile diagnostics**
  - POINT, TS, ECE, XCS, ME-SXR, HCN, Reflectometry, Recip.-LPs, He-BES, Li-BES, XCS, CXRS
- **Plasma impurities & radiation**
  - filterscope, Vis Spec, EUV, XEUV, SX-PHA, Divertor W Spec, Vis Brems., CXRS, XCS, Bolometer, AXUV
- **Energetic particles:**
  - FIDA, FILDs, ssNPA, neutron camera
- **Multi-scale fluctuations**
  - Mirnov, soft X-ray, ECE/ECEI, POINT, BES, DBS, ECEI, GPI, CO2 laser

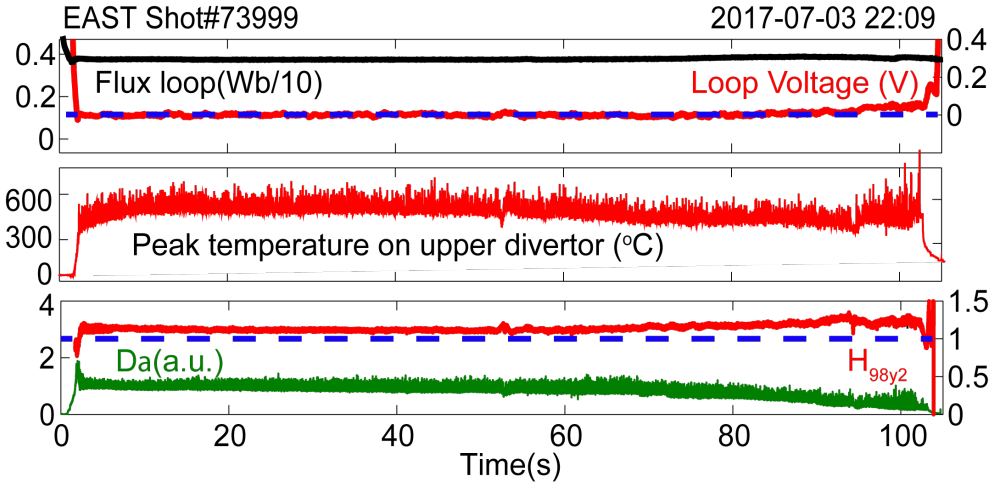
ASIPP

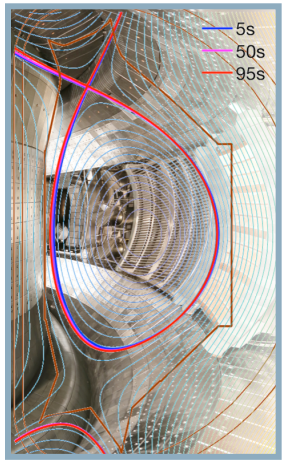
Outline

- Introduction
- **Extension of steady-state operational regime with dominant RF H&CD**
- Physics studies to resolve scientific and technical issues for EAST steady state operation
  - LHW PI effect
  - ELM control
  - Particle/power exhaust control
- Summary and future Plan

ASIPP

EAST long pulse steady-state H-mode operation with tungsten divertor





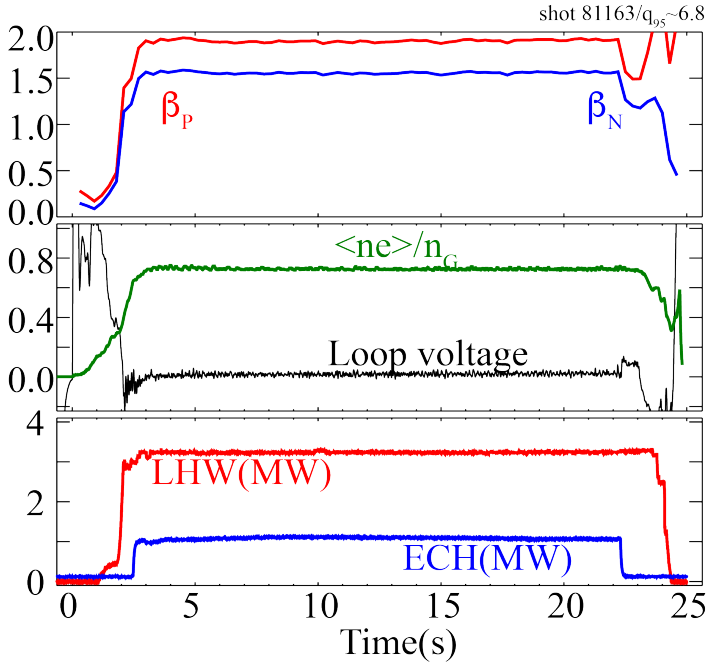
- **Integrated plasma control**
- **Saturated W-Div. surface temperature (~10 sec)**
- **Good confinement (LHW+ICRF+ECH)**
  - H_{98y2} ~ 1.1 with e-ITB
- **Small ELM**

ASIPP

X. Z. Gong EX/3-1

Recent experiments extended steady-state high β_p scenarios with f_{bs}~45% using RF H&CD only

- **Pure RF heating， Vloop~0.0**
  - P_{LHW} ~3.2MW,
  - P_{ECRH} ~ 1.0MW;
- **Good confinement**
  - H_{98y2} ~ 1.2, β_p ~ 1.9, β_N ~ 1.5
  - f_{Gr} ~ 0.8, f_{BS} ~ 45%
- **Good control of impurity accumulation**
  - Small ELMy, on-axis ECH
- **Demonstrated steady-state operations with similar q_{95} and good confinement under ITER and CFETR relevant condition**
  - Metal wall, zero torque, e-heating

