Summary of Experimental Progress

-- the 12th IAEA TM on EPsat Austin, Texas, U.S.A.--

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ITER Issues

(A) Mitigation and control of runaway electrons generated by disruption

(B) Good confinement of energetic alphas

(C) Controlled confinement of helium ash generated by slowed-down alphas
Statistics

This TM covers the following 5 categories and experimental presentations are counted to be totally 39.

(a) Alpha particles physics, (b) Transport of energetic particles, (c) Effects of energetic particles in magnetic confinement fusion devices : 5

(d) Collective phenomena: Alfven eigenmodes, EPMs and others : 26

(e) Runaway electrons and disruptions: 1

(f) Diagnostics for energetic particles: 7
Classical/Neoclassical Losses of Energetic Ions

- Losses of energetic ions due to irregularities of magnetic fields (ripple and externally applied magnetic perturbations) must be minimized in ITER.
- Reduction of TF field ripple is done by ferittic plates inside the ITER vacuum vessel.
- TBM planned to be placed asymmetrically \(\Rightarrow\) introduce magnetic irregularity \(\Rightarrow\) loss of alphas would be slightly enhanced.
  
  Experimental test was done in DIII-D (22th IAEA FEC, Deajeon)

- RMP by ELM control coils for H-mode operation in ITER \(\Rightarrow\) enhanced loss of alphas?
  
  Experimental test has started on AUG using ELM coils.
In-vessel ELM mitigation coils at AUG

\[ \delta = \frac{B_{\text{max}} - B_{\text{min}}}{B_{\text{max}} + B_{\text{min}}} \]

- 8/24 in-vessel saddle coils have been installed in AUG:
  - 4 upper, 4 lower
- \( I_{\text{coil}} = \pm 0.95 \text{ kA} \rightarrow B_{\text{pert}} \) mainly outward (inward) direction

\[ B_{\perp,\text{pert}} \text{ on } \rho = 0.99 \]

Simulation by ASCOT code:
Orbit following Monte Carlo code
(Combined Guiding center + Full orbit code)
3D wall and field to simulate AUG with ELM control coil
200,000 test particles
Bt=1.8T, Ip=0.8MA, Teo=Tio=1.4keV, neo=5~5x1019 m^-3

Q5, Q8 perpendicular, Q6 parallel
One at a time, 93 keV and 2.5 MW each
Modelled with ASCOT NBI

Large wall load from Q6 is predicted by the simulation, i.e., 2% to 8% enhanced loss by RMP.
Provisional comparison between simulation results and FILD data.

O-15 O. Asunta et al.
Impact of RMP by ELM Coil in ITER 15 MA Scenario

- 3 ELM coils (upper, middle, and lower rows) on each of the 9 vessel sectors which are centered on the toroidal angles, $\phi_{\text{tor}}^{1,2,9} = 30^\circ, 70^\circ, 110^\circ, ..., 350^\circ$
- ELMC is modeled as filament loops

Alpha particles born in the region where $\psi_N > 0.7$ are expelled.

n=4 RMP
TFC+F1+Min_n4
Alpha particles

P2-10 K. Shinohara et al.
### Results of F3D OFMC calculation

<table>
<thead>
<tr>
<th>Fast ion species</th>
<th>Magnetic field</th>
<th>Loss power fraction [%]</th>
<th>Maximum heat load [MW/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>alpha</td>
<td>Case1: TF ripple alone</td>
<td>0.8</td>
<td>0.06</td>
</tr>
<tr>
<td>By NB</td>
<td>Case1: TF ripple alone</td>
<td>0.8</td>
<td>0.02</td>
</tr>
<tr>
<td>alpha</td>
<td>Case2: TF ripple + FI</td>
<td>0.04</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>By NB</td>
<td>Case2: TF ripple + FI</td>
<td>0.05</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>alpha</td>
<td>Case3: TF ripple + FI + Min_n4</td>
<td>0.95</td>
<td>0.06</td>
</tr>
<tr>
<td>By NB</td>
<td>Case3: TF ripple + FI + Min_n4</td>
<td>7.5</td>
<td>0.27</td>
</tr>
<tr>
<td>alpha</td>
<td>Case4: TF ripple + FI + Min_n3</td>
<td>1.6</td>
<td>0.06</td>
</tr>
<tr>
<td>By NB</td>
<td>Case4: TF ripple + FI + Min_n3</td>
<td>10.0</td>
<td>0.21</td>
</tr>
<tr>
<td>alpha</td>
<td>Case5: TF ripple + FI + Max_n4</td>
<td>6.2</td>
<td>0.21</td>
</tr>
<tr>
<td>By NB</td>
<td>Case5: TF ripple + FI + Max_n4</td>
<td>26.2</td>
<td>0.36</td>
</tr>
<tr>
<td>alpha</td>
<td>Case6: Axisymmetric TF + Min_n4</td>
<td>0.9</td>
<td>0.06</td>
</tr>
<tr>
<td>By NB</td>
<td>Case6: Axisymmetric TF + Min_n4</td>
<td>7.0</td>
<td>0.24</td>
</tr>
<tr>
<td>By NB</td>
<td>Case7: Axisymmetric TF + (n=4, 30kAt, zero phase difference between upper, middle, lower coils)</td>
<td>0.6</td>
<td>0.03</td>
</tr>
<tr>
<td>By NB</td>
<td>Case8: Axisymmetric TF + (n=4, 15kAt)</td>
<td>2.4</td>
<td>0.09</td>
</tr>
</tbody>
</table>

**Note:** Shielding effect of plasmas on field penetration is not considered.
Heating Scenarios for Enhanced Ion Tail by ICRF(1)

- Measurement and simulation of ICRF minority-heated fast-ion distribution function on C-Mode

Compact neutral particle analyzer (CNPA) has been developed to measure ICRF generated ion tail up to 1.5MeV on C-Mod, where charge exchange with B^4+ is dominant in the range of E > 0.3MeV.

