Conference Summary

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

26th IAEA Fusion Energy Conference

By David N. Hill


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

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

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

DC current drive by AC Ohmic operation

- 400 kA generated by merging compression in MAST

Coaxial Helicity Injection

Startup using CCC antennae

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

TCV data – TORPEX simulation

- T_e, T_i (keV)
- r_{eff}/a_{99} w/o tune-up
- r_{eff}/a_{99} w/ tune-up
- r_{eff}/a_{99} w/o tune-up (#129018)
- r_{eff}/a_{99} w/ tune-up (#129040)

LHD

- T_i w/o tune-up
- T_i w/ tune-up
- T_e w/o tune-up (#129018)
- T_e w/ tune-up (#129040)

- T_i, T_e
- n_e (x 10^19 m^-3)

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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**LATE**

**Tanaka EX/P4-40**

**Idei EX/P4-50**
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
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)
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

Wright P3-5, Litaudon OV1-3, Ongena 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

Interplay of Sawteeth and AEs in JET

- JET shows chain of energetic particle transport:
  - TAE $\rightarrow$ sawtooth $\rightarrow$ fast ion losses

![Graph showing interplay of sawteeth and AEs in JET](image)
Significant Fast Ion Transport & Losses Result From Interplay of Energetic Particle Driven Modes

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

- DIII-D finds critical gradient behavior as multiple FI modes overlap.

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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$^1$

![ECH modification of RSAEs in DIII-D$^1$]
Key Progress in Understanding Drives and Influences of Energetic Particle Instabilities

- DIII-D: Higher \( T_e \) closes resonance window for Reverse Shear AEs\(^1\)

- 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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2. Liu, et al. EX/9-3

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Promising Runaway Electron Dissipation Techniques Developed on DIII-D and HL-2A

- **DIII-D**: Neon Shattered Pellet Injection results in significant dissipation\(^1\)
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- **HL-2A**: Supersonic Molecular Beam scatters REs by MHD oscillations\(^2\)
  - Results in significant dissipation

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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

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1. Martin, et al. EX/P6-23  
2. Papp, et al. EX/9-4
Newly developed scenarios for reliable RE generation on AUG and TCV\(^1\)

- AUG: Increased MGI quantity increases RE dissipation
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- TCV: Full conversion of pre-TQ Ohmic current into RE current

- 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
Disruption experiments show path to control thermal and vessel forces with high-Z mitigation

- JET system can reduce both radiation asymmetry and vessel forces

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
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 $\nu_e^*$ yields suppression

ELM suppression @ low $\nu$

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

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

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

  Demonstrates reliability for extrapolation towards ITER
New Understanding of Plasma Response Extends RMP ELM Suppression to Full W Wall and Long Pulse

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- Full RMP ELM suppression was obtained for >10s at **KSTAR** and ~20 s at low rotation on **EAST**

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Y.-K. Oh, OV/2-4
Y. Sun, EX/P4-7
Kallenbach, OV/2-1
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Nazikian PD/1-2
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.

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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 $\nu^*$, with new EM continuous mode

- **DIII-D** ITER baseline: D2 pellets or Li granules pace ELMs but heat flux reduction not observed at constant $\nu^*$
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

\[ \varepsilon_{\parallel}(MJ/m^2) \propto R^{1.0} n_{e,ped}^{0.75} T_{e,ped}^{0.98} (\Delta W/W)^{0.5} \]
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

EMC3-EIRENE Simulation
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

TCV

Reimerdes EX/2-3
Covele EX/P3-28
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
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:** D$_2$ 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
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°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°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
• 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

Litaudon OV/13, Hakola EX/P6-21
Onward Towards ITER and Fusion Energy!