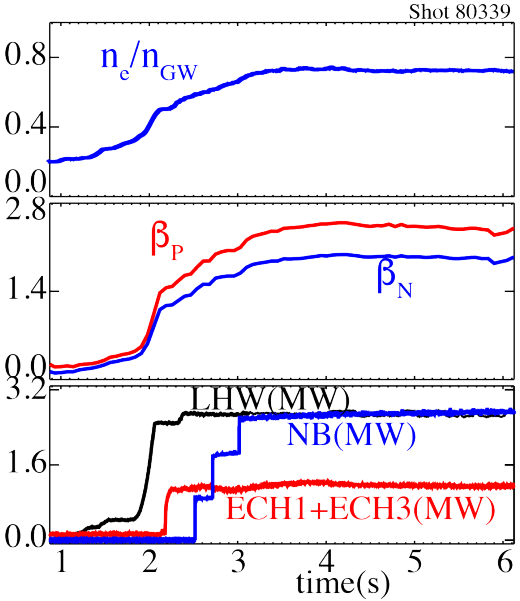


ASIPP

X. Z. Gong EX/3-1

Achieved f_{bs} over 50% using RF+NB H&CD

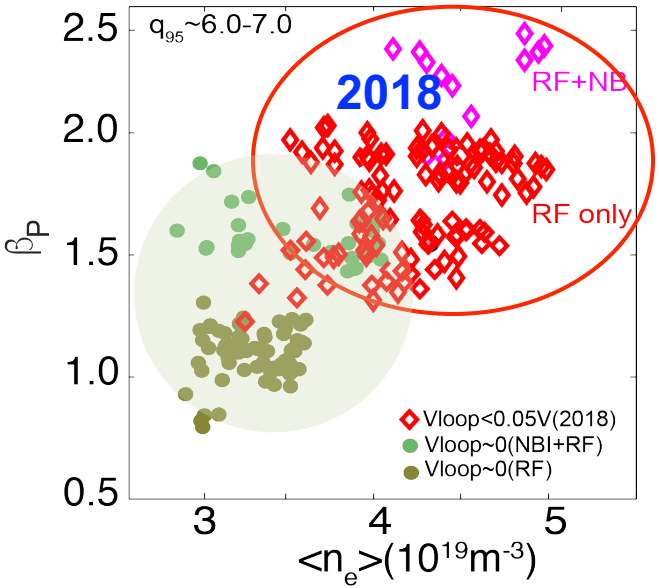
- **RF+NB H&CD,**
  - P_{LHW} ~ 2.5MW,
  - P_{ECH} ~ 1.0MW;
  - P_{NB} ~ 2.2MW
- **Plasma parameters**
  - β_p ~ 2.5, β_N ~ 1.9
  - $f_{BS} \geq 50\%$
  - q_{95} ~ 6.8
- **Density and beam voltage optimized to reduce fast ion losses**
  - f_{Gr} ~ 0.7, $V_{beam} \leq 65$kV



ASIPP

Extension of operational regime towards steady-state operation for ITER and CFETR

- **β_P versus line-averaged density of low loop voltage plasmas**
  - $V_{loop} < 0.05V$, $q_{95} \sim 6.0 - 7.0$
- **Extended operational regime**
  - High density $f_{Gr} \sim 0.8$
  - $f_{BS} \sim 45\%$ pure RF
  - $f_{BS} \geq 50\%$ NB +RF
- **Good confinement**
  - $H_{98y2} \leq 1.3$
  - ITB inside $\rho < 0.4$

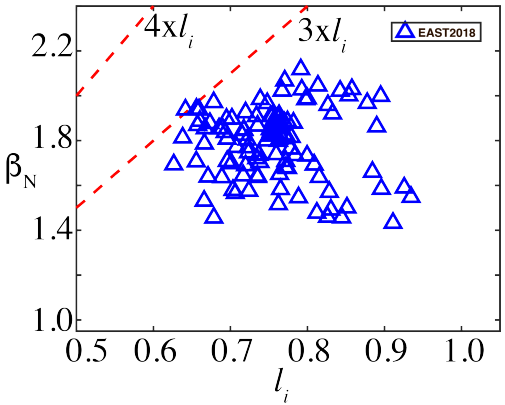


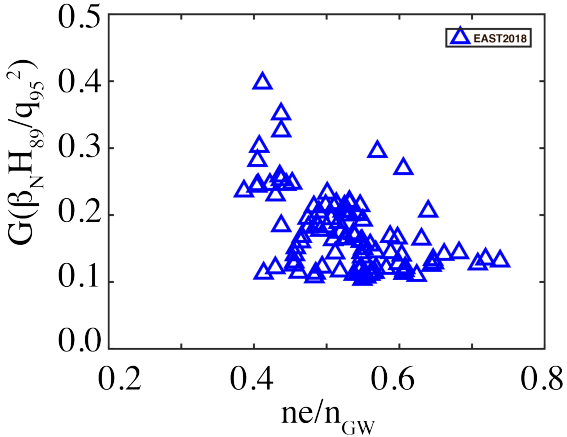
ASIPP

Development of high β_N scenarios in the low q_{95} regime

- **High G (>0.3) plasmas obtained with q_{95} = 3.5 - 4.0 and β_N ~2.0**
  - β_N ~3 x l_i
  - B_T~1.5-1.8 T

- **Double barrier structures (ITB+ETB) observed in different q profiles**
  - Montonic, central flat and weakly reversed shear