For discharges with different Ip, simulation with AORSA (solvers for plasma wave field) + CQL3D (solvers for particle motion) agrees well with experiment.

O-27: A. Bader et al.
ICRF heating scenario in burning D-T plasmas
( P1-14: Ye.O. Kazkov et al.)

Direct ion heating is very effective to enhance D-T fusion reactivity. In T-ritch plasma of ~85%, effective ion heating is expected.

Energetic ion behaviors during H or He3 minority heating in C-Mod
(P2-1: K.T. Liao et al.)

Fast and thermal minority ion distribution was measured by charge exchange spectroscopy using 50 keV diagnostic beam. Energetic ions in plasma core is measured by CNPA.
Energetic Ion Driven Global Modes

AEs and other global modes excited by Energetic Particles
- Linear mode identification
- Stability (Damping rates and Drive)
- Nonlinear mode evolution

Radial transport (redistribution and/or losses) of EPs by energetic ion driven global mode

Radial transport of EPs by micro-turbulence in background plasma
Alfven Eigenmodes in 2D & 3D Plasmas

Tokamaks, Spherical tokamaks, Helicals/Stellarators, Reversed field pinch

TAE, EAE, NAE exist in both 2D & 3D plasmas.
GAE and RSAE exist in both 2D & 3D plasmas.
HAE and MAE exist only in 3D plasmas.
Non-perturbative modes such as EPM and Fishbones in both 2D & 3D plasmas.

New comers!
Identifications of Energetic Ion Driven Modes

-- TAEs, RSAEs, BAEs, BAAE, GAM—
2D Measurement of TAE & RSAE Structures in DIII-D

- 2D measurement of TAE by ECE imaging (ECEI)
- Observed twist of eigenfunction in poloidal direction is caused by energetic ion effects.
- This result has excellent agreement with the gyro-fluid calculation by TAEFL code (D.A. Spong).

Dual detector Arrays can monitor Simultaneously LFS and HFS.

B.J. Tobias et al., PRL(2011)
2D Measurement of BAAE (OANBI case)

- ECEI has provided the first 2D images of the BAAE
  - Highly localized radially about ρ = 0.2 (≤ q_min)
  - Modes rotate in same sense as RSAEs/TAEs (ExB and normal \( \omega^*_{\text{t,thermal}} \) direction)
  - Phase shear curvature is reversed w.r.t. RSAEs/TAEs

P2-11  B.J. Tobias et al.
In an RS plasma generated in current ramp up phase in AUG, several interesting modes of which mode frequency is lower than \( f_{\text{TEA}} \) are detected.

I-5  Ph. Lauber et al.
‘extended’ Alfvén spectroscopy

frequency difference of radial harmonics of RSAEs gives constraint on curvature of q at q_{\text{min}}.
analyse a set of test-profiles: keep q_{\text{min}} constant and vary curvature

experiment: $\Delta f \approx 8 \text{kHz}$

rather flat q-profile is consistent with frequency difference
also radial width of measured modes supports flat q-profile
BAE mode structures, NBI-driven

\[ \gamma = 2.1\% \]
Alfven/Acoustic Mode Excitation by Off-Axis NBCD

**DIII-D**

- **RSAE**
  - 2 On-axis Beams
  - 2 Off-axis Beams
  - Frequency (kHz)
  - Time (ms)
  - R=197 cm

- TAE drive proportion to $\nabla \beta_f$
- The stability boundary is higher for off-axis beams.

- **BAAE**
  - 2 On-axis Beams
  - 2 Off-axis Beams
  - R=188 cm

- The frequency pattern in the off-axis case suggests the modes have negative toroidal mode numbers.

O-9  W.W. Heidbrink et al.
Energetic Ion Driven GAM (EGAM) in DIII-D

Recipe for E-GAM Excitation in DIII-D: Counter Tangential Beam Injection into High $q_{\text{min}}$ Plasma

- $q_{\text{min}} > 3 T_i$, $T_e < 2 \text{ keV}$, typically. Why?
- 80 keV bounce frequency $\approx$ GAM frequency at high $q$ in DIII-D
- Ion Landau damping minimized at high-$q$ through sideband resonance
- Note: co beams can drive modes, but typically much weaker, shorter
Strong Outward Radial Propagation of E-GAM Observed in Simulation and BES Measurement

- Directional sensitivity of mode excitation confirmed from Hybrid simulation, orbit analysis and resonance condition
  - prediction of large losses over a broad energy range observed

- Theoretical prediction of nonlinear structure of second harmonic validated using BES, can be used to infer $E_r$
SPIRAL Code Simulations Are in Good Agreement with
of Fast Ion Loss Detector For Pitch and Energy of Loss

- First-orbit losses from:
  - 10L third-energy fraction
  - 210R half-energy fraction
  - 210L full-energy fraction
- First-orbit losses from:
  - 210R third-energy fraction
  - 210R half-energy fraction
- EGAM induced losses

Note: No E-GAM losses observed for co-injected particles

FIELD1: Pace, Fisher
SPIRAL: Kramer

O-2 R. Nazikian et al.
Up–sweeping n=0 modes associated with neutral flux increase were observed for low density LHD plasmas.

- The typical initial frequencies are 50–70 kHz and their frequencies chirp–up during their mode activity activities.
- No significant increase of Hα–signals were observed.
- Typical estimated slowing–down time is ~8[s] at the core.
Temporal behavior of the mode and neutral flux indicates either anomalous heating or radial transport of bulk ions by the mode activity.

