Summary:
Innovative Confinement Concepts, Operational Scenarios and Confinement

23rd IAEA Fusion Energy Conference

R. J. Hawryluk
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Innovative Confinement Concepts
Stimulate New Ideas

Address a broad range of configurations and topics:

- Levitated Dipole
- Field Revered Configuration
- Mirror machines
  - Spheromaks
  - Helical-tokamak hybrid
  - Magneto-inertial fusion
  - Direct energy conversion
Levitated Dipoles (LDX and RT-1) Demonstrate Inward Turbulent Pinch and Validates Flux Expansion Concept

Profile shape remains unchanged near \( nV = \) constant while source term is modulated.

Error field optimized RT-1 plasma achieved peak 70% beta (H. Saitoh, EXC/9-4b).
FRC Decay Time Increased by Neutral Beam Injection Suggesting MHD Stabilization

M. Inomoto ICC/P7-01
Increased Heating Power Extended Mirror Machine Performance

GDT achieved 60% beta and reached ballooning limit

In Gamma10, ECH reduced fluctuations and inferred radial particle flux.

E. P. Kruglyakov, OV/P-6

M. Yoshikawa, EXC/P8-21
Outline

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Sustainment of Super-Dense Core by Pellet Injection and Internal Diffusion Barrier in LHD

- Diffusion in edge mantle much greater than in the core.
  - Enhanced by the application of resonant magnetic field perturbations
- Impurity accumulation in the core avoided.
- LHD has also attained 15keV peak electron temperatures in plasmas with electron ITB (H. Takahashi, EXC/P8-15)
Operational Challenges of Superconducting Tokamaks Successfully Being Met by KSTAR and EAST

- **Wall conditioning**: ICRF conditioning, HF GDC, Li Wall Coatings (EAST OV1-2)
  - Also on Tore Supra (D. Douai, FTP/P1-26)
- **Low voltage startup (0.9MA EAST OV/1-2, 0.5MA KSTAR OV/1-1)**
  - ECH assisted startup (also FTU, A. Tuccillo, OV/4-2)
  - Lower hybrid assisted current ramp (also, E. Marmar, OV/3-2)
- **Magnetic material and eddy current compensation for discharge evolution on KSTAR. (S. W. Yoon, EX/5-1)**
Progress Developing ITER 15MA Startup and Shutdown Scenarios

- JET 4.5MA operation reestablished
- Active ELM moderation required about 3.5MA to prevent carbon ablation.
  - Modest impact on $\tau_E$
- Successful startup and shutdown techniques for ITER demonstrated on JET, DIII-D, and C-Mod
  - See A. C. C. Sips, EXC/P2-08,
    J. R. Wilson, EXC/P2-02,
    G. L. Jackson, EXS/P2-11

I. Nunes, ECX/P8-03
Impurity Seeding Successfully Reduced Divertor Heat Flux

- Improvement in $\tau_E$ obtained in AUG
  - Critical for operation with tungsten divertor.

- JET and C-Mod obtained similar reductions in heat load and operational benefits but did not obtain an improvement in $\tau_E$.
  - See C. Giroud, EXC/P3-2 and J. Hughes, EXC/P3-6
Threshold Power Required for Transition from L to H-mode Has Been Better Characterized for ITER

- $P_{LH}$ compared for He with D for ITER non-nuclear phase:
  - Threshold is density dependent (DIII-D, EXC/2-4Ra and JET, EXC/2-4Rb)
  - In NSTX, $P_{LH}$ is 20 to 40% greater (NSTX, EXC/2-3Rb)
- Low $n$ perturbation increase $P_{LH}$ by 50% (NSTX, EXC/2-3Rb) and 80% (MAST, EXC/2-3Ra)
- $P_{LH}$ significantly increased in DIII-D due to RMP perturbations above a threshold level,
  - Smaller change for non-resonant fields
  - No significant change in DIII-D test blanket simulation. (M. J. Schaffer, ITR/1-3)
Recycling Conditions Have a Large Impact on L to H Power Threshold

Lithium decreases $P_{\text{LH}}$ (NSTX)

Low triangularity decreases $P_{\text{LH}}$ (NSTX)

Depends on height of the x-point (MAST, DIII-D, P. Gohil, EXC/2-4Ra)

Too many hidden variables remain unaccounted for in $P_{\text{LH}}$ scaling.
Advanced Inductive Scenarios Are Potentially Attractive Long Duration Discharges in ITER

- Advanced inductive discharges operate at lower current enabling longer duration discharges.

