Summary: EXC, EXS and PPC

Y. Kamada, QST

Papers: EXC 101, EXS 57, PPC 26 from 40 devices

MEDUSA (Costa Rica): $R \approx 0.14m$, $a \approx 0.1cm$, GLAST-III (Pakistan): $R=0.2m$, $a=0.1m$

... JET (EU): $R \approx 3m$, $a \approx 1.2m$
W7-X, Welcome to EX sessions!

First plasma operation of Wendelstein 7-X

10 weeks of plasma operation from 10 Dec 2015 until 10 March 2016

Integral commissioning of superconducting stellarator, device control, plasma heating systems and diagnostics

ECRH power up to 4.3 MW, $T_e \leq 8$ keV, $T_i \leq 2$ keV, $n_e \sim 3 \times 10^{19}$ m$^{-3}$, pulse durations up to 6 sec ($\int P dt \leq 4$ MJ)

Studies of plasma start-up, power balance, confinement (core electron-root conf.), bootstrap current, on-/off-axis heating, X2- and O2-ECRH, ECCD, plasma exhaust and SOL physics
Welcome to EX! Start New Operation

**KTX**

University of Science and Technology of China
RFP
R=1.4m, a=0.4m
Ip=0.5MA (=>1MA)
Bt max=0.35T (=>0.7T)

**NSTX-U**

Ip~1MA H-modes,
H\(_{98}\) \(\geq\) 1, \(\beta_N\) \(\sim\) 4 \(\geq\) n=1 no-wall limit
with weak/no core MHD

**SST-1**

Upgraded with Plasma Facing Components.

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Welcome to EX!
Contents

1. Edge Pedestal System
2. Core Transport
3. Core MHD Stability
4. Operation & Control

* Disruption Mitigation is treated in the next talk by Dr. D. Hill
H-mode Pedestal Structure and Dynamics

- **Shafranov Shift**
  - Fast particles

- **Plasma Shape** ($\kappa$, $\delta$, $A$)
  - $\tilde{B}$ field (3D): RMP plasma response
  - impurity mitigation

- **Heat & Particle to Divertor**
  - EHO, WCM, QCM Stochasticity

- **ELM**
  - ELM = Peeling-Ballooning modes (PBM)
  - width: small-scale turbulence (KBM...)

- **Diffusion**
  - Pinch

- **Turbulence**
  - Flow

- **Core**
  - Pressure ($T, n$)

- **Pedestal**
  - Height

- **Width**

- **Minor radius**

- **Illustration of EPED1.6 Model, DIII-D 132003**

- **Graph**
  - Pedestal Height vs. Pedestal Width

- **Grassy ELM**
  - EDA H-mode
  - I-mode
  - QH-mode
  - small/no ELM regimes
Pressure Gradient ~ Peeling Ballooning Mode

COMPASS: The experimental data are in agreement with the EPED model. \((\text{EXP6-35, Komm})\)

MHD simulations reproduce experiment very well.

JT-60U and JET: MINERVA-DI: Rotation can destabilize PBMs due to minimizing the \(\omega*i\) effect \(\Rightarrow\) better fit to exp. data. \((\text{TH8-1, Aiba})\)

Multi-machine: JOREK simulations at low resistivity/viscosity reproduce experiment \((\text{TH8-2, Pamela})\)

Shafranov shift stabilizes the pedestal gradient,

**JET and JT-60U:** confirmed in a wide space of \((\kappa,\delta)\). Low \(\kappa\) high \(\delta\) gives lower grad-\(p\), but wider pedestal width, then grassy ELM & good confinement. \((\text{EX/3-4, Urano})\)

TCV, MAST and JET: The pedestal height has been significantly increased by early increase of \(\beta_p\)-core. \((\text{EX3-6, Chapman})\)
**KSTAR:** Three-stage evolution of ELM was identified using a 2D imaging: (1) quasi-steady filamentary mode with long life time n=4-15, (2) abrupt structural transformation into filaments with irregular poloidal spacing near the onset of crash, (3) and multiple filament bursts during the crash. *(EX10-3, Yun)*

**Pegasus:** J-edge across single ELMs shows the nonlinear generation and expulsion of current-carrying filaments. *(EXP4-51, Bongard)*
Pedestal evolution during the ELM cycle