- The mode grows very quickly at its initial phase ($\gamma_{\text{eff}} \approx 4.6 \times 10^3 \text{[s}^{-1}]$).

- The ion temperature starts to increase when the mode amplitude reaches a certain value ($\approx 2 \times 10^{-2}$ [a.u.]), and the effective growth rate of the mode decreases ($\gamma_{\text{eff}} \approx 2.3 \times 10^2 \text{[s}^{-1}]$), simultaneously.

- When the mode frequency reaches to a certain frequency close to the orbital frequency of the energetic particle produced by the NB, the mode amplitude starts to decrease gradually ($\gamma_{\text{eff}} \approx -69 \text{[s}^{-1}]$).
Observation of Two Types of Energetic Ion Driven GAM on LHD

(Type I) GAM excited quasi-stationary in reversed shear plasmas by EPs

(Type II) This GAM is excited just after the switch-on of NBIs

Nonlinear evolutions: pitchfork splitting, mostly up-ward frequency chirping
This GAM may be controllable and sustainable.

K. Toi et al., PRL(2010)

T. Ido et al., NF(2011)
This is excited transiently (just after NBI switch on ) in very low density range
(<n_e> < 0.2x10^{19} m^{-3}).

O-4 K. Toi et al.
Amplitudes of potential and density fluctuations induced by GAM gradually increase with the decrease in the rotational transform.

These fluctuation amplitudes are very large near the GAM center:

\[(\delta n_e)_{\text{rms}}/n_e \sim \text{up to 15\%}, \quad (\delta \phi)_{\text{rms}}/T_e \sim \text{up to 70\%}\]
Measurement of Damping Rate of TAEs
--Alfvén Eigenmode Active Diagnostics--

Aim: address physics of mode damping, identify modes most prone to instability in different burning plasma scenarios, and parameters to control stability.

ITER-relevance for size and shape scaling, scenarios

D. Testa, CRPP-EPFL

O-10 D. Testa, A. Fasoli et al.
Ex. of $\gamma/\omega$ measurements for $n=7$ TAE

Note: in the absence of fast ion drive, $g/w$ is the mode damping rate

Antenna configuration to drive odd modes ($3<|n|<11$) $n=3$ mode dominates.

$\Rightarrow$ Dependence of $\gamma/\omega$ on $\kappa_{95}$ and $q_0$ for $n=3$ TAE
plasma shape effect for n=3 TAEs: measurements vs. modeling

- **LEMan**: gyro-kinetic approach → good agreement with data
- **CASTOR**: fluid approach → large discrepancies with data
- **TAEFL**: $\gamma/\omega$ extrapolated back from marginal stability threshold for fast-ion driven modes → good agreement with data, very important to test validity of the modeling approach

Agreement with numerical codes based on gyro-kinetic or gyro-fluid models has reached quantitative level.
Excitation of Alfvénic and Acoustic Modes by Energetic Electrons

Alfvénic and acoustic global modes can be destabilized through wave-particle resonance interaction which depends on particles speed but not on particle mass.

Characteristic orbit size and gyro-radius is small.

\[
( \rho_{he}/a \sim 0.005 \ll (\rho_{\alpha}/a)_{ITER} \sim 0.03 \ll (\rho_{hi}/a)_{JET} \sim 0.3 )
\]

Energetic electron study may bridge the gap in orbit width and gyro-radius.

O-14(FTU & Tore Supra_el-fishbone), O-20(LHD, el-AEs), P2-5(TJ-II, el-driven mode),
Electron Fishbones in LH Plasmas of FTU

**e-fishbones in FTU tokamak**

In LHCD discharges two regimes of e-fishbones were observed according to the LH power:

- An almost steady state (fixed point) at moderated values of LH power (1\textsuperscript{st} branch)

- A regular bursting behavior (limit cycle) at high LH power (2\textsuperscript{nd} branch)

[FTU #20865 graph]

[F.Zonca, Nucl. Fusion 2007]

**O-14  Z.O. Guimaraes-Filho et al.**
Electron Fishbones in LH Plasmas of FTU

**e-fishbones in Tore Supra**

- At moderate Lower Hybrid power, 1 MW, and low density, \( n_0 \approx 2.5 \times 10^{15} \text{ m}^{-3} \), MHD modes identified as precessional e-fishbones may be destabilized.
- Frequency jumps between modes with different structures are observed.

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**References**

- [A.Macor, PRL 2009]
Global Modes Excited by Energetic Electrons on LHD

Frequency of magnetic fluctuation varies according to ECRH turn-on/off

- Electron density is constant during ECRH modulation.
- MP frequency goes down after ECRH turn-off and goes up following ECRH turn-on, suggesting that the frequency change is associated with plasma temperature.

It looks that the mode excited in 2nd harmonic ECRH plasmas of LHD has an acoustic nature rather than Alfvénic.

$T_e > T_i$
$T_e = 10$keV
$T_i = 1$keV
$\langle n_e \rangle < 0.2 \times 10^{19}$ m$^{-3}$
$T_{e_{\text{tail}}} \sim 150$ keV

$\langle n_e \rangle > 0.2 \times 10^{19}$ m$^{-3}$

: no mode exciation
Global Modes Excited by Energetic Electrons on LHD

Rapid jump of potential to positive at plasma core while bursting Mirnov activities are present

Enlarged pulses

- Potential changes to positive as magnetic fluctuation grows
- Note that fluctuation on potential has not been visible.

