Recent Progress in High Power Heating and Long Pulse Experiments on EAST

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Outline

• Introduction
• System status
• Experiments
• Near future plan
• Summary
Introduction

• EAST aims at long pulse operations with plasma current Ip ~ 1 MA, and high performance plasma.

• Key milestones until last IAEA FEC
  2006.9.26 First plasma (GA,PPPL)
  2007.1.25 First diverter plasma (GA)
  2008.1.14 President Hu visited EAST
  2008.5.10 Actively cooled C PFC finished
  2008.7.10 Iso-flux control, 20s DN plasma (GA)
  2008.10 The first class national S&T reward

• New capabilities developed in last two years allow us to investigate some ITER relevant issues.
Present Status and System Capabilities

- Graphite PFC (tiles with $2\text{MW/m}^2$)
- Internal Cryo-Pump, Removable limiter
- RTEFIT/Isoflux control, limiter, SN, DN
- Plasma: $I_p\sim0.9\text{MA}$, $B_t\sim3\text{T}$, $P_{\text{hcd}}\sim1.2\text{MW}$, $P_{\text{crf}}\sim1.6\text{MW}$, $T_d\sim60\text{s}$ (DN)
- Shaping: $\kappa\sim1.9$, $\delta\sim0.65$

System Capabilities:
- LHCD: 2.45GHz, 2MW
- ICRF: 30-110MHz, 1.5MW
- ICRF: 20-70MHz, 4.5MW
- Diagnostics: >40, in 2010 for all key profiles
- Multi-purpose gas injection at different location for various gas (D2, CD4, Ar, N2 ...)
Present Capabilities

• ICRF system of 3*1.5MW at 25-70MHz, two double loop antenna
• LHCD system of 2MW at 2.45GHz, multi-junction launcher
• Wall conditioning technique (RF, High frequency glow discharge)
• Key diagnostics provide profiles, including:
  - Multi-channel Thomson scattering (25 polychromators, two 5J YAG lasers at 10Hz)
  - Two 2D soft-X ray crystal spectrometer-XCS (toroidal and poloidal view sights)
  - Bolometer arrays
  - Two Fast reciprocating probe systems (toroidally separated)
  - 2D ECEI
  - SX arrays (for kinetic equilibrium reconstruction)
  - And more (optic and spectroscopic diagnostics, neutron, gamma-ray…)

ASIPP
ICRF system

- Power generator:
  - 3*1.5MW in CW
  - 25~70MHz
- Pressurized coaxial transmission line (50Ω)
- Liquid stub tuner
- Tow double straps antenna

Fed by two generators
Fed by one generator
Liquid stub tuner

Antenna configuration
1. ICR conditioning were successfully carried out in EAST, a divertor SC tokamak with metal/C walls.
2. ICR cleaning, recycling control, boronization and oxidation have been carried out and compared with GDC.
3. High pressure and RF power are favorable for removal of hydrogen and impurities.
4. Wider operation widows (EAST: 15-30kW, $10^{-4}$-$10^{-1}$Pa ) and higher removing rate were obtained.
5. RF-Boronization has been routinely used for all campaigns with about 200nm thickness. 30-60 min. He RF conditioning was used for control recycling. Very good plasma performance can been easily obtained.
New Method: HF GDC

• Power Supply: U=1.0KV, f=100KHz, I~0.5-1.0A
• Work Gas: Ar, He, H2.
• GDC electrode
• HT-7: 5x10-4Pa-0.5Pa, Bt=0.5-2

HF-GDC is routinely used for wall conditioning, siliconization and recycling control between shots which shows almost the same effects with RFWC.

Recovery from 10Pa leakage
Plasma Recovery by Strong HF_GDC
Li Wall Conditioning

RF Li coating, Li evaporating and Li Droplets

MHD was suppressed,

Lower recycling and broader Te profile

H/(H+D) control: from 35% to 7%

Very promising technique

By D. Mensfeild
2D-XCS

Ar as probing particle

- Two XCS are installed in both poloidal and toroidal view sights
- They provide: Ti (Doppler broadening), Te (line intensity ratio) and toroidal and poloidal plasma rotation (Doppler shift)

In collaboration with PPPL and NFRI
Fast reciprocating probe system

- Two probes toroidally separated by 90°
- Scanning rate up to 2m/s
- Multi scanning in one shot
- Radial scanning up to 20cm
- Exchangeable probe head

Allow edge profile and turbulence measurements at multi time slices in one shot
Divertor Physics Experiments

- Assessment of basic divertor plasma behavior
- Effect of divertor configurations – *Comparison between single null and double null*
- Divertor asymmetry and drift effects – *Comparison between normal and revered toroidal fields*
- Effect of gas puff locations on divertor asymmetry and fuelling efficiency
- Divertor screening for intrinsic carbon by CH$_4$ puffing
- Active control of divertor heat flux by Ar puffing
- Effect of divertor cryopump

Search for div. operational scenarios relevant to SSO

Guo, P3-14
Divertor Plasma Detachment Was Clearly Demonstrated on EAST by density ramp-up

Sheath-Limited
- Ion saturation current $I_s$ (particle flux) increases with density $n_e$

Conduction-Limited
- $I_s$ further increase until roll over

Detachment
- Particle flux starts to decrease as $n_e$ increases

Plasma detachment reduces peak particle & heat fluxes, as well as associated material damage, essential for steady-state operations.
EAST adopted ITER-like vertical target configuration, which promotes detachment near strike point. However, this scenario by density ramping is not fully compatible with LHCD and high confinement scenario, radiative divertor is required.