- Recent JET experiments, by ramping the current down prior to main heating phase achieved $H_{98} \sim 1.3$.
  - Significantly improved relative to earlier data.

- Further work is planned on $\rho^*$ and $\nu^*$ scaling to improve the extrapolation to ITER:
  - Bohm $\rho^*$ scaling between JET and DIII-D
  - Current penetration mechanism

E. Joffrin, EX/1-1
T.C. Luce, ITR/1-5
QH-mode and I-mode Offer the Possibility of ELM Suppressed Operation

- NTV provides ExB shear to maintain QH-mode even after NBI torque ramped to zero using non-resonant fields. (A. Garofalo, EXS/1-2).
- I-mode usually accessed by operating in unfavorable B×∇B direction (away from active X-point) D. Whyte, EX/1-3
- Can these scenarios be used on ITER?
Lithium Improves Energy Confinement and Widens the Operating Window in a Number of Devices

- FTU, NSTX and TJ-II have obtained up to ~50\% $\tau_E$ enhancements
  - FTU obtained peaked profiles with $n_e$ up to $\sim 1.6 \, n_e^{GW}$ at high $q$.
  - TJ-II obtained more peaked density profiles
  - NSTX combined lithium with EP H-mode to achieve $H_{98} \sim 1.8$
RFX and MST Have Extended Their Operating Regimes

RFX observed linear increase in $T_e$ with $I_p$.

MST attained $\tau_E = 12$ ms by current profile control.
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Subtle Differences in Electron Transport and NBI Sources Lead to Different Reversed Shear States in JET and JT-60U

• Good match in dimensionless parameters except:
  – Mach number
  – Differences in $\nu^*$ and $\beta$ due to density profile.

• Density profile peakedness in JT-60U enables a higher bootstrap current fraction.

• Need good predictive model to extrapolate to ITER.

X. Litaudon, EXC/P4-12
Influence of Collisionality on Turbulence Spectra Studied in Tore Supra

• Dimensionless scans were conducted to determine the effect of $\nu^*$
• Does not support standard explanation on effect of $\nu^*$ on zonal flows.
Experimental Test of Predicted Turbulence Amplitudes and Cross-Phases Conducted in the Core

As $T_e/T_i$ increases with the addition of ECH to an NBI heated L-mode...

DIII-D

$\rho = 0.6$

- NBI only $T_e \approx T_i$
- NBI+ECH $T_e > T_i$

- GYRO reproduces many features in the core but not in the edge ($\rho > 0.75$) or the core of L-mode discharges.
  - Experiments used to establish the range of validity of the codes.

T. L. Rhodes, EXC/7-2
Density Profile Peaking is Reproduced by Gyrokinetic Modelling (at $r/a=0.5$)

- Central density increases with the application of ECH to NBI heated plasmas.
  - Flattens the ion temperature and rotation profile
- In simulations the measured profiles are used as input.
- Results are sensitive to input parameters (e.g. $T_e/T_i$, $R/L_{Te}$, $\nu_{ei}$)
Initial DIII-D Measurements Near Top of the Pedestal Indicate Non-axisymmetric Fields Modify Density Turbulence

- Increased particle transport also occurs outside of ELM suppression window.
Long Coherence Length Temperature Fluctuations
Found in LHD

Radial correlation length ~ a
Ballistic transport from core to the edge inferred
Impact of long-range fluctuations on transient particle transport was studied.