Pulsatile potential change to positive is probably due to rapid expulsion or radial transport of suprathermal electron

Spanish Heliac T-JII

In TJ-II Heliac (CEAMAT, Spain), global modes are excited by intense ECH, [P2-5: K. Nagaoka et al.]
Contributions from New Groups to this IAEA TM
Reversed field pinch & Shearless stellarator

Fast Ions are Barely Studied in RFP Concept

- Fast ion confinement and transport in Reversed Field Pinch (RFP) devices could be quite different from in Tokamaks.
  - $B_t \sim B_p$, $\rho_f/a: 0.1 \sim 0.25 \rightarrow$ large prompt loss
  - Large magnetic fluctuations, stochastic magnetic field
    $\rightarrow$ could lead to rapid diffusion of charge particles
  - $V_{\text{fast-ion}} > V_{\text{Alfvén}} \rightarrow$ fast ions could drive Alfvén instabilities

- The newly installed 1 MW neutral beam injector on MST provides a good test-bed for fast ion study in RFPs.
  - Interplay between magnetic fluctuations and fast ion confinement
  - Fast ion driven instabilities
  - Control of MHD dynamo and tearing modes?
  - Plasma beta limit?

NBI: tangential injection
$E=25\text{keV}$ (positive ion source)
1MW, 20 ms pulse
Fast ions in MST behave roughly classically in spite of stochastic magnetic field. NBI induces bursting modes at frequencies of 60-150kHz that scales with density, not magnetic field.
Studies of AEs in HJ with low magnetic shear

- Heliotron J: low magnetic shear, + magnetic well for MHD stability.
- The observed modes during NBI are identified as GAEs by the comparison between exp. results and shear Alfvén spectra in 3D magnetic configuration.
- In the range of $0.45 < i/2p < 0.65$, GAEs are dominant in $f < 500$ kHz. HAE frequency is $f > 1$ MHz.

P2-18  S. Yamamoto et al.
Nonlinear Evolution of TAEs

- Steady state evolution, periodic (pitchfork split), chaotic v.s. Bursting: This is controlled through competition between electron drag and velocity diffusion (pitch angle scattering).

This physics are more general, because these kind phenomena are not sensitively affected by a system, i.e., magnetic configurations.

These modes are seen at ratio of $\Delta \Omega_{\text{Diff}} / \Delta \Omega_{\text{Drag}} \approx 0.5$, in line with the stronger competition between the drag acting to deepen the hole and diffusion that acts to destroy the hole.
Nonlinear Evolution of TAEs

In MAST, electron drag always prevails the diffusion. ➜ always, bursting with rapid frequency chirping?

STeady-State TAE: Possible Observation of Steady-State BGK Mode Similar to M. LLILLEY’s Modelling

TAE excited in MAST discharge #12883 during NBI power increase

Zoom of the spectrogram in the early phase, from 80 to 100 msec

ITPA Joint experiments are going on.
III
Radial transport of EPs by energetic ion driven global modes

- Velocity-space resolved (pitch angle and energy) diagnostics for confined and lost energetic ions are crucially important to clarify energetic ion transport mechanisms.
  
  FIDA (fast ion CX spectroscopy) ;
  FILD or SLIP (lost fast ion probe)

- Experimental results from
  Tokmaks: DIII-D(I-6, P1-18),
  NSTX(I-3, O-1, O-12, P1-7, P1-18)
  Helicals/stellarators: LHD (I-7)
Energetic ion redistribution by sawteeth in DIII-D

Sawteeth strongly couple to ICRF-accelerated trapped ions

- Observed enhanced transport of trapped ions during ICRF due to bounce/precession resonance

\[ n\omega_{pr} = s\omega_b \]

Moderate energy fast ions: transport by flux attachment
High energy ions: resonant interaction
Energetic ion losses by fishbones in DIII-D

Off-axis fishbones observed to expel fast ions due to precession resonance

- 7 independent fast-ion loss detectors observe beacon-like losses
- Fishbones interact with deeply trapped via precession resonance

\[ \omega = \omega_{\text{pr}} \]

Fishbones: resonant kicks into loss boundaries
Coherent losses by TAEs & RSAEs in DIII-D

Coherent loss measurements during strong AE activity

- Fast-ion loss detector measures signal coherent with TAEs and RSAEs
- Modeled losses reproduces measured signal with approximately correct energy band and pitch

TAEs/RSAEs: resonant kicks into loss boundaries
Coherent losses by TEAs, RSAEs & EGAM on DIII-D

Coherent losses by TEAs, RSAEs are detected by two FILDs. The loss by EGAM excited by counter NBI is also observed.

<table>
<thead>
<tr>
<th>FILD</th>
<th>$\tau_L$ (cm)</th>
<th>$\alpha$ ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FILD1</td>
<td>1.5-5.0</td>
<td>30-75</td>
</tr>
<tr>
<td>FILD2</td>
<td>2.5-8.0</td>
<td>35-85</td>
</tr>
</tbody>
</table>

Generally, FILD1 has stronger signal in oval shape plasmas while FILD2 is more suitable in circular shape plasmas.

P1-3    X. Chen et al.
Energetic ion losses by EGAM in DIII-D

-- SPIRAL Simulation --

- SPIRAL successfully reproduced the experimental results from FILD, so we can use it now to look into details of the EGAM-particle interaction.
- Coherent losses are found in the simulations when particles are loaded uniformly in energy between 20 and 80 keV and pitch between -1 and 1 at R,Z=(2.0,0.0) m.

SPIRAL code is also successfully applied to NSTX data.

P1-18 G.J. Kramer et al.
A burst in which several TAEs of differing n occur is termed an “avalanche”.