- D2+5.7% Ar mixture puffing was initiated at 5s led to detachment at both upper and lower outer divertor targets.
- Significantly reducing the peak heat fluxes, $q_{\text{peak}}$, near outer strike points.
- $Z_{\text{eff}}$ is reduced.

Ar puffing in divertors promote partial detachment and reduce peak heat flux.
Effect of Gas Puff Locations

DOME D$_2$ puffing has highest fuelling efficiency, less from inner target plate, lowest from outer target plate. Compared to SN configuration, DN is more sensitive to gas puffing location.
LHW coupling optimization by regulation of gap between the launcher mouth and the last closed flux surface and plasma shape versus plasma density

Total RC: 5~7% has been achieved for routinely LHCD experiments

EXW/P7-03 Ding, B.J.
• Fully non-inductive discharge has been achieved both in DN and SN configuration.
• All PF currents reached to steady-state 4s after LHW applied.
• Higher injected LHW power results lower li.
• The electron temperature profiles were not significantly changed.

Ready for long pulse discharges.
Over current drive

- Local over current drive leads to reversed ohmic current simulated by C3PO/LUKE, (CEA)
- Loop voltage was included in simulation, diffusion of fast electrons was not considered

Ohmic current: -14kA  LHW driven current: 280kA
All these LHCD plasmas in L-mode
Long Pulse Discharges

Long pulse discharges can be achieved in both DN and SN configurations

EXS/P2-18, Xiao, B.

EXC/P2-01, Ding, S.
Long Pulse Discharges

- Optimized LHW coupling with reliable plasma shape control based on RTEFIT/Iosflux control algorithm
- Higher fuelling efficiency from Dome (see divertor experiments) reduced the fuelling gas amount for same line averaged density, e.g. retention of gas
- Slow drift of strike points avoid over-heating on the divertor plates
High power heating & current drive

- LHCD: max output power 1.5MW, ~1.2MW was absorbed
- ICRF: max 2.4MW was injected. Antenna-I 2*0.8MW and antenna-O 0.8MW. Scenarios of H 2nd harmonic, minority with H and He3 and mode conversion (He3, H) were tested in D plasma.

Ip~0.5MA
Ne~2.5*10^{19}m^{-3}
DN

- LHCD was very reliable and effective.
- No effective heating by ICRF.
- Too low density at front of antenna may be main reason?

Faraday shielding

EXW/P7-13 Li, X.L.  EXW/P7-30 Zhang, X.J.  EXC/P2-01, Ding, S.
Efforts for 1MA operation

- Stable 0.8MA plasma in DN divertor configuration
- RTEFIT/Iso-flux control
- LHCD assistance

Broadening electron temperature and current density profiles during ramping up

EXC/P4-06  Gao, X.
Effort for 1MA operation

- Up 0.93MA plasma in DN divertor configuration
- Ramping phase due to striking point on dome
- Confinement improvement, ITB?

Configuration at 1, 3, 5 s → stable configuration control during ramping up
Effort to achieve improved confinement

- Current ramping up in DN divertor configuration
- 1MW LHW power
- Outer shift of LHW power deposition location

Trans analysis shows a possible weak ITB at rho~0.45
Effort to achieve improved confinement

- LHW + current ramping-up
- Pre-program control to increase loop voltage (e.g. ohmic power)
- Elongated limiter configuration ($\kappa \sim 1.3$)
- Improved particle confinement and energy confinement

More peaked $T_e(r)$ at 4s during high ohmic power phase

Increased $V_p$ at 3.4s by pre-program contr.
• A minimum (dip) $V_\phi$ at $\sim$1 cm inside the separatrix.
• Collisionality $> 4$, in the Pfirsch-Schlüter regime.
• It is situated at the same location of a dip of $E_i(r)$
• But a dip of $V_\phi(r)$ not observed in the discharges that the plasma edge touches the outer limiter
Toroidal flow at edge

- $M_\parallel$ in the near SOL decreases with the increase of $\bar{n}_e$.
- $M_\parallel$ scales linearly with $V_{\parallel PS}$ at the outboard midplane.
- $V_{\parallel neo} > V_{\parallel meas}$, but $V_{\parallel PS}(r) \sim V_{\parallel meas}(r)$.
- Analysis suggests that the structure in the parallel flow could be due to the balance between the neoclassical viscosity and the neutral friction.
Toroidal rotation in LHCD plasma