**JET:** Pedestal evolution during the ELM cycle: not always consistent with EPED (EX3-3, Maggi)

Low D2 Gas:
low-βN: Gradient increases and width constant: not consistent with KBM constraint

**ASDEX-U:** 70µs resolution Ti (r) measurement: At ELM, heat flux is first increased at the separatrix, then Ti(r) becomes flatter. $\chi_i$ comes back soon to its pre-ELM neoclassical level. (EXP6-30, Viezzer)

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**Graphs and Diagrams:**
- **Left Graph:** Average $dp_e/dV_N$ [kPa/\(V_N\)]
  - $\beta_n = 1.3$
  - $\beta_n = 2.8$

- **Right Graph:** $\Delta V^N$ [\(V_N\)]
  - $\beta_n = 1.9$
  - $\beta_n = 2.8$

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**Is J-edge expelled by an ELM crash?**

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**Illustrations:**
- **Top Left:** Illustration of EPED1.6 Model, DIII-D 132003
- **Top Right:** Comparison of modelled and measured $T_e$ [keV]
- **Bottom Left:** Pedestal Height vs Pedestal Width (\(\Lambda_{\nu N}\))
- **Bottom Right:** Pressure vs Height, minor radius vs Width

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**ASDEX-U:** D fueling shifts density profile outward, and T profile anchored at separatrix => causes a significant degradation of the pedestal top pressure. (EX3-5, Dunne)

**JET:** Pedestal stability improves with reduced radial shift. JET-ILW tends to have larger relative shift than JET-C. (EXP6-13, Giroud)
**L-H Transition Threshold Power**

**DIII-D:** Dual Mode Nature of Edge Turbulence May Explain Isotope and Density Scaling of L-H Power Threshold (EX5-1, Yan)

**JET:** Isotope Effect: Non-linear mass dependence on L-H power threshold (EX5-2, Hillesheim) PD, Nunes)

**Pegasus:** Ultralow-A
At low A (~1.2), \( P_{LH} \gg ITPA \) scaling by one order of magnitude. (OV5-4, Fonck)

**KSTAR:** \( P_{LH} \) increases with \( \delta B \) for any cases with \( n=1, n=2 \) or mixed-\( n \). (EXP4-4)
L-H transition: Behavior of turbulence

**JET:** Radial wavelength of Stationary Zonal Flows scales with the radial correlation length of turbulence, ~ several times smaller than the width of the edge radial electric field well. (EX5-2, Hillesheim)

**DIII-D:** The main-ion poloidal flow acceleration is quantitatively consistent with Reynolds-stress-driven shear flow amplification (EXP3-11, Schmitz)

**NSTX:** The energy exchange between flows and turbulence was analyzed using GPI. The edge fluctuation do not vary just prior to the H-transition. => Turbulence depletion is probably not the mechanism of the L-H transition in NSTX. (EX5-3, Diallo)

**ASDEX-U:** L-I Transition: Negligible contributions of ZFs. (EXP6-29, Putterich)
**ELM-free regimes: extended remarkably**

### I-mode

**Alcator C-mod:**
High energy confinement with Temperature pedestal, L-mode Density pedestal, Small impurity, Stationary and ELM-free. Extended to full field 8T and current 1.7MA. Confirms weak L-I threshold dep. on B, and wide power range at high B. *(EX3-1, Hubbard)*

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### QH-mode

**DIII-D:** Discovered Stationary Quiescent H-mode with Zero Net NBI Torque in double-null shaped plasmas, characterized by increased pedestal height & width: sustained for $12\tau_E$ with excellent confinement ($H98y2 \sim 1.5, \beta N \sim 2$). *(EX3-2, Chen)*

- Decreased edge $ExB$ shear enables destabilization of broadband turbulence
Pedestal fluctuations: variety of interplay

**EAST:** A new stationary small/no ELM H-mode was found at low $\nu e^* < 0.5$, $H98 \gtrsim 1.1$, exhibiting a low-n electro-Magnetic Coherent Mode. It appears at the low frequency boundary of TAE gap. (+ ELM pacing)(EX10-2, Xu)

**KSTAR:** Broadband turbulence induced by RMP damps the ELM amplitude (EXP4-15, Lee)

**HL-2A:** EM turbulence was excited by locally-accumulated impurities. Double critical gradients of impurity density were observed and reproduced by theoretical simulation. (OV4-4, Duan)

**HL-2A:** Synchronization of GAMs and magnetic fluctuations was observed in the edge plasmas. (EXP7-27, Yan)
Remaining Issue:
How is the Pedestal Width determined?