- Burst separation 0.5 – 2 ms
  - No systematic variation with \( n_\theta, T_e, P_{NB}, \ldots \)
  - Frequency evolution does not follow unique pattern (e.g. \( t^{-1/2}, \) linear, exponential)
- Usually, each mode chirps independently of the others...
- ...but, eventually, avalanches occur:
  - Drop in neutron rate, FIDA
Energetic ion losses by TAE Avalanche in NSTX L-Mode Plasmas

Mode structure maintains its shape even during strong, multi-step avalanches

- Re-scaled $dn/n$ shown (compare radial structure, not amplitude)
- Outward propagation of unstable front during burst not observed
  - Broad mode structure, ~ minor radius
  - Incomplete transition TAE $\rightarrow$ EPM?

Zona et al., NF 2006
Energetic ion losses by TAE Avalanche in NSTX

Coupling between multiple TAEs with $\Delta n_{tor} = 1$, enhanced losses observed during explosive modes’ growth

- Coupling generates higher/lower frequency modes
- Multiple modes follow similar dynamic during the burst
  - Transition from single- to multi-mode regime

Podestà et al., NF 2011
TAE avalanche in NSTX H-mode

**ORBIF simulations predict losses in good agreement with observed neutron rate drop**

- **ORBIF simulation** is done for 1ms burst at 0.285s.
- **Mode amplitude, frequency evolution in ORBIT** are from experimental measurements.
- **Mode structure from NOVA.**
- **Initial fast ion distribution** is from unperturbed TRANSP calculation – not necessarily self-consistent.
- **Losses are strongly non-linear with mode amplitude** – as expected for avalanche.
Test whether code-modeled stochastic domain presence coincides with lost pitch angle ranges

- Stochastic maps shown on following slides for 4 pitch angles marked (4 $\mu$ values)

Losses appear at a given pitch angle only if (1) Beam deposited in stochastic region, and (2) Stochasticity expands all the way to the loss boundary along the line of transport.
Energetic ion losses by Low f-Modes in NSTX

In NSTX H-mode early kink \((n=1,2)\) is accompanied by \(n_{\text{FIDA}}\) depletion and CAE destabilization.

**ELM-free H-mode**

- PNBI [MW]
- Neutron rate [a.u.]
- Mirnov Probe [kHz]
- Compressional AE
- Kink \((n=1, n-2)\)

**FIDA density** \(n_{\text{FIDA}}\) [a.u.]

- Electron temperature \(T_e\) [KeV]
- Electron density \(n_e\) \([10^{19} \text{ m}^{-3}]\)

**\(\xi_{\phi}(\phi=0)\)**

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O-12  A. Bortolon et al.
Energetic ion losses by Low f-Modes in NSTX

- Kink effect from differential distribution $\Delta F = F_{\text{kink}} - F_{\text{equi}}$

- Redistribution of core confined particles towards the edge

- Slowing down distribution shifts towards $v_\parallel/v = 1$

- Net decrease in the region of maximal FIDA response

Full Orbit simulation with SPIRAL code indicate Redistribution in *real* and *velocity* space (3% losses)
Energetic ion losses by AEs on AUG

Redistribution / Loss Due To NBI Driven Alfven Eigenmodes

FIDA System Measures a Drop in Central Fast-Ion Population as $q_{min}$ Passes Through an Integer

- At $q_{min}=2$ crossing, several RSAsEs are excited by 60kV beams (Grand Cascade)
- Rapid drop in central fast ion density corresponding to peak in RSAE amplitude
- No fast ion losses observed during this event
  - May be geometrical effect. Plasma shape not FILD friendly

M. García-Munoz et al., IAEA FEC, Daejeon, Korea (2010)
M. García-Munoz et al., Nucl Fusion 51 103013 (2011)
M. García-Munoz, 12th IAEA Technical Meeting on Energetic Particles Austin, Texas USA

O-11 M. García-Munoz et al.
Energetic ion losses by AEs on AUG

TAEs Observed to Cause Fast Ion Loss

\[ \omega_{n,p} \sim \omega_{\text{MHD}} - n \cdot \omega_{\text{tor}} - p \cdot \omega_{\text{pol}} \]

Resonances \( n=1-5, p=1-4 \)
- FILD spectrogram shows clear coherent losses from beam driven TAEs
- FILD Scintillator indicates TAE induced losses appear near gyro-radius corresponding to injection energy

Wave-Particle Resonances are in Phase-Space Region Corresponding to Passing-Ions

Larger Fast-Ion Losses

M. Garcia-Munoz et al., IAEA FEC, Daejeon, Korea (2010)
M. Garcia-Munoz et al., Nucl Fusion 51 103013 (2011)
Deeply trapped particles are strongly affected. Several loss mechanisms are present.
B=2.7T, I=1.2MA, q95=6.5, $\beta_N=2.6$, $\beta_{pol}=1.8$, $\delta \sim 0.4$, $n_e/n_{GW}=0.77$, 15 MW NBI, 6 MW RF (H-minority)

- NPAs and gamma ray spectrometers show negligible second harmonic D acceleration (in agreement with PION and SELFO)
- 95% of neutrons originate from beam-target or beam-beam (TRANSP)
- Timing of FB occurrence and RF-free reference discharge show that FBs destabilised by NBI
- One of the $^{235}$U fission chambers connected to fast DAQ, measures fast drops in neutron rate correlated with the FBs
• Neutron drops simulated for a set of runs with varying fishbone amplitude (using ASCOT-HAGIS-MISHKA)

• Experimental measurements evaluated for an ensemble of 40 fishbones (t=19.6-22.3 s)

• For this range of amplitudes simulations predict drops of order 0.5-1.5%. Quadratic dependence on FB amplitude (diffusive-type transport)

• To within a factor 2 measured drops are consistent with simulations.
Energetic ion losses by AEs in LHD

To clarify dominant mechanism of losses induced by TAEs is also very important on the Large Helical Device (LHD). In LHD, a large Shafranov shift increases by increased plasma beta, generating magnetic well. On the other hand, large shafranov shift tends to increase energetic ion losses. Moreover, the energetic ion losses increase, having stronger dependence for \((b_{\theta TAE}/Bt)^s\), that is, \(s=1\) to \(2\), and \(>2\).