ASIPP

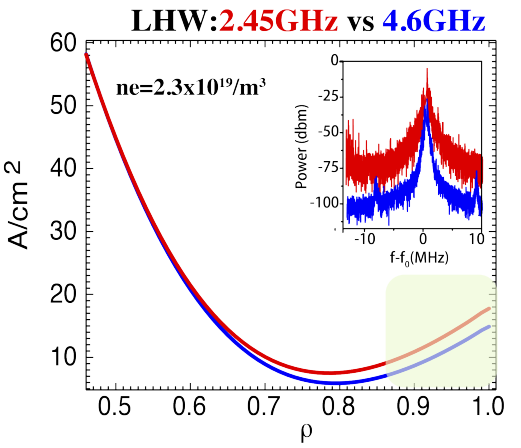
Outline

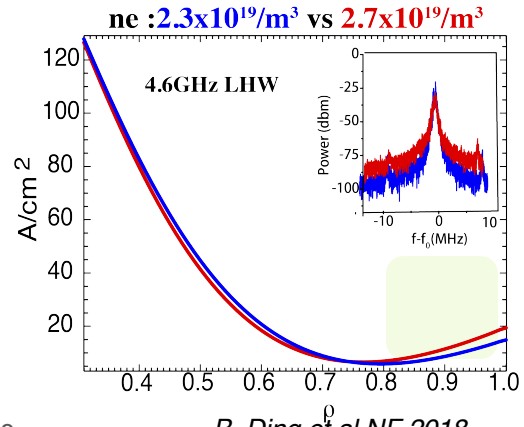
- Introduction
- Extension of steady-state operational regime with dominant RF H&CD
- **Physics studies to resolve scientific and technical issues for EAST steady state operation**
  - LHW PI effect
  - ELM control
  - Particle/power exhaust control
- Summary and future Plan

ASIPP

Correlation between the parametric instability of LH waves and modification in edge current profile

- **Stronger PI was observed**
  - With reduction in source frequency
  - With increase in plasma density
- **Stronger PI with the increase of plasma edge current**
  - More LHW power dissipates in edge
- **Control of PI is essential to access higher density regimes in a steady state H-mode plasma.**
  - Lithium coating and injection
  - LHW at higher frequency





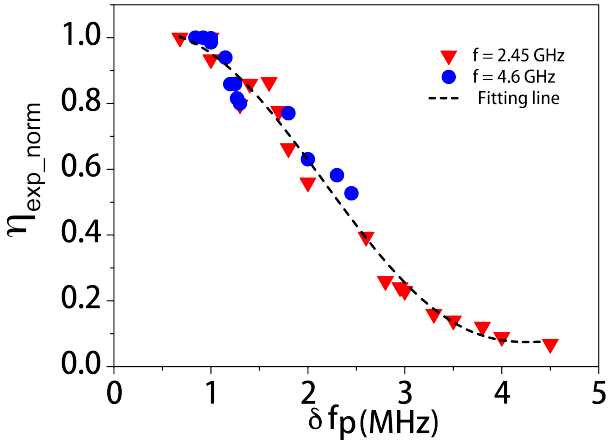
B. Ding et al NF 2018

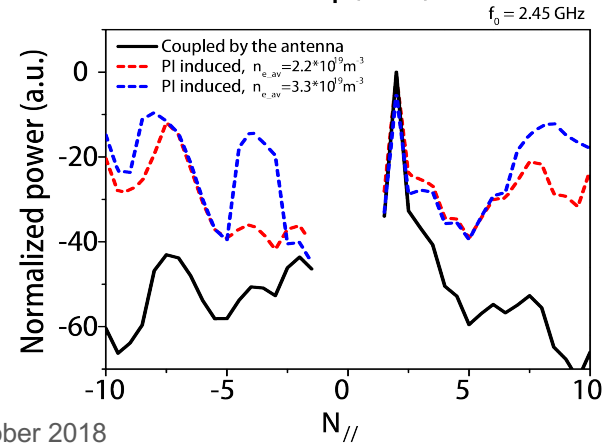
ASIPP

Effect of PI induced spectral broadening on LH current drive efficiency

- **Spectral broadening has negative effect on CD efficiency and LH power absorption**

- **Modeling result shows ion-sound quasi-mode-driven PI can redistribute the launched parallel refractive index ($N_{//}$) spectrum**





B. Ding et al NF 2018

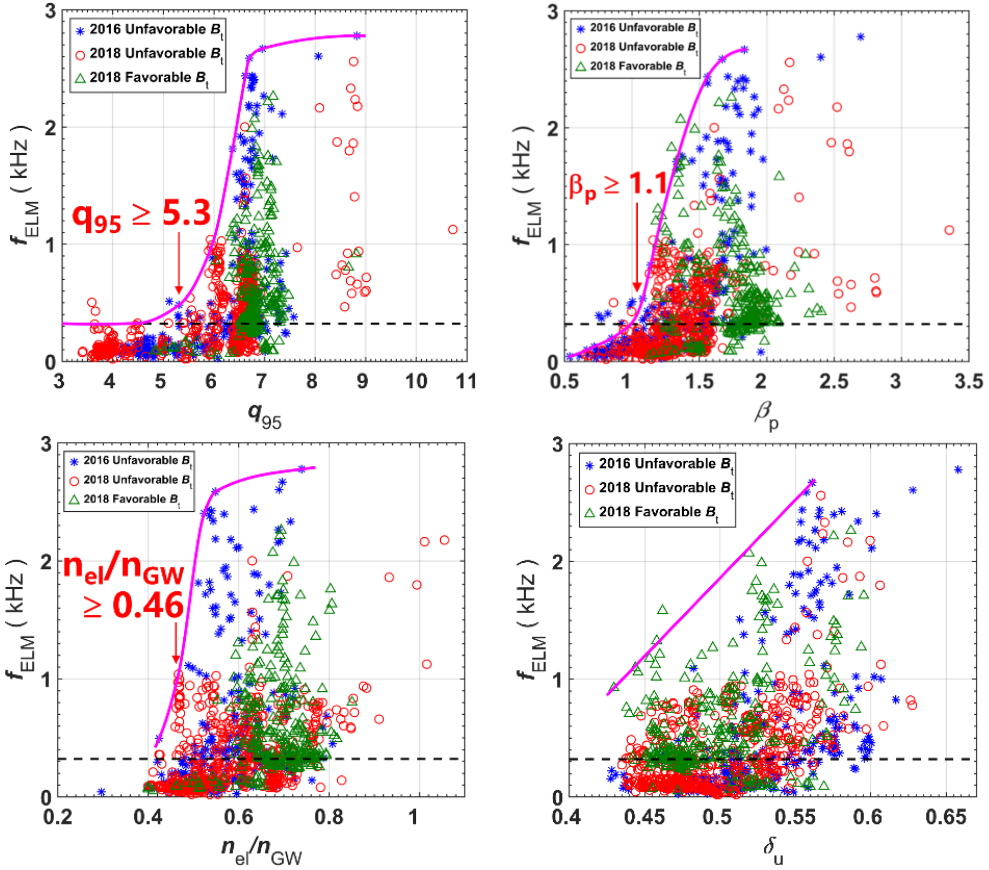
Extension of parameter space for the EAST grassy ELM regime towards lower q_{95} and higher density

