Innovative Confinement Concepts, Waves and Energetic Particles
SOL and Divertor Research

26th IAEA Fusion Energy Conference

By David N. Hill

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October 22, 2016
Significant Advances for ITER Operation and Fusion Energy Reported During This Meeting

• ICC (16 papers)
  ST, FRC, Spheromak, Pinch

• EX-W (56 papers)
  Wave-plasma interactions, current drive & heating, and EPs

• EX-D (61 Papers)
  Plasma-material interactions, divertors, limiters, and SOL
Novel approaches to fusion are progressing

**Spheromak**
HIT-SI (Washington) demonstrates sustainment of spheromak plasmas with oscillating injector

**Z-Pinch**
ZaP-HD (Washington)
Significant Z-pinch shear-flow stabilization observed: modeling points toward sustained, stable Z-pinch configurations

T. Jarboe, EX/P3-33
A. Hossack, EX/P3-42
U. Shumlak, EX/P3-32
Field-Reversed Configuration Sustained via 10 MW Neutral-Beam Injection on the C-2U Device

- **Upgraded C-2U device**
- **Advanced beam-driven FRC state produced via ~10 MW NBI**
- **Key FRC plasma parameters (e.g. radius & $T_e$) were sustained for >5 ms**
- **Significant improvement in transport and confinement**

![C-2U Device at Tri Alpha Energy](image)

Time evolutions of normalized plasma radius & electron temperature in C-2 / C-2U experiments

H. Gota, EX/P3-41
T. Asai, EX/P3-37
Small-scale Spherical Tokamak Experiments Address Non-solenoidal Startup and Sustainment

Pegasus

Localized helicity injection (also: $\beta \rightarrow 1$ in high normalized current regime)

HIST

Coaxial Helicity Injection

TST-2

DC current drive by AC Ohmic operation

Startup using CCC antennae

• 400 kA generated by merging compression in MAST

R. Fonck, OV/5-4
Y. Takase, OV/5-5
EX-W: Wave-Plasma Interactions, H&CD, Energetic Particles (> 50 papers)

- **Wave-particle interactions, Heating and Current Drive**
  - Electron Cyclotron and EBW
  - LHCD: high density operation and edge coupling
  - ICRF: better reactor-relevant schemes and antenna design

- **Energetic Particle Transport**
  - Multimode effects result in stiff fast-ion transport
  - Progress in understanding instability drives
  - Current and Fast Ion profiles strongly effect the fast ion losses

- **Significant Progress on Runaway Electron Mitigation**
  - Recent/planned shattered pellet experiments (ITER baseline mitigation) address key issues
  - Expanding studies of Runaway Electrons to provide physics basis for control
Modeling Advances Facilitate Optimized Applications Using Electron Cyclotron Waves

- High T plasma achieved on LHD with optimized aiming through upgraded ray-tracing code.

- NTM stabilization sensitive to beam broadening by edge fluctuations.

- EC modeling matches measured scattering by edge turbulence: important first step

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**Measurement**

**Modeling**

![TCV data – TORPEX simulation](image)

**LHD**

- $T_e, T_i \text{ (keV)}$
- $r_{\text{eff}} / a_{99}$
- $n_e \text{ (} \times 10^{19} \text{ m}^{-3} \text{)}$
- $r_{\text{eff}} / a_{99}$

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Tsujimura, EX/P8-2
Goodman, EX/P8-28
Heating of Overdense Plasmas by Electron Bernstein Waves Is Effective in Low $|B|$ Devices

- Non-inductive startup achieved via O to X to Bernstein mode conversion: > 6x cut-off.

**QUEST tokamak**

- Non-inductive startup and current sustainment achieved with dual frequency (8.2/28 GHz) injection

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**Diagram:**

- Graph (a) shows the pinj (kW) andPref (kW) over time, with a peak at 270 kW.
- Graph (b) displays the lp (kA) and Bv (G) over time with a peak at ~60 G.
- Graph (c) illustrates the $R_d$ (m) and $\beta_p$ over time, with a peak at $\beta_p = 20$.
- Graph (d) shows the $f_n$ $d_l$ ($R_T = 0.12m$) $\left(10^{17} \text{ m}^{-2}\right)$ over time, with a peak at ~6 $n_c$.
Improved Understanding of LHCD Efficiency Increases Confidence in Application to ITER