- Core and edge toroidal rotation were simultaneously measured.
- Both $\Delta V\phi$ is increased in co-current direction in DN configuration.
- $\Delta V\phi$ is very prompt to LHW at the edge.
- While $\Delta V\phi(0)$ is increased in a much slower time scale.
- Decay lengths in SOL are much shorter in LHCD plasma, (larger PS flow)

DN $\kappa \sim 1.8$, $P\text{hi} \sim 0.9\text{MW}$, $I_p \sim 250\text{KA}$, $n\text{el2} \sim 1.1$, $B_t \sim 2\text{T}$
• These observations suggest possible linkage between edge and core rotation.

ΔV∥(z) profiles measured by XCS

Measured by probes
EAST 2010-2011 Targets

PF power supply upgrade
New modules of IC power supply
PFC modification for 250°C and longer pulse with different puffing

- 2(4)MW LHCD @ 2.45GHz √
- 1.5MW ICRF @ 30-110MHz √
- 4.5MW ICRF @ 25-75MHz ~√

- Second TS YAG laser in operation and further improvement for reliability
- New detector of XCS for higher time resolution
- New soft-X ray spectrometer for high-Z impurity monitoring
- New 32-chs ECE and a new 2D ECEI

Full 1MA operation
H-mode operation
For ITER related issues
Safe start-up & termination
VDI
PWI
Fueling
Wall conditioning
ELM control

EXW/P7-29  Yang, Y.
Research focus on EAST

• RF physics and performance
  - Scenarios for heating and current drive in D(H) plasma, coupling issues
  - Heating in conjunction with achievement of high performance
  - Flow drive and momentum transport

• Long pulse diverted plasma discharges
  - At 0.5MA for time scale of >100s
  - Divertor physics and technologies
  - Plasma control, plasma and surface interaction
  - Scenarios for steady-state operation

• Other issues
  - Start-up scenarios with superconducting PF features
  - Wall conditioning to support ITER (DC&HF GDC, ICWC)
  - Edge physics (turbulence and H-mode physics)
  - Core fluctuation (ECE&ECEI) and MHD activities
### EAST 5 year Plan

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With over 20MW CW power and 50 diagnostics, EAST could play a key role for long pulse advanced high performance plasma for ITER within next 5 years.

EXW/P7-29 Yang, Y.
Summary

• Basic divertor plasma behavior has been systematically accessed. Ar puffing in divertors promote partial detachment and reduce peak heat load, which is essential for long pulse discharges.

• LHCD have been systematically investigated. Full current drive and minute long pulse diverted plasma discharges have been achieved.

• Effort to approach 1 MA plasma discharge achieved 0.93MA plasma discharges with assistance of LHCD.

• High power injection up to 3MW has been realized. Effect heating is still a concern.

• LHCD toroidal flow driven in plasma core was observed. It may be account for momentum transport from edge, which corresponds to PS flow.

• EAST will be aimed on achievement and sustaining of high performance plasma in next two years.
EAST Posters

- FTP/P1-30, Song, Y.T.  Fully actively-cooled in-vessel components of EAST tokamak
- EXC/P2-01, Ding, S.  Performance predictions of RF heated plasma in EAST
- EXC/P2-09, Yuan, Q.P.  Plasma Shape Feedback Control on EAST
- EXS/P2-18, Xiao, B.  Optimization of EAST Plasma Start-Up for Simulations of ITER with Low Loop Voltage
- EXW/P2-04, Huang, H.H.  Power Supply of Vertical Stability coil in EAST
- THC/P2-03, Guo, Y.  TSC simulation and prediction of Ohmic discharge in EAST
- EXD/P3-12, Gong, X.  A New Explore: High Frequency Glow Discharge Cleaning on EAST
- EXD/P3-14, Guo, H.Y.  Recent Advances in Long Pulse Divertor Operations on EAST
- EXC/P4-06, Gao, X.  Experimental Study of Plasma Confinement on EAST
- EXW/P7-03, Ding, B.J.  Recent Experiments of Lower Hybrid Wave-Plasma Coupling and Current Drive in EAST
- EXW/P7-13, Li, X.L.  Neutron Flux Measurements in ICRF Plasmas on HT-7 and EAST
- EXW/P7-16, Lu, H.W.  Investigation of Fast Pitch Angle Scattering of Runaway Electrons in the EAST Tokamak
- EXW/P7-24, Shi, Y.  Investigation of runaway electron beam in EAST
- EXW/P7-29, Yang, Y.  A New 4MW LHCD System for EAST
- EXW/P7-30, Zhang, X.J.  Physics and Engineering Aspects of the ICRF Heating System on EAST
Collaborators

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