Parameter space for f_{ELM} > 500 Hz:

- $q_{95} \geq 5.3$
- $\beta_p \geq 1.1$
- $n_{el}/n_{GW} \geq 0.46$, up to 1.1
- β_N up to 2
- H_{98y2} up to 1.4
- f_{BS} up to 70% (@300kA)

Overlap with CFETR 1GW scenario:

q_{95}=5.5-7, β_N~2, f_{BS}~50%, n_{el}/n_{GW}~0.7

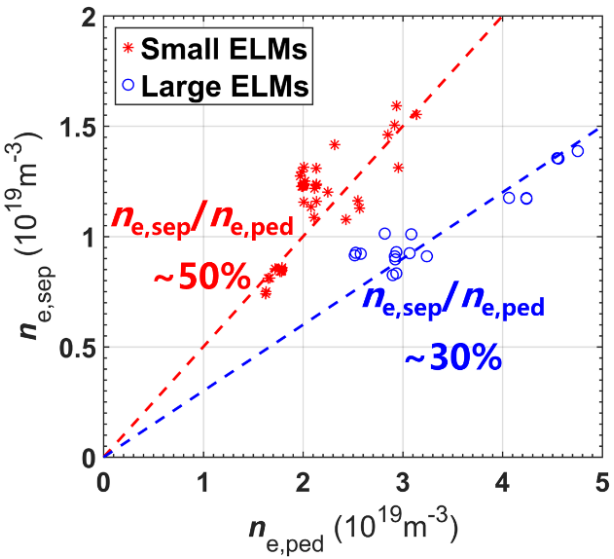


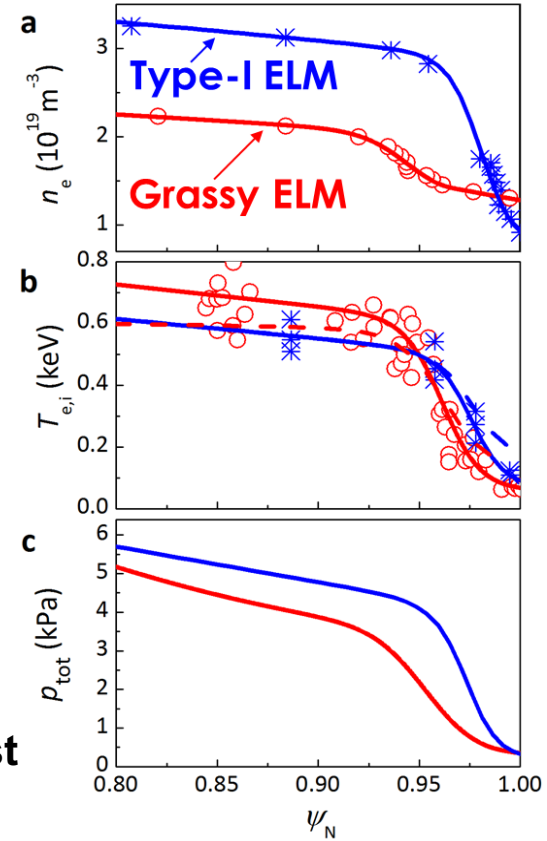
G.S. Xu EX/P2-4

ASIPP

Pedestal profiles of grassy ELM regime characterized by a wide pedestal and low pedestal density gradient

- **Characterized by**
  - Relatively wide pedestal
  - Low pedestal density gradient
  - Low pedestal bootstrap current density
  - High $n_{e,sep}/n_{e,ped}$ (up to 0.6)
- **Good compatibility with**
  - Low rotation
  - High density
  - Radiative divertor
  - High bootstrap current fraction
  - Fully non-inductive operation
  - Strong tungsten impurity exhaust capability