- **LHCD applied on conventional, superconducting & spherical tokamaks**
  - C-Mod: Edge absorption studies
  - EAST: efficiency vs. frequency
  - FT-2: Parametric decay
  - HL-2A: Passive-active multijunction launcher
  - TST-2: LH startup

- **Wave physics organized and understood by $f_{pe}/f_{ce}$**

- **All experiments observe loss of current drive at sufficiently high density**
  - Parametric instabilities
  - Collisional absorption
  - Scattering from density fluctuations

Contours of Constant $f_{pe}/f_{ce}$

Density ($1/m^3$)

Magnetic Field (T)
Coupling of High Harmonic Fast Waves Presents Significant Challenges

• Significant power can be coupled directly to divertor: may be explained by strong RF fields in SOL plus rectification in the divertor

• High-harmonic fast wave coupling also explored in conventional tokamaks as potential current drive scheme (DIII-D, KSTAR)

Perkins EX/P4-42
Pinsker EX/P3-22, Oh OV2-4
Three-Ion ICRF Absorption Scheme Shown to Provide Effective Heating

- ~50% more efficient than D(He$^3$) in C-Mod
- Potential ITER applications:
  - mimic fusion-born alphas in non-active phase
  - Use during D-T operation with Be

![Graphs showing energy and electron temperature changes](image)

Wright P3-5, Litaudon OV1-3, Ongen P5-12
Improved Antenna Design Mitigates Impurity Generation with ICRF

AUG: 3-strap antenna designed to reduce rf interaction at the antenna reduces W input

- IShTAR: linear facility characterizing ICRF antenna-plasma interactions

Noterdaeme P6-26
Crombe P6-48
Significant Fast Ion Transport & Losses Result From Interplay of Energetic Particle Driven Modes

- JET shows chain of energetic particle transport:\n  \( \text{TAE} \rightarrow \text{sawtooth} \rightarrow \text{fast ion losses} \)

Interplay of Sawteeth and AEs in JET

- TAEs reduce fast ions
- Leads to sawtooth crash

EAEs

TAEs reduce fast ions

Leads to sawtooth crash

Time (s)

f (kHz)
Significant Fast Ion Transport & Losses Result From Interplay of Energetic Particle Driven Modes

- JET shows chain of energetic particle transport\(^1\):
  \[ \text{TAE} \rightarrow \text{sawtooth} \rightarrow \text{fast ion losses} \]

- DIII-D finds critical gradient behavior as multiple FI modes overlap\(^2\)

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1 Sharapov EX/P6-8
2 Collins EX/P6-2
Key Progress in Understanding Drives and Influences of Energetic Particle Instabilities

- DIII-D: Higher $T_e$ closes resonance window for Reverse Shear AEs\(^1\)
Key Progress in Understanding Drives and Influences of Energetic Particle Instabilities

- DIII-D: Higher $T_e$ closes resonance window for Reverse Shear AE$s^1$

- LHD: EGAM observed to drive intense GAM via nonlinear

GAM drives zonal flow and may alter transport
Energetic Particle & Current Distributions Are Central to Understanding and Control of Fast Ion Losses

- New off axis beam in NSTX-U reduces fast ion gradient to stabilize GAE\textsuperscript{1,2}
  - Validates HYM code predictions

- Heliotron-J: ECCD alters magnetic shear to stabilize GAE activity\textsuperscript{3}

1 Fredrickson EX/P4-4
2 Gorelenkov Postdeadline
3 Nagasaki EX/P8-19
Promising Runaway Electron Dissipation Techniques Developed on DIII-D and HL-2A

- **DIII-D: Neon Shattered Pellet Injection** results in significant dissipation\(^1\)
  - Dissipation depends on impurity species, but not strongly on injection technique

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- **HL-2A**: Supersonic Molecular Beam scatters REs by MHD oscillations\(^2\)

\[\text{MGI (Ar) SMBI (He)}\]

\[\text{92\% Ne / 8\% D}_2\]

2. Liu, et al. EX/9-3
Newly developed scenarios for reliable RE generation on AUG and TCV\(^1\)

- **AUG**: Increased MGI quantity increases RE dissipation
  - LFS vs. HFS injection identical

- **TCV**: Full conversion of pre-TQ Ohmic current into RE current

1. Martin, et al. EX/P6-23
2. Papp, et al. EX/9-4
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- **AUG**: Applying pre-TQ \(n=1\) RMP field inhibits RE generation\(^2\)

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1. Martin, et al. EX/P6-23  
2. Papp, et al. EX/9-4
Runaway Physics and Control Progressing Worldwide

