SUMMARY of

STABILITY and ENERGETIC PARTICLES

WAVES and CURRENT DRIVE

IAEA 2004

R. D. Stambaugh

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<td>65</td>
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Wall stabilization physics understanding is key to sustained plasma operation at maximum $\beta$

- High $\beta_t = 39\%$, $\beta_N = 6.8$ reached
- Operation with $\beta_N/\beta_N^{no-wall} > 1.3$ at highest $\beta_N$ for pulse >> $\tau_{wall}$
- Global MHD modes can lead to rotation damping, $\beta$ collapse
- Physics of sustained stabilization is applicable to ITER

Sabbagh, EX/3-2
NEW INTERNAL CONTROL COILS ARE AN EFFECTIVE TOOL FOR PURSUING STABILIZATION OF THE RWM

- Inside vacuum vessel: Faster time response for feedback control
- Closer to plasma, flexible magnetic field pattern: more efficient coupling

- 12 "picture-frame" coils
- Single-turn, water-cooled
- 7 kA max. rated current
- Protected by graphite tiles
- 10 gauss/kA on plasma surface

Okabayashi  EX/3-1Ra
Reimerdes  EX/3-1Rb

269-04/01/jy
RWM FEEDBACK ASSISTS IN EXTENDING $\beta_n \approx 4$ ADVANCED TOKAMAK DISCHARGE MORE THAN 1 SECOND

- The rotation is similar for both cases

Okabayashi EX / 3-1Ra
Reimerdes EX / 3-1Rb
see also Ferron EX/P 2-21
“Optimizing the Beta Limit in DIII-D”
Both the ideal kink and RWM mode branches must be considered in feedback dynamics.

- Coupled kink-wall mode system has two weakly damped roots in rotationally-stabilized regime.
- At low $s$, response decays quickly.
- Near ideal-wall limit, rotating plasma root decays slowly and phase-oscillations indicate plasma root’s real frequency.

<table>
<thead>
<tr>
<th>Discharge #</th>
<th>Estimate</th>
<th>$\tau_s$ (ms)</th>
<th>$f_r$ (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>39262</td>
<td>0.50 ± 0.25</td>
<td>0.70 ± 0.2</td>
<td>5.5</td>
</tr>
<tr>
<td>39263</td>
<td>0.92 ± 0.33</td>
<td>0.50 ± 0.15</td>
<td>5.1</td>
</tr>
<tr>
<td>39267</td>
<td>0.72 ± 0.30</td>
<td>0.50 ± 0.15</td>
<td>4.8</td>
</tr>
<tr>
<td>39245</td>
<td>0.51 ± 0.25</td>
<td>0.60 ± 0.2</td>
<td>6.1</td>
</tr>
<tr>
<td>39264</td>
<td>0.75 ± 0.31</td>
<td>0.43 ± 0.15</td>
<td>5.3</td>
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<tr>
<td>39258</td>
<td>0.24 ± 0.20</td>
<td>0.23 ± 0.1</td>
<td>&lt; 4.0</td>
</tr>
<tr>
<td>39534</td>
<td>0.11 ± 0.15</td>
<td>0.15 ± 0.1</td>
<td>&lt; 6.5</td>
</tr>
<tr>
<td>39255</td>
<td>0.22 ± 0.18</td>
<td>0.30 ± 0.1</td>
<td>&lt; 3.5</td>
</tr>
</tbody>
</table>
WALL STABILIZATION IN THE RFP

MST: test theory of mode locking by wall eddy currents

One free parameter: momentum confinement time

Experiment consistent with theory

EXTRAP T2R: Feedback coils (16 toroidal and 4 poloidal) suppress a spectrum of unstable modes

Prager OV / 4-2

Drake EX/P 2-20
WHAT DISSIPATION MECHANISMS PROMOTE STABILITY?