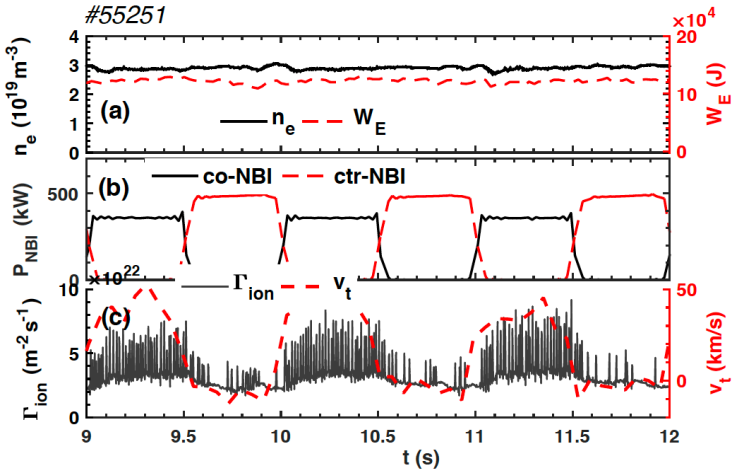


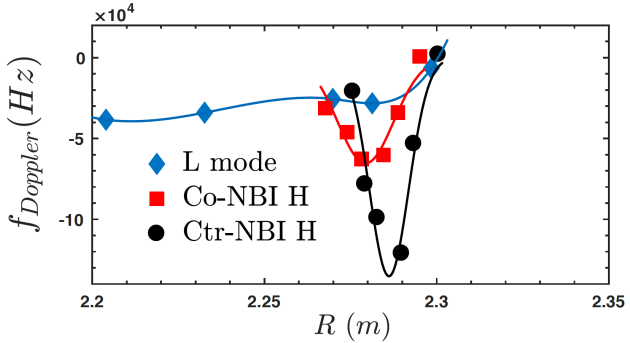
G.S. Xu EX/P2-4

ASIPP

E_rxB shear has a great impact on the ELM size

- **Experimental modulation co- and ctr-Ip NB;**
- **Smaller ELM size observed at ctr-NBI**
  - stored energy and density profiles keep the same (same collisionality)
- **Toroidal rotation (or $E_r \times B$ shear) plays an important role in modifying the ELM**



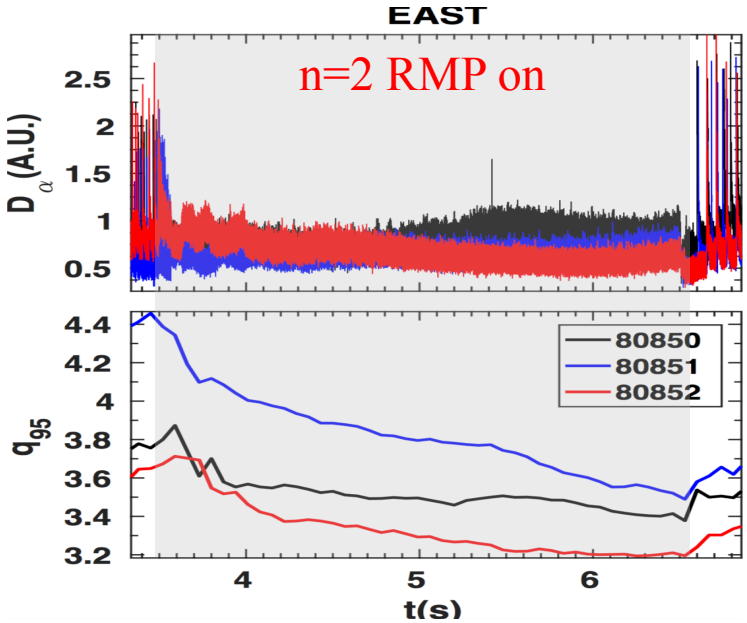


D.F. Kong EX/P2-1

ASIPP

Achievement of ELM suppression using n=2 RMP in a wide low q_{95} window

- Achieved ELM suppression in standard type-I ELMy H-mode with low q_{95} (~3.7) window
- Robust ELM suppression in a wide q_{95} window 3.2-4.2 with n = 2 RMP achieved



B_T ~ 1.6T, β_N~1.5, N_{e0}~ 3x10^{19}m^{-3}, $\nu_{*e,ped}$~0.5

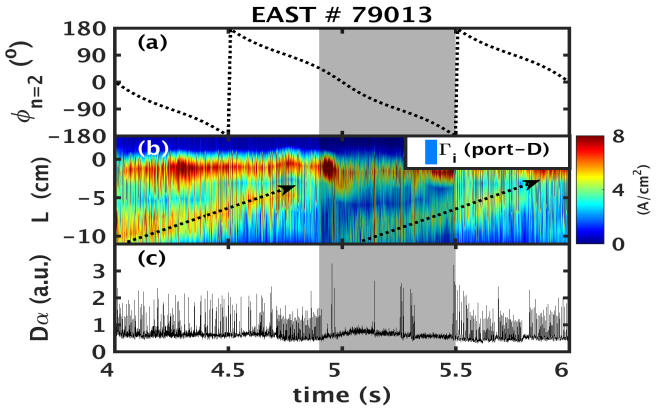
P_{NBI} ~ 2MW, P_{LHCD} ~ 1MW, $\Omega_{\Phi 0}$ ~ 50krad/s

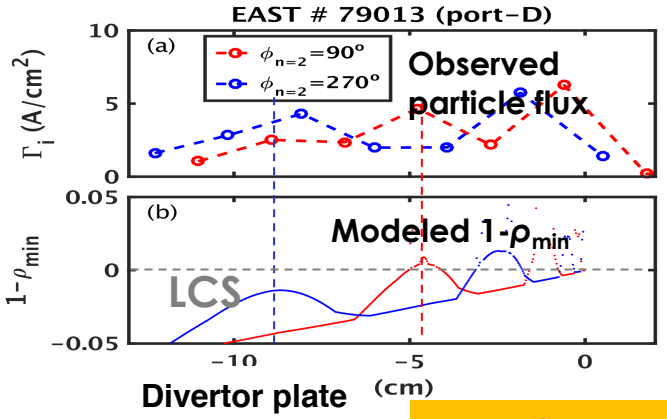
ASIPP

Y. W. Sun EX/7-2

ELM suppression achieved using a rotating n=2 + static n=3 RMP field

- **ELM suppression using rotating *n*=2 superimposed on a static *n*=3 RMPs achieved in EAST**
- **control of 3D pattern of the particle flux on the divertor**
  - Footprint of particle flux is periodically changing during n=2 RMP rotation
  - consistent with modeling by TOP2D with plasma response by MARS-F