Guiding center Monte Carlo code: DELTA 5D in LHD plasma
Full orbit code: in the vacuum (from the lost ion probe head to plasma surface)
Connection of a fast ion orbit at LCFS: smooth orbit connection=> lost to the detector
Energetic ion losses by AEs in LHD

Image of scintillator plate

Time trace of TAE₂, RIC and \( I_{\text{SLIP}}^{\#9091} \)

TAE induced loss dependence on Mirnov fluctuation amplitude

Eigenfunction of TAE in each configuration

I-7 K. Ogawa et al
**Energetic ion losses by AEs in LHD**

- **Loss flux dependence on fluctuation amplitude.**
  - \( b_0 \) indicate the fluctuation amplitude at peak position in a plasma
- **Relation between \( b_0 \) and \( b_{TAE} \) observed in experiment have a certain relationship in each configuration.**
  - \( b_0 \) have same connection with \( b_{TAE} \).
- **Loss flux dependence on fluctuation amplitude have some relation as that of at LCFS.**
- **Loss flux dependence on fluctuation amplitude is similar as observed in experiments on \( R_{mag} \) of 3.75 m and 3.86 m.**

I-7 K. Ogawa et al
A Unknown Interesting Phenomenon in NSXT

- At a certain condition where high frequency mode GAEs are excited and low frequency modes such as NTM are suppressed in H-mode, the charge exchange flux close to the injection energy is strongly enhanced (by a factor of ~4). This is called High Energy Feature (HEF).

- The NPA charge exchange spectrum exhibits enhanced signal only near $E \sim E_D$ (e.g. never at $E_D/2$ or $E_D/3$).

- HEF can be characterized by peak-to-base flux ratio $H = F_{\text{max}}/F_{\text{min}} \sim 10$.

- Lack of evolution of a slowing-down distribution below the HEF is a common (and not understood) feature.

GAE may play a role in triggering HEF
(P1-15 Y. Kolesnichenko, this conf)
Integrated Approach to Predict AE Stability and Induced Energetic Ion Losses in DIII-D & ITER

- Stability analysis of AEs (TAEs, RSAEs) using NOVA-K code using experimentally obtained profile data and calculated fast ion distribution function.
- Fast ion losses calculated by ORBIT and SPIRAL codes.

- Oval chosen to accommodate up/down symmetric equil. codes
- High q-min during current ramp
- Beam pressure profile obtained by subtracting thermal pressure from MSE constrained equilibrium pressure
- Pitch angle distribution obtained from TRANSPI – primarily co-injection
Integrated Approach to Predict AE Stability and Induced Energetic Ion Losses in DIII-D & ITER

- Stability analysis of AEs (TAEs, RSAEs) using NOVA-K code using experimentally obtained profile data and calculated fast ion distribution function.
- Fast ion losses calculated by ORBIT and SPIRAL codes.

- Continuum and modes are calculated with NOVA for range of $q_{\text{min}}$ (frequency variation aids mode identification)
- NOVA-K calculates stability in presence of beam ions
- ECE, ECEI, magnetics, BES, etc. all used to identify eigenmode
  - Radial, toroidal, poloidal structure, frequency variation with $q_{\text{min}}$, etc.
- Several $n=3$ modes are identified experimentally in agreement with NOVA-K
- TAEFL also finds similar modes unstable*

*B.J. Tobias, et.al., PRL 106, 075003 (2011)

Searching of unstable TAEs and RSAEs
Check of experimental data
Integrated Approach to Predict AE Stability and Induced Energetic Ion Losses in DIII-D & ITER

Measured Modes Correspond Well with Modes Predicted to be Unstable by NOVA-K (n=1-6)

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</table>

- Stability for hundreds of AEs calculated
- Most unstable mode observed experimentally in all cases except n=1
- Low-n more unstable as observed experimentally
- RSAEs typically most unstable
  - Radial harmonic RSAEs also unstable
  - Fundamental is most unstable - as in expt.
- Dominant damping mechanisms are e-collisional, e-landau, and radiative
Integrated Approach to Predict AE Stability and Induced Energetic Ion Losses in DIII-D & ITER

This approach works very well for DIII-D data. This was applied to ITER-ISO 8MA scenario → n=5 & 6 RSAE, n=6 TAEs

- Loss simulations follow particles from TRANSP distribution function in presence of NOVA eigenmodes
  - Amplitudes obtained from experiment
- Losses at FILD peak near injection energy (80 keV)
- Most common loss mechanism observed is transition of counter passing particles to trapped lost orbit

Impact of micro-turbulence in background plasma on energetic articles.