- Control of beam will be necessary for controlled dissipation
  - FTU: $I_p/V_{loop}$ control achieved, spectrum studied
- Characterization of distribution function is enabling validation
  - FT-2: DeGaSum deployed to understand HXR emission from Res
  - DIII-D: Gamma ray imaging resolves spatial distribution
- Important role of MHD being investigated in RE seed formation
  - Compass: Filamentary structure underlines MHD role

Images from wide-angle real color fast camera, COMPASS

$t_{puff} + 1\text{ms}$
$t_{puff} + 3\text{ms}$
$t_{puff} + 4\text{ms}$

1. Esposito EX/P8-27
2. Carnevale EX/P8-22
3. Shevelev EX/P7-42
4. Mylnar EX/P6-34
Disruption experiments show path to control thermal and vessel forces with high-Z mitigation

- JET system can reduce both radiation asymmetry and vessel forces

**JET Asymmetry Mitigation with timing**

**Vertical Force Mitigation**

1. Joffrin EX/9-1
2. Commaux EX/9-2
Disruption experiments show path to control thermal and vessel forces with high-Z mitigation

- JET system can reduce both radiation asymmetry and vessel forces
- Shattered pellet injection allows tuning of disruption properties

1. Joffrin EX/9-1
2. Commaux EX/9-2
Disruption mitigation found to remain effective despite pre-existing MHD modes

- Disruption loads equally mitigated with or without MHD modes
  - Also observed on DIII-D

Conclusions obtained from healthy plasmas are still applicable to ITER
EX-D: ELMs, Divertors, Materials (> 60 papers)

- ELMs and their Control
  - ELM suppression
  - 3D effects on the boundary
  - ELM heat flux

- Divertor Heat Flux
  - Edge transport
  - Divertor detachment and control
  - Core-edge integration

- Plasma Facing Components
  - Tungsten operation experience
  - Fuel retention in Be/W
  - Alternative PFCs
New Understanding of Plasma Response Extends RMP ELM Suppression to Full W Wall and Long Pulse

- DIII-D: resonant field amplification at low collisionality $v_e^*$ yields suppression

![Graph showing ELM suppression at low $v$](image)

$HFS$ Response $(G)$

$0$ $0.5$ $1.0$ $1.5$ $2.0$

$0$ $90$ $180$ $270$ $360$

$applied n=2$ spectrum ($\Delta\phi_{UL}$)

Paz-Soldan, EX/1-2  
Y.-K. Oh, OV/2-4  
Y. Sun, EX/P4-7  
Kallenbach, OV/2-1  
B. Wan, OV/2-2  
Nazikian PD/1-2
New Understanding of Plasma Response Extends RMP ELM Suppression to Full W Wall and Long Pulse

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- **ASDEX-Upgrade** obtained full ELM suppression with full W wall matching DIII-D collisionality and shape

  Demonstrates reliability for extrapolation towards ITER

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Y.-K. Oh, OV/2-4
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  ▶ Demonstrates reliability for extrapolation towards ITER

- Full RMP ELM suppression was obtained for $>10s$ at **KSTAR** and $\sim 20\ s$ at low rotation on **EAST**
3D Divertor Fluxes Can be Controlled and Mitigated by Density and Applied RMP Spectrum

- **ASDEX-Upgrade**: Striated heat flux pattern vanishes with density increase.

- **DIII-D**: 3-D temperature lobes and inter-ELM heat flux striation vanish at detachment transition.

- **KSTAR**: Link between plasma response and strike line striation was demonstrated.

J.-W. Ahn, EX/P4-30  B. Sieglin, EX/7-3 Ra  A. Briesemeister, EX/7-3 Rb
Alternative Approaches to ELM Control Are Being Developed

- **EAST:** Lower hybrid used to pace ELMS and reduce peak heat flux

- **EAST:** New “no-ELM” regime with steady LH heating observed at low $v^*$, with new EM continuous mode

- **DIII-D**ITER baseline: D2 pellets or Li granules pace ELMs but heat flux reduction not observed at constant $v^*$
New ELM Divertor heat flux Scaling Projects to smaller ELMs in ITER