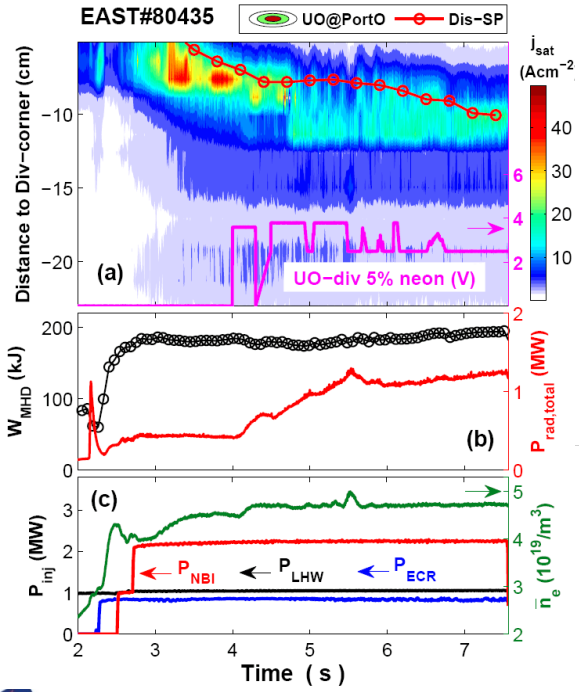




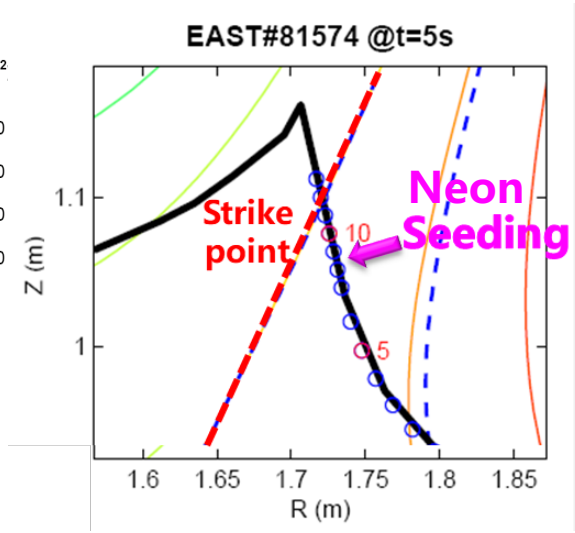
Y. W. Sun EX/7-2

Demonstration of radiative divertor without confinement degradation with feedback control on J_{sat} or P_{rad}

Target J_{sat} feedback



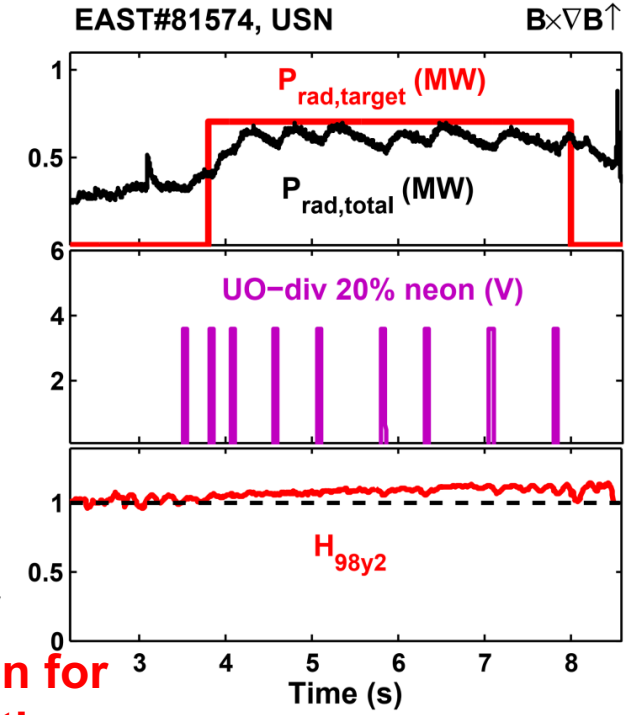
L. Wang EX/P2-8



T_{et} is sustained at ~ 10 eV

Promising diveror solution for long-pulse H-mode operation

Radiation power P_{rad} feedback

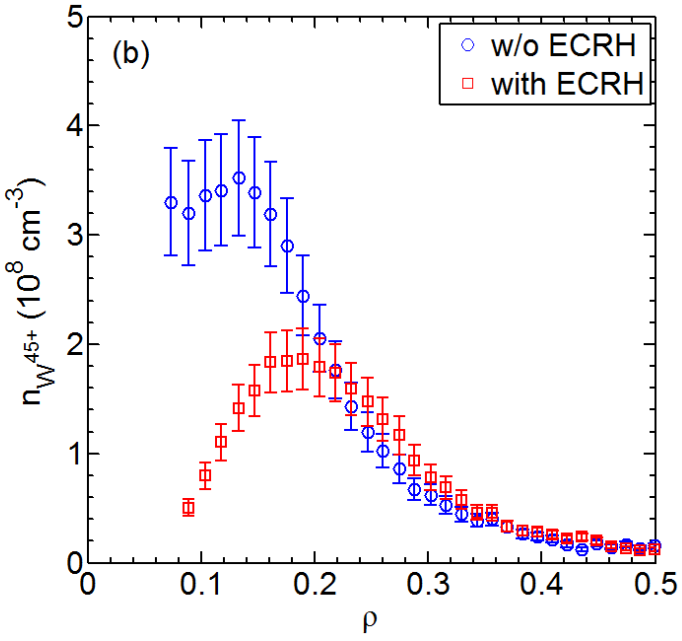


G.S. Xu EX/P2-4

ASIPP

ECRH is essential to alleviate accumulation of high-Z Impurities in long pulse operation

- **Discharges are often terminated due to tungsten accumulation**
- **High-Z impurity control**
  - ECRH power deposition at ρ<0.1
- **Radial profiles clearly indicate the reduction of tungsten ions in plasma core regime (ρ<0.2)**