When pedestal grad-p is below Peeling-Ballooning limit, how does the pedestal width evolve and saturate?
During the ELM cycle? Controllable?
Success of RMP ELM Suppression = Phase and Shape

DIII-D: ELM control requires the applied field to couple to an edge stable MHD mode, directly observed on high field side. The response is inversely proportional to $\nu^*$. (EX1-2, Paz-Soldan) 
(AUG : EXP6-25, Willensdorfer MAST: peeling, OV5-3, Kirk )

KSTAR: Optimal phasing for n=1 RMP is consistent with an ideal plasma response modeling. (EX1-3, In)

ASDEX + DIII-D: ELM Suppression was obtained for the first time in AUG at low $\nu^*$ with a plasma shape matched to DIII-D ($\delta \sim 0.3$) showing the importance of stable edge kink response. (PD, Nazikian)

EAST: n=1 RMP, Plasma response behaves a nonlinear transition from mitigation to suppression of the ELMs (EXP7-4, Sun)
**DIII-D:** Fully Noninductive plasmas with high $\beta$ ($\leq 2.8\%$) and high confinement ($H \leq 1.4$) sustained for $\leq 2$ current relaxation with ECCD and NBCD, and integrated with ELM suppression by $n=3$ RMP; the strong resonant interaction allows ELM suppression over a wide range of $q_{95}$ (EX4-1, Petty)

**KSTAR:** $n=1$ RMP ELM suppression was sustained for more than $\sim 90$ $\tau_E$ ($H98=1.5$), and also confirmed to be compatible with rotating RMP, wide $q_{95}$ (4.75 – 5.25) (EX1-3, In), (PD, Jeon)

**EAST:** $n=1$ RMP ELM suppression in long-pulse (> 20s) was realized with small effect on plasma performance ($H98>1$) (P7-4, Sun)
Core Plasma Transport issues for ITER & DEMO

Te/Ti ~ 1 (<= electron heating (α, high energy NB, IC, ECH), high ne)
Electron Transport
Small rotation due to small external torque (=> intrinsic torque)
Small central fueling (high energy NB) => density profile?
Confinement performance with metal divertor can be recovered?
Accumulation of heavy impurity (metal wall)?
Isotope Effects on Confinement?
**Thermal Transport at high Te/Ti**

**DIII-D and JT-60U**: Positive Shear (PS) shows reduction in $T_i$ when ECH is added. Negative Central Shear (NCS) minimizes confinement degradation even with increasing $T_e/T_i \sim 1$. DIII-D shows smaller rise in low-k turbulent fluctuations in NCS than PS. *(EX8-1, Yoshida)*

**DIII-D / JT-60U**

$T_e/T_i \sim 1$

<table>
<thead>
<tr>
<th>Shear Type</th>
<th>Magnetic Shear</th>
<th>$\chi_i$ (High Te/Ti)</th>
<th>$\chi_i$ (Low Te/Ti)</th>
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<tbody>
<tr>
<td>DIII-D, PS</td>
<td>-2</td>
<td>1</td>
<td>1</td>
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<tr>
<td>JT-60U, PS</td>
<td>-1</td>
<td>0.5</td>
<td>0.5</td>
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<tr>
<td>JT-60U, NCS</td>
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<td>1.5</td>
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<tr>
<td>DIII-D, NCS</td>
<td>1</td>
<td>2</td>
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</tbody>
</table>

**DIII-D**

<table>
<thead>
<tr>
<th>Fluctuation Type</th>
<th>Magnetic Shear</th>
<th>$\Sigma \tilde{n}$ (High Te/Ti)</th>
<th>$\Sigma \tilde{n}$ (Low Te/Ti)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS</td>
<td>-2</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>NCS</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