- Peak ELM heat load proportional to machine size and pedestal pressure
- Projection for ITER significantly lower than previous estimates (10x reduction)
- ELM simulation with JOREK reproduces empirical scaling

\[
\frac{\varepsilon_{\parallel}}{\epsilon} (\text{MJ/m}^2) \propto R^{1.0} n_{e,ped}^{0.75} T_{e,ped}^{0.98} (\frac{W}{W})^{0.5}
\]
Measured PFC temperature profile shapes agree qualitatively with modeled heat flux in helical scrape-off layer of Wendelstein 7-X

- Highest heat flux for longest connection length
- Lowest heat flux at tangency points

[ F. Effenberg, EX/P5-Th/P6-11 ]
[ G. Wurden, EX/P5-S. Boszhenkov, EX/P5-11 ]
Kinetic Simulation With Turbulence Predicts Broader Divertor Heat Flux Profile for ITER

Divertor Heat Flux

- XGC1: Kinetic code reproduces ITPA heat flux width scaling
- Size scaling of electron turbulence expected to broaden heat flux in ITER
New 2d Measurements Show Importance of Drifts On Asymmetries and Detachment Threshold

- $\nabla B$ drift into divertor: Asymmetric $T_e$, $n_e$ and detachment

- Major features are reproduced in models when drifts are included
New 2d Measurements Show Importance of Drifts On Asymmetries and Detachment Threshold

- $\nabla B$ drift into divertor: Asymmetric $T_e$, $n_e$ and detachment
- $\nabla B$ drift out of divertor: Symmetric $T_e$, $n_e$ and detachment

- Major features are reproduced in models when drifts are included
Flexible Shaping Exploited to Test Impact of Divertor Geometry on Detachment

- Detachment onset measured with $R_{maj}$, flux expansion, $L_{||}$ and flaring variations
- Access to deep detachment without X-point degradation in X- and Super-X divertor
- Large database for 2D model validation

[Diagrams and images showing different configurations and parameters]
New Real-time Divertor Measurements Increase Options for Heat Flux Control

- **C-Mod**: Real-time measurement of divertor heat flux and controlled by nitrogen injection
- **DIII-D**: Direct measurement of divertor $T_e$ by Thomson scattering
- **AUG**: Nitrogen seeding more effective than neon due to higher divertor compression

A remaining issue is control of fast divertor transients by slower gas puff and recycling response

Bruner EX/P3-7  Reimold EX/P6-22  Eldon EX/P3-29
Impact of Boundary Plasma Conditions on Pedestal Performance Is Being Quantified

- **AUG**: N seeding leads to improved pedestal temperature
- **C-Mod**: Balanced DND exhibits steep profiles and good impurity screening on the high-field side, favorable for inside launch hardware
- **DIII-D**: D₂ gas puffing at high power improves pedestal stability and confinement in DND hybrid plasmas
- **NSTX**: Edge electron particle and thermal diffusivity drop by >95% and 80% respectively in high triangularity, high elongation lithium enhanced NSTX H-modes

Kallenbach, OV/2-1  Petrie, EX/P3-27
Dunne, EX/3-5  Maingi, EX/P4-38
LaBombard, EX/P3-6
Alternative PFCs for Fusion May Include Liquid Lithium and Tin

**Lithium:**
- Operation with liquid Li/W limiters in T-10 led to strong suppression of W accumulation in the plasma center
- Lithium vapor in equilibrium with $600\degree C$ liquid in CPS can detach DEMO divertor, with modest Li efflux

**Tin:**
- Corrosion-compatibility of liquid Sn with Mo and W was demonstrated at temperatures up to $1000\degree C$.
- The new Tin cooled liquid limiter has been installed on FTU and first experiments will start in Autumn 2016
AUG “Massive W Divertor” Showed Cracking After Operation, Little Change in Surface Morphology

- Cracks normal to B-field.
- FEM calculations: vertical tile cuts may avoid cracks
- He exposure to pre-treated nanostructure surface shows only smooth overcoat layer

Progress on structural material R&D, but higher ductility tungsten remains challenging
JET-ILW Hydrogenic Retention Studies Are Advancing Predictive Capability and Wall Designs

- Hydrogenic retention reduced more than an order of magnitude
- Well reproduced by models

[Schmid et al. NF 2015]
JET-ILW Hydrogenic Retention Studies Are Advancing Predictive Capability and Wall Designs

- Hydrogenic retention reduced more than an order of magnitude
- Well reproduced by models
- Fuel retention in Be castellation gaps show Low contribution (3%) to global fuel inventory
- High fraction of co-deposited D retained after high temperature bake
Onward Towards ITER and Fusion Energy!