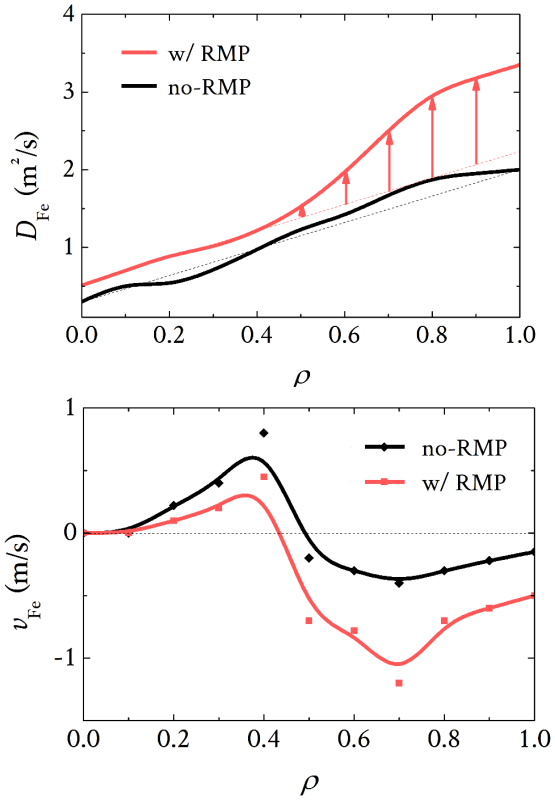


ASIPP

L. Zhang EX/P2-3

RMP applied for eliminating impurity accumulation

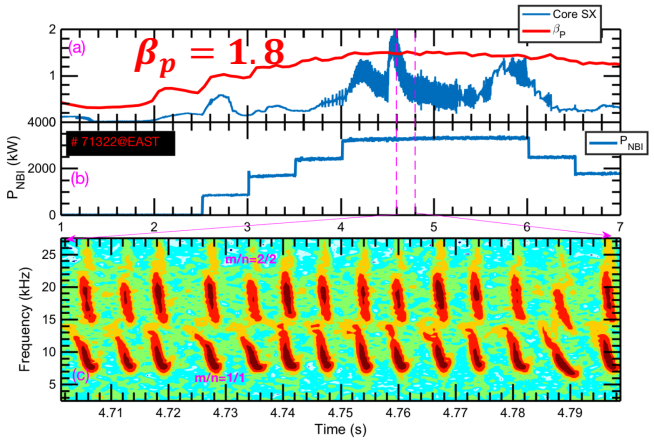
- **High-Z impurity concentration can be significantly decreased with an Z-dependence**
  - Stronger effect on higher-Z impurities
- **RMP induced change significantly in transport, leading to a flattened impurity profiles.**
  - Increase in diffusion
  - Larger outward pinch velocity

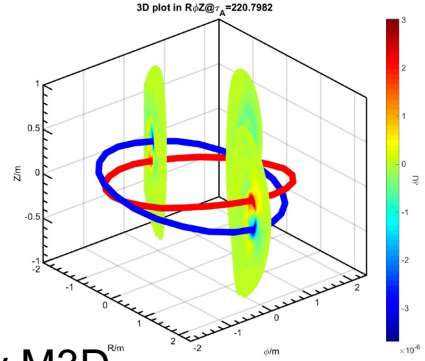


ASIPP

3D helical mode favorable to maintain advanced high β_p operation in weak magnetic shear

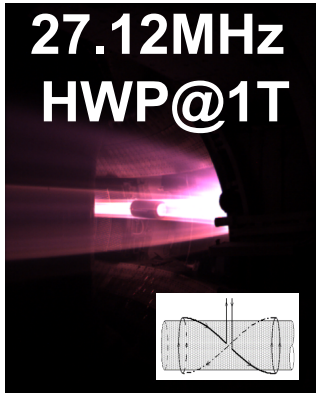
- **Long-lived mode was observed in high β_p plasma with q_{min} $\gtrsim$1** (low magnetic shear) **via flux pumping mechanism**
- **No large sawtooth crash in the core and no NTM**
- **This mode helps avoiding high-Z impurity accumulation**





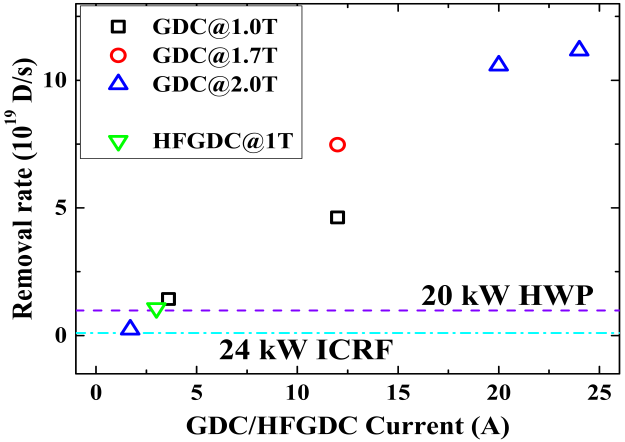
3-D nonlinear simulation by M3D

New method of discharge cleanings under strong magnetic field



Collaboration with Suzhou University

First successful operation of Helical Wave Plasma (HWP) and Direct-Current Glow Discharge Cleaning (GDC) in tokamaks under strong magnetic field!