**JET**: High Te/Ti plasmas: Electron transport evaluated with linear gyro-kinetic simulations GENE: most consistent with ( ITG/TEM) + ETG. => Multi-scale non-linear gyro-kinetic simulation underway. *(EXP6-14, Mantica)*

\[ \frac{R}{L_{Te}} = 8.5 \text{ to } 9.5 \]
**Electron thermal Transport**

**NSTX:** Electrostatic low-k Gyrokinetic Simulation (GTS) explains ion thermal transport, but is not able to explain electron transport. => high-k ETG / EM is important for electron transport. Nonlinear GYRO simulation explains grad-n stabilization of ETG, but not enough => EM? (EXP4-35, Ren)

**W-7X:** $T_e$ profile shape follows the ECRH Power deposition -> no indication of profile stiffness (EXP4-5, Hirsch)

**MAST:** Fluctuation measured at the top of pedestal is consistent with Electron transport evaluated with linear gyro-kinetic simulations GENE: consistent with ETG. (OV5-3, Kirk)

**MST:** Drift wave turbulence (TEM) emerges in RFP plasmas when global tearing instability is reduced by PPCD. (EXP5-17, Brower)
Density Profile => low $\nu^*$ ITER?

**JET:** Density peaks with decreasing $\nu^*$ => experimentally determined particle transport coefficients. => suggest that NBI fueling is the main contributor to the observed density peaking. (EXP6-12, Tala)

**DIII-D:** The density scale length R/Ln is well-correlated with the frequency of the dominant unstable mode, with the peaking when the turbulence switches from ITG to TEM. (EXP3-9, Mordijck)

**FTU:** The density profile evolution in high density regime has been well reproduced using a particle pinch term with dependence on temperature gradients ($U = DT/Te \partial Te/\partial r$) (EXP8-24, Tudisco)

**DIII-D:** Change in peaking is reproduced by changes in core fueling only. (EXP3-9, Mordijck)

**ISTTOK:** Edge electrode biasing improves particle confinement by reducing radial transport via ExB shear layer formation. (EXP7-36, Malaquias)
Confinement towards ITER: high $\beta_N$ is the key

**AUG, C-Mod, DIII-D, JET and JT-60U:**
Stationary H-mode discharges at $q_{95}=2.7-3.3$:
1) The maximum $H_{98}$ increases at lower $\nu^*$. 
2) $H_{98}$ increases with $\beta_N$, however for metal wall $H_{98}$ significantly reduced ($\sim0.8-0.9$) at $\beta_N\leq1.8$, $H_{98}\sim1$ is obtained only for $\beta_N\sim2$ or higher. (EX6-42, Sips)

**JET-ILW:** stationary (5s) ITER Baseline Operation at high-$\delta$ ($\sim0.4$) achieved at $2\text{MA}/2.2\text{T}$, $q_{95}=3.2$. New high-$\delta$ configuration optimized for pumping $H=1-1.1$, $\beta_N=1.8-2.1$ but $n/n_{GW}\sim0.5$ (EX/P6-11, De la Luna)
Avoidance of Heavy Impurity Accumulation ~ good

T-10: W / ECH
After ECRH start a fast decay of core radiation occurs. (EXP8-36, Nurgaliev)

ASDEX-U: Central ECH and ICRH to NB heated H-mode shows the impact of Qe/Qi on the impurity turbulent diffusion as predicted by Nonlinear gyrokinetic simulations with GKW (THP2-6, Angioni)

KSTAR: Ar / ECH (EXP4-18, Hong)

HL-2A: Al / ECH m/n=1/1 (EXP7-21, Cui)

JET: W / ICRF minority
Central ICRH is beneficial on tungsten transport in the ITER baseline scenario (EXP6-16, Goniche)

Alcator C-mod: W / ICRF minority (EXP3-3, Reinke)

ITER Prediction: No strong W accumulation expected in ITER Q = 10 plasmas due to low NBI fueling. W accumulation in H-L transitions can take place, optimization of heating and fueling ramp-down required. (PPC2-1, Loarte)
Impurity Transport in the helical system: rotation shear & turbulence drive

**LHD:** Carbon density profile peaks with decreasing Mach number ~ rotation gradient (EXP8-4, Nakamura).

**TJ-II:** Dual HIBP: ECRH enhances turbulence and amplitude of Long-Range-Correlations (LRC) for potential. (EXP7-44, Hidargo)
**Intrinsic Torque & NTV**

**DIII-D + JET**: The total intrinsic torque in the plasma is found to increase at lower $\rho^*$ (=favorable way to ITER).