First recognition: deficit of energetic ions in plasma core (AUG, DIII-D)

Study of this topic in a plasma with off-NBCD on DIII-D (ITER relevant: to realize broad current density profile for improved global stability)

O-9 (DIII-D)

Basic study of microturbulence induced energetic ion transport using a simple tokamak with vertical field and linier device

O-24 (TOPEX)

O-25 (LAPD)
Effects of Micro-Turbulence on EP transport - Off axis current drive in DIII-D -

1. Are there significant deviations from classical behavior in low-temperature quiet plasmas?
2. Does plasma microturbulence cause additional fast-ion transport?
3. What is the effect of off-axis beam injection on Alfvén eigenmode stability? (This is shown above)
Preliminary Analysis: No evidence of enhanced transport at higher $T$ or $\beta$ in new experiments

- Off-axis beam ions are as well confined as on-axis
- Detailed comparison with gyrokinetic simulations in progress
The TORPEX device

- Open field lines - no plasma current
- Plasma production by EC waves
- Extensive diagnostic coverage (electrostatic, magnetic, fast camera)
- B, curvature, pressure gradients

H₂, D, He, Ne, Ar plasmas

R = 1 m; a = 0.2 m

B₀ = 76 mT; Bₓ = 0 - 6 mT

Tₑ = 2 – 20 eV

nₑ = 0.1 – 5 x 10¹⁶ m⁻³
Fast ion current profile – theory vs. experiment, \( \Delta \phi = 42 \text{cm} \)

**Theory**
- Without plasma
- With plasma

**Experiment**
- Without plasma
- With plasma
Effects of Micro-Turbulence on EP transport
-- Experiment in LAPD --

UCIrvine

UCLA

O-25  S. Zhou et al.
Drift waves induced by an annular obstacle placed perpendicular to the Axial magnetic field enhance radial diffusion of fast ions. Obit averaging effect for fast ions having large Larmor radius is imperfect. ➔ Radial diffusion of fast ion is enhanced by micro-turbulence.
IV
Development of Diagnostics for fusion $\alpha$-particles in JET DT Experiments

◆ Fusion $\alpha$-particle source diagnostics
  Neutron and $\gamma$-ray emission profiles; Neutron spectrometry
◆ Confined $\alpha$-particle diagnostics
  $\gamma$-ray diagnostics; Neutral Particle Analysers
◆ Escaped $\alpha$-particle diagnostics
  Scintillator Probe; $\alpha$-particle collectors

Required quantities to be measured in DT experiments
• Fusion reaction rate: Neutron and $\gamma$-ray diagnostics
• Spatial $\alpha$-particle distribution / redistribution effects: Neutron and $\gamma$-ray diagnostics
• $\alpha$-particle energy distributions: $\gamma$-ray and neutron spectrometry, neutral particle analyser
• $\alpha$-particle slowing down & confinement: $\gamma$-ray diagnostics
• $\alpha$-particle losses: Scintillator Probe, Faraday Cups
Development of Diagnostics for fusion $\alpha$-particles in JET DT Experiments

Fusion $\alpha$-particle source diagnostics

Neutron and $\gamma$-ray emission profiles; Neutron spectrometry

(P1-12; C. Hellesen)

Detectors:
- NE213 liquid scintillators (2.5 & 14 MeV)
- Bicron-418 plastic scintillators (14 MeV)
- CsI(Tl) photo-diodes (hard X-rays and $\gamma$-rays)

Detectors are absolutely calibrated

Tracer T Experiments
Development of Diagnostics for fusion $\alpha$-particles in JET DT Experiments

Confined $\alpha$-particle diagnostics: $\gamma$-ray diagnostics

$\gamma$-ray spectrometer: $^9\text{Be}(\alpha, n\gamma)^{12}\text{C}$ reaction

New capabilities

LaBr$_3$ (or BrilLanCe): $\Delta E/E \approx 3\%$,
Decay times - $< 20$ ns
DAQ allows up to 2 MHz PHA

HpGe: $\Delta E/E \approx 0.3\%$ - the Doppler broadening of $\gamma$-lines can be measured
DAQ allows up to 0.5 MHz PHA

Quasi-tangential BGO-spectrometer: front and rear collimators to improve S/B ratio

A similar diagnostic System was installed On AUG. The $\gamma$-ray Generated to a Nuclear raecion of Proton has been Dtected. (P2-7: M. Nocente Et al.)
Development of Diagnostics for fusion $\alpha$-particles in JET DT Experiments

Confined $\alpha$-particle diagnostics: $\gamma$-ray diagnostics

\textbf{$\gamma$-ray emission profile: $\alpha$-particle redistribution measurements}

\textbf{Scheme of the neutron attenuator assembly in the cameras}

\begin{tabular}{|l|l|l|l|}
\hline
Neutron & Material & Neutron energy & \\
attenuator & & 2.45 & 14.1 \\ & & MeV & MeV \\
\hline
\hline
Horizontal & $\text{H}_2\text{O}$ & $10^2$ & 15 \\
\hline
Vertical (normal) & $\text{H}_2\text{O}$ & $10^2$ & 15 \\
\hline
Vertical (long version) & $\text{H}_2\text{O}$ & $10^4$ & $10^2$ \\
\hline
\end{tabular}

(*) Experimentally confirmed on a prototype V.L. Zolta, MEDeC

\textbf{Vertical Camera can be used for $\gamma$-ray emission profile in DT discharges with up to $10^{17}$ n/s !}
Development of Diagnostics for fusion $\alpha$-particles in JET DT Experiments

Escaped $\alpha$-particle diagnostics: Scintillator Probe

- **Entrance aperture**
- **Limiter guide tube**
- **W-coated graphite**
- **Scintillator plate**
- **Image fibre bundle**
- **PMT Array**
- **CCD Camera**

P56 scintillator: 2 ms decay-time $\Rightarrow$ now TG-Green: 0.5 $\mu$s decay

CCD camera: 512x512 pixel, 10-50 Hz $\Rightarrow$ now 128x256 pixels, 20 kHz

PMT detectors: 4x4 PMT array, rate 5 kHz (fibre bundle should be protected!)