Is this the long sought explanation for cold pulse propagation or non-local transport?
“Impurity Holes” Observed in LHD in Discharges with Large $T_i$ Gradients

- Large anomalous outward convective impurity transport inferred.
  - In spite of negative $E_r$
Momentum Transport Studies Show No Dependence on Collisionality of Either Prandtl or Pinch Numbers

\[ mR \frac{\partial nV_\phi}{\partial t} = \sum \eta - \nabla \cdot \left( -mnR \left( \chi_\phi \frac{\partial V_\phi}{\partial r} - V_\phi \frac{V_{\text{pinch}}}{\text{diffusion}} \right) + \Pi_{RS} \right) - \frac{mnR (V_\phi - V_\phi^*)}{\tau_{\text{damp}}} + \left( \tilde{J} \times \tilde{B} \right) + \ldots \]

Rate of change of angular momentum
Input torque

\[ \chi_\phi \frac{\partial V_\phi}{\partial r} \]
Diffusion

\[ V_\phi \frac{V_{\text{pinch}}}{\text{pinch}} \]
Residual stress "Intrinsic source"

Neoclassical viscous drag
Maxwell stress

JET experimental data is compared with GS2 calculations in red.

T. Tala, EXC/3-1
Edge Intrinsic Rotation Appears to Be Driven by Pedestal Gradients

- Suggestive that turbulent residual stress may be key in generating intrinsic rotation (DIII-D, C-Mod, LHD, JT-60U, …)
- Reynolds stress sufficient to account for intrinsic rotation in CSDX at UCSD, but not on DIII-D.

W. Solomon, EXC/3-5

J. Rice, EXC/3-3
Intrinsic Drive in the Core Can Also Influence Rotation Shear

- ITBs with strong pressure gradients (JT-60U)
- Other residual stress drive, including effect of ECH observed on DIII-D.

M. Yoshida, EXC/3-2
W. Solomon, EXC/3-5
Core MHD Can Also Modify Rotation Profile

- Rotation profile in TCV modified by sawteeth crash.
- Detailed measurements of Maxwell stress in MST following a sawtooth event in agreement with flux induced flow.
- Extrapolation to ITER remains to be established.
The L-H transition appears more correlated with the development of fluctuating flows than mean shear $E_r$ effects.

- TJ-II as well as MAST (H. Meyer, EXC/2-3Ra) and NSTX (S. Kaye, EXC/2-3Rb) reported no significant change in mean shear prior to transition.

Doppler reflectometry enables local measurements of oscillating radial flows.
Time Evolution of Flows and Turbulence in a Slow Transition to H-Mode Indicates a Predator-Prey Behavior

Is this a high frequency dithering H-mode?

T. Estrada, EXC/P3-01
Are GAM’s the Missing Link During the Intermediate Phase Prior to Transition to H-mode?

- Is the AUG I(termediate)-phase related to the C-Mod I-mode?
What Are the Role of Zonal Flows?

Probe measurements in the edge (near LCFS) of HL-2A indicate that GAMs are dominant:
- Further inside GAMs and Zonal Flows coexist.
- Also see Y. Xu, EXC/9-3

To fully understand the dynamics of the turbulence in the edge leading to an L to H transition would want to measure the spatial evolution of turbulent structures.

K. J. Zhao, EXC/7-3
Detailed tests of EPED Model and Peeling/Ballooning Paradigm in Progress

- **EPED 1.6 works well for range of devices**
  - High frequency coherent modes during QH-mode looks like KBM in DIII-D (Z. Yan, EXC/P3-5)
- **Pressure gradients saturate at least \( \frac{1}{2} \) way thru ELM cycle in AUG**
  - edge current diffusion calculations suggest \( j_{BS} \) equilibrates rapidly
    - What kicks off the next ELM? (B. Kurzan, EXC/P3-3)
- **MAST plasma can stay above ballooning boundary for \( \sim10\text{ms before ELM} \)**
  - New MSE measurements of bootstrap current compared with neoclassical model
ELM Mitigation Results in Loss of Density and/or Confinement

- Good confinement during ELM mitigation (unfuelled) $\rightarrow H_{98} \sim 1.1$ but density reduced by 20%

- Density can be restored by gas fuelling but confinement decreases.

- Ultimately may have to reduce ITER performance to avoid ELM damage to divertor tiles.
Congratulations on Excellent Progress!

Results presented at the 23rd FEC meeting are significant contributions to the success of ITER and W7-X.