(EX11-1 Grierson
EXP3-13 Degrassie)

**DIII-D**: Simulations with GTS gyro-kinetic code reproduces reversal of core intrinsic rotation (EX11-1 Grierson)

**Alcator C-mod**: Direction of core rotation changes in the following LHRF injection depends on the whether $q_0$ is below or above unity. (EXP3-2, Rice)

**KSTAR+NSTX**: Neoclassical Toroidal Viscosity (NTV) Torque: The measured rotation profile change due to the 3D field (EXP4-33, Sabbagh)
Confinement: Isotope Effects / Mass Dependence

**Heliotron-J:** The turbulence scale size increases as D2 gas becomes dominant. = The first evidence for the isotope effect on turbulence-zonal flow system in helical systems. *(EXP8-20: Ohshima)*

**RFX-mod:** 3D RFP Confinement is better for D than H *(OVP-2, Zuin)*
**Improved Confinement Performance: ITB**

**DIII-D:** Large radius ITB and excellent confinement due to Shafranov Shift Stabilization. *(EX4-2, Qian)*

**LHD:** High $T_i$ & $T_e > 6$ keV were simultaneously achieved by high power ECH injected into NB heated plasmas characterized by simultaneous formation of electron and ion ITBs. *(PPC1-1, Takahashi)*

**HL-2A:** Ion ITB was observed at the $q=1$ surface. ITG is suppressed by the toroidal rotation shear. *(EX8-2, Yu)*
Transport hysteresis & non-localness

Multiple Machine: Transport hysteresis in core plasmas is widely observed.

The core hysteresis involves two elements:
1. Interaction at long distance
2. Direct influence of heating on transport/fluctuations

=> ‘The heating heats turbulence’ (OVP-8, Itoh)

Modulation ECH: Difference between results from the inward pulse and the outward pulse becomes larger as the harmonic number increases (EXP8-15, Kobayashi)

KSTAR: The non local transport (NLT) can be affected by ECH, and the intrinsic rotation direction follows the changes of NLT. (EXP4-17, Shi)
Effects of 3D field on equilibrium & stability

**DIII-D & RFX-mod**: Role of MHD dynamo in the formation of 3D equilibria.

**High-β tokamak**: The MHD dynamo model predicts current redistribution consistent with DIII-D experiments (EX1-1, Piovesan)

**LHD**: Phase shifted magnetic islands from externally imposed m/n = 1/1 RMP was observed (EXP8-8, Narushima)

**J-TEXT**: RMP increases the density limit from less than 0.7nG to 0.85nG and lowers the limit of the edge safety factor from 2.15 to 2.0. (OVP-6, Zhuang)

**EXTRAP T2R**: The resonant MP produces tearing mode braking and locking consistent with the prediction. (EXP5-18, Frassinetti)
Sawtooth, high $\beta$ stability

**KSTAR:** validated $q_0>1$ after sawtooth crash: tearing mode evolve (e.g. 3/3 to 2/2, 1/1) (EXP4-3, Park, EXP4-27, Ko)

**LHD:** Central $\beta$ of the super dense core plasma is limited by "core density collapse" (CDC). A new type of ballooning mode destabilized from the 3D nature is the cause of the CDC. (EXP8-10, Ohdachi)

**RELAX:** The discharge duration is limited (RWM). The central $\beta_p \sim 15\%$ was achieved in the Quasi-Single Helicity (QSH) state. (EXP5-22, Masamune)
Alcator C-mod & EAST: Developing Disruption Warning Algorithms Using Large Databases. (EXP3-8, Granetz)

NSTX: Disruption Event Characterization and Forecasting (DECAF) code has the potential to track RWM stability in real-time for disruption avoidance. (Berkery, EX/P4-34)

ADITYA: The current quench time is inversely proportional to q-edge. (Tanna, OV/4-3Rb)
Expanded High $\beta$ Regimes

**LHD:** High-\(\beta\) ~ 4% was produced by multi-pellet injections at low \(\nu^*\). Improved particle confinement was observed during a high-beta discharge produced by gas-puff. (EX4-4, Sakakibara)