Electrically-heated (up to $200^\circ$) hose for fibre optic bundle will be installed before DT campaign. It is not be degraded by nuclear irradiation up to a total dose of $10^8$ rad.

**Scintillator probe: first orbit loss measurements**

1-MeV tritons and 3-MeV protons

- **Discharge 2.7T / 1.8 MA**
- **Discharge 2.7T / 2.5 MA**
Development of Diagnostics for fusion $\alpha$-particles in JET DT Experiments

Escaped $\alpha$-particle diagnostics: Faraday cup Probe with energy discrimination

Faraday cup type is also installed inside the vacuum vessel of JET. Energy resolution is done with a detector composed of multiple metal foils.

Observation (a): Lost alpha particles (or deuterons) with energies up to about 7 MeV (4 MeV) generated during ICRH (up to 6 MW) $^4$He/d plasmas
Diamond Neutral Particle Spectrometer for JET & ITER

Aims:

- Charge-exchange atom spectroscopy with high temporal resolution applies to study effectiveness of additional heating, interaction of plasma instabilities with fast ion component.
- Demanded spectroscopy temporal resolution \( \sim 1 \text{ ms} \).
- Demanded energy resolution \( < \sim 10 \text{ keV} \).
- Demanded peak count rates \( \sim 10^6-10^7 \text{ cps} \).

O-22 V.A. Krasilnikov et al
Diamond Neutral Particle Spectrometer for JET & ITER

- Diamond has unique properties that enable it to be effectively used as a sensitive element in the high-energy particle detectors.
  - 5.5 eV - energy band gap
  - $>10^{15}$ Ohm*m – electrical resistance
  - $10^7$ V/cm – breakdown voltage
  - $2 \times 10^7$ cm/s - saturated drift velocity
  - 10-15 ns - charge collection time

Spectroscopy electronics

The very new spectroscopy amplifiers and pulse analyzers are capable of processing particle fluxes of up to $10^7$ cps. They require extremely low-noise conditions.

- Specially designed electronics
  - Preamplifier
  - Supply unit

allows to digitize and process signal with count rates up to $10^6$ cps at relatively high noise levels.
Neutron Emission Profile Monitor for MAST

Most of the fusion neutron production is due to injected neutral deuteron reacting with the thermal deuteron population (beam-thermal) while the beam-beam term accounts for 10 - 20% of the total and the thermal-thermal contribution is negligible.

\[ D + D \rightarrow ^3\text{He} (0.82 \text{ MeV}) + n (2.45\text{MeV}), \ Q = 3.27\text{MeV} \]

Detectors: Liquid scintillator coupled to PMT
2x5x1 cm³ act. V.
14 bit, 256 MB
250 MHz sample

O-23 M. Cecconello et al
Neutron Emission Profile Monitor for MAST

**Fishbones**

This neutron emission Profile monitor is Successfully employed In MAST experiments.
In LHD, a spectroscopic system to measure charge exchange recombination by energetic beam ion up to 190 keV is under development for study of NBI produced energetic ion profile and redistribution of energetic ions due to AEs. This system is similar to those used in DIII-D, AUG and NSTX, but aims at extended energy range up to ~150 keV.

The initial data have been obtained, which are responding to the relevant NBI (#2 NBI: shown in red).
Collective Thomson Scattering System

Geometry of probing and receiving beams for collective Thomson scattering in LHD

\[ k^S = k^S - k^i \]

The scattered signal is sensitive to the direction of \( k^S \)

\[ \angle(k^S, B) = 100.4 \text{ deg.} \]

Scattering geometry for probing and receiving beams in LHD.
\( R_a = 3.6 \text{m}, B_t = 2.4 \text{T} \)

CTS heterodyne receiver system

- Probing beam from the gyrotron
- 77GHz

- Notch filter
- Mixer
- <6GHz amplifier
- 32 channel filters
- 32 channel diodes
- 32 channel video amplifier

CTS system is under Development for Fast ion measurements On LHD.

P2-6 M. Nishiura et al
Runaway Generation & Disruption

- At plasma densities typical for tokamaks, \( n \sim 10^{19} - 10^{20} \text{ m}^{-3} \) the electric field is small and RE can be produced only during abnormal events such as plasma disruption.

- It is known from experience in tokamaks that RE can damage in-vessel component (notorious accident in TFR with burning hole in vacuum vessel).

- RE are dangerous for the plasma facing components because of long range in FW materials and possible deep melting.

- Massive RE generation is expected during plasma disruptions in ITER (up to 12 MA of RE current).

- RE must be suppressed in ITER.

- Due to small ratio \( V_{\text{perp}}/c \) loss of runaway electrons is extremely localized.

- Expected wetted area in ITER is only 0.3-0.6 m\(^2\).
Possible strategies

\[ \frac{dI_{RA}}{dt} = I_{RA} \left( \gamma \left( \frac{E}{E_c} - 1 \right) - \frac{1}{t_{loss}} \right) + S \]

- Increase density (Rosenbluth's density)
- Collisional \( E/E_c < 1 \)
- Reduce \( E \)
- Suppress avalanche

Disruption

- Magnetic confinement of RE current
- In ITER decay of RE current is determined by MGI
  \[ t_{CQ,RE} \sim 5-6 \text{ s} \]

MGI experiments are conducted in some large tokamks.

De-confinement by RMP in ITER is discussing.
(O-26: G. Papp et al.)
Summary and Future Prospect

- Large progress in experiments and development of diagnostics has been made for last two years. Further progress is required toward future burning plasma experiments such as ITER, having frequent and effective interactions among experimentalists and theorists.

- Energetic particle research area are still in a growing phase and will provide a lot of interesting physics.