- **DC-GDC @ 2T is more efficient for retention removal**
- **Uniform plasmas & high current density (0.4 A/m^2)**

ASIPP

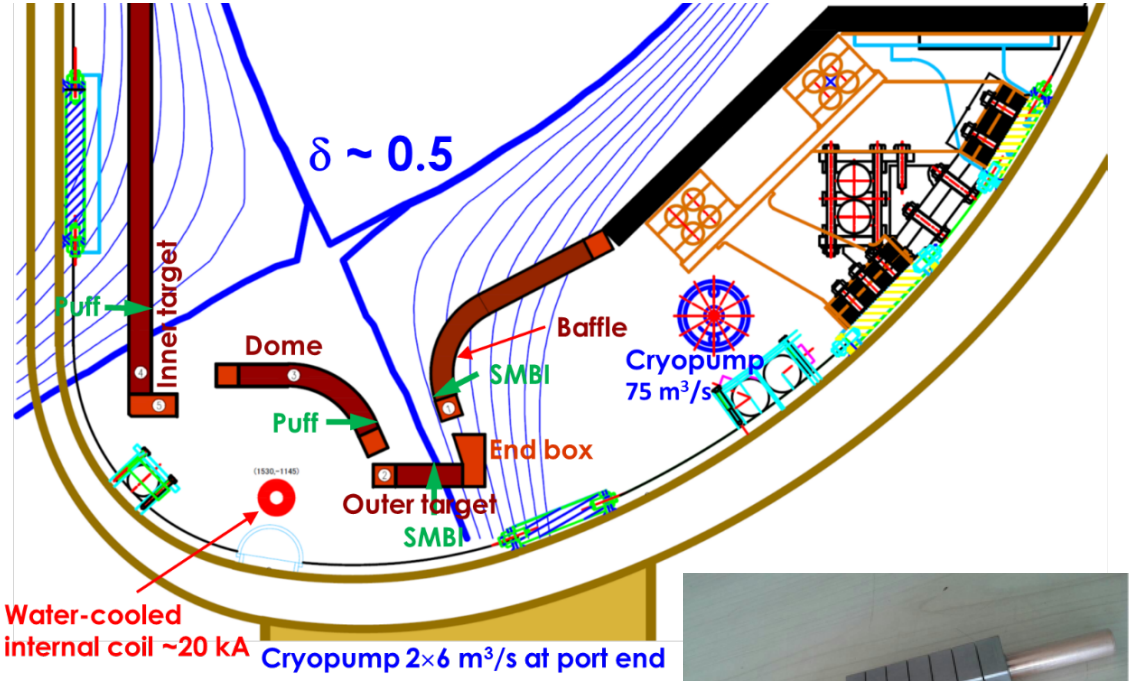
Outline

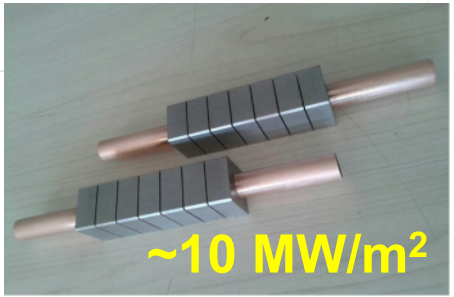
- Introduction
- Extension of steady-state operational regime with dominant RF H&CD
- Physics studies to resolve scientific and technical issues for EAST steady state operation
  - LHW PI effect
  - ELM control
  - Particle/power exhaust control
- **Summary and future Plan**

ASIPP

EAST new W lower divertor upgrade scheduled in 2019 for radiative divertor feedback control and X-divertor

- Simple flat targets to reduce installation error and thus leading edges
- Closed outer divertor and open inner divertor for balanced detachment
- A water-cooled internal coil for X-divertor operation
- SMBI for impurity seeding feedback control





ASIPP

Summary

- **Significant progress has been made in steady state long pulse operation**
  - 101.2 s H-mode with H_{98y2}>1.0 achieved with pure RF powers and W-divertor
  - Extended pure-RF scenarios with $\beta_p \leq 2$, $f_{BS} \leq$40-50%, f_{Gr}~0.6-0.8 at q_{95}~6.0-7.0 relevant to CFETR, demonstrated for longest 20s
  - High performance SSO scenarios have been developed for further long pulse operation

- **Physics research has been conducted to resolve scientific and technical issues for EAST long pulse operation, delivering steady state operation in ITER and CFETR**
  - LHW PI effect, ELM suppression , radiative divertor, high Z impurity control etc.

- **≥400s Long pulse & high performance operation are planned with more gyrotrons (2019-2020) and upgrade in lower divertor (2019)**

ASIPP

Contribution to 27th IAEA FEC from EAST team and collaborators

[Overview & operation]

- OV/2-2 B. N. Wan EAST overview
- EX/3-1 X. Z. Gong Integrated operation
- EX/3-2 G. Calabro ELM-absent H-mode
- EX/P2-26 D. Moreau Model-Predictive control
- EX/P2-16 A. Ekedahl RF heated H-mode
- EX/P5-1 Z. X. Liu I-mode
- EX/P6-21 J. Barr Low-disruptivity rampdowns
-

[ELM&RMPs]

- EX/7-2 Y. W. Sun RMP control
- EX/P2-4 G. S. Xu Grassy ELM regime

[PSI&Divertor]

- MPT/2-2 R. Ding High-Z material erosion & migration
- TH/P1-5 F. Schluck PSI 3D modeling
- EX/P2-8 L. Wang PSI control for H mode
- EX/P2-3 L. Zhang Tungsten control
- FIP/3-5Ra R. Maingi Li limiter and conditioning

[Transport & turbulence]

- EX/P2-12 P. J. Sun Microturbulence & MHD modes
- EX/P2-2 Y. Yu Anisotropic turbulence
- TH/P4-2 T. Y. Xia Particle & heat fluxes
- TH/P6-2 S. Y. Ding Gyrokinetic Simulations on H-mode
- TH/P6-1 G. Q. Li integrated modelling of transport
- TH/P7-21 X. Q. Xu Boundary turbulent transport

[MHD&EP]

- TH/1-1 W. Shen EP instability & redistribution
- EX/P2-15 J. Huang EP studies
- EX/P2-14 L. Q. Xu Kink mode study
- TH/P5-14 X. Q. Wu Magnetic Coherent Mode

[CFETR]

- OV/3-2 G. Zhuang CFETR Design
- TH/P5-16 R. Han RWM Stabilization
- FIP/P7-27 H. L. Chen Vertical Displacement
- TH/P7-3 M. Y. Ye Impurity Radiation

[Machine learning]

- EX/P6-20 R. Granetz Distruption warning

ASIPP


Thank you !