**KSTAR:** High $\beta_N$, up to 4.3 was achieved with high ratios of $\beta_N/l_i$ up to 6.3. High $\beta_N$ ~ 3.3 was sustained for 3 s, and was limited by a 2/1 tearing mode. (EXP4-2, Park)

**PEGASUS:** With Local Helicity Injection (LHI), $\beta t$~100% was achieved, often terminated by disruption (n=1) (OV5-4, Fonck)
**Operation: Plasma Current Rump-up → ITER & DEMO**

**MAST:** In $I_p$ ramp-up, the real current diffusion is slower than TRANSP. But, it is well modeled during $I_p$ flat top. *(OV5-3, Kirk)*

**DIII-D:** There are strong interactions between $T_e$, fluctuation, thermal transport, safety factor, and low-order rational surfaces. *(EXP3-10, McKee)*

**JA-DEMO:** Reduction of CS flux consumption at $I_p$ ramp-up *(EX/P8-38, Wakatsuki)*

*By optimization of both $T_e$ and $q$ profiles, ~20% reduction of flux consumption is possible.*

Improved modeling is needed for DEMO design

=> CS size = economy of DEMO
Control of ITER & SC tokamak operation

For ITER Plasmas Control system (PCS)
• Preliminary design of the ITER PCS focusing on the needs for 1st and early plasmas. (EXP6-36, Snipes)

• Control analysis and design tools developed at DIII-D have been applied in studies supporting the ITER PCS design. (EXP6-37, Humphreys)

Real-time Error Field Correction:
Varies correction field amplitude phase to maximize plasma rotation

• Generation of the disruption mitigation. (EXP6-38, Pautasso)

KSTAR: Extending vertical stabilization controllability (EXP4-12, Hahn)

KSTAR: Trapped Particle Configuration for EC plasma breakdown (EXP4-14, Lee)

TCV: EC wall conditioning for JT-60SA (EXP8-31, Douai)
Advanced control

DIII-D: demonstrated Adaptive Real-Time Pedestal Control with RMP by real time stability evaluation (EXP3-21, Kolemen)

DIII-D: Physics-model-based q-profile Feedback Control (EXP3-23, Schuster)

KSTAR: Physics-Based Profile Control (EX/P4-13, Kim)

Realtime tokamak simulation with a first-principle-based neural network turbulent transport model (EX/P6-45, Citrin)

NSTX-U: Feedback Control Using TRANSP for Non-inductive Scenarios (EX/P4-43, Boyer)

TCV, ASDEX-U & ITER: Real-time model-based plasma state estimation (EX/P8-33, Felici)

TCV: Beta is estimated by model-based and controlled with two gyrotrons to follow Ref.

STOR-M: Toroidal Flow was modified through Momentum Injection by CT Injection (EXP7-39, Xiao)

FT-2: Improved Core Confinement Observed with LHCD (EXP7-41, Lashku)
ASDEX-U: Fully non-inductive operation with W wall at \( I_p = 0.8 \) MA (40% NBCD, 50% bootstrap, 10% ECCD). ECCD is used to tailor current profile for optimum stability and \( q_{\text{min}} > 1.5 \) (PD, Stober)

KSTAR: Fully non-inductive current drive with \( fBS < 0.5 \), \( \beta_p > 3 \), \( \beta_N \sim 2 \), H89 ~ 2.0 with NBCD & ECCD (\( I_p=0.45\)MA) (EXP4-1, Yoon)

EAST: 60sec H-mode
Demonstration of full-CD (LHCD, ECCD, ICRRF) with W wall, \( \beta_p \sim 1.1 \); \( q_{95} \sim 6.3 \), \( t/\tau R \sim 15 \), H98>1.1. (EX4-3, Garofalo)
New Tokamak World Record of volume averaged pressure 2.05 atm was achieved in Alcator C-mod
Summary: EXC, EXS and PPC

'3D' has become more common language and tool.

Understanding of H-mode & ELMs, and practical control scenarios have been progressed toward ITER.

( such as, wide applicability & steady-state ELM mitigation by RMP, understanding of confinement with W-divertor )

Transport / turbulence / instabilities are reproduced well by simulations

Encouragements towards next FEC

Width of the H-mode pedestal
Electron Transport / multiple scale transport
Disruption Prediction
Enhanced Effort towards SS tokamak operation