Comparisons with MARS calculations:

- Critical rotation velocity
- Resonant Field Amplification

![Graph showing comparisons with MARS calculations](image)

DIII-D
- Okabayashi EX/3-1Ra
- Reimerdes EX/3-1Rb

JET
- Hender EX/P 2-22

Other papers: Liu TH/2-1 and Strauss TH/2-2
Successful Disruption Mitigation by Massive Gas Injection.

Runaway avalanche suppressed with sufficient electron injection.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Gas</th>
<th>$\frac{N_e}{V_{\text{plasma}}}$</th>
<th>$\frac{N_{0,\text{inj}}}{V_{\text{plasma}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIII-D</td>
<td>Ne, Ar</td>
<td>3e19</td>
<td>2e21</td>
</tr>
<tr>
<td>Tore Supra</td>
<td>He</td>
<td>3e19</td>
<td>3e21</td>
</tr>
<tr>
<td>JT-60U</td>
<td>Ar, Kr, Xe, He</td>
<td>1e19</td>
<td>6e19</td>
</tr>
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</table>
Runaways Tremendously Suppressed.

He Jet, EX/10-6Rc Tore-Supra

Gas Jets Better Than Pellets.
EX/10-6a DIII-D Hollmann

[Graphs showing neutron emissions and X-ray brightness in the context of plasma parameters and injection rates]
Pretty good in terms of underlying NTM physics and metastable threshold...

- power ramp-down experiments measure $\beta$ at which $3/2$ NTM self-stabilises

- ITER baseline operation point deeply into metastable region
  - small triggers can excite mode
  - mode removal requires driving island down to small sizes
Destabilisation of fast particle stabilised sawteeth now achieved:
- core ICRH stabilises sawteeth
- ICCD destabilises as inversion radius is approached
2/1 TEARING MODE IS COMPLETELY SUPPRESSED BY ECCD

2/1 mode suppressed in hybrid discharge with $\beta_N$ well above ITER baseline scenario

The (2/1)-NTM is preceded by a phase (grey shaded) where the mode is locked to the vacuum vessel

“Target lock” algorithm uses small, rapid variations in $B_T$ to optimize suppression

Petty    EX / 7-3

Maraschek  EX / 7-2
Early ECCD is more effective for an NTM suppression, even at high $\beta_N$.

- Early ECCD is more effective to suppress NTM:
  - island size ($\sim |dB/dt|/f$) quickly suppressed
  - less power for full stabilization
  - calculated necessary power for full suppression based on mod. Rutherford eq. agrees well with the experiments (arrows).

K. Nagasaki (EX/10-3, Thu.)
(3,2) NTMs in FIR regime for $\beta_N > 2.3$

FIR regime similar in dimensionless parameters (ASDEX Upgrade and JET)
Active stabilization on ITER only for (2,1) NTM needed?

Guenter  OV / 1-5
Maraschek EX / 7-2
PEELING-BALLOONING MODEL OF ELMS CONVERGING

EX/2-5Rb DIII-D Fenstermacher

EX-P/1-4 JET Stober

EX-P/3-4 AUG Horton

EX/2-1 JT-60U Oyama
Most unstable modes from ELITE linear P-B stability analysis are $16 \leq n \leq 24$

CIII emission structure during ELM suggests $n \sim 17$
FILAMENTARY STRUCTURE SEEN IN MANY MACHINES

EX/2-3 MAST Kirk

EX/2-4Rb AUG Hermann

EX/2-6 AUG Lang

EX/2-2 NSTX Maingi

Detailed Filamentary Nature of ELMs In EX/2-4Ra JET Fundamenski

Strike Point Jump EX/P1-3 JET Solano
ELM CONTROL BY PELLET PACE MAKING

Replace linearly unstable peeling/ballooning mode by local trigger perturbation

- only minor confinement degradation with increased ELM frequency compared to, e.g., gas puffing (pedestal temperature reduced!)
- energy loss per ELM for pellet triggered ELMs as for “natural” ELMs
- successful ELM control also by small wobbling
QH-MODE IN ASDEX UPGRADE

- Large $E_R$ in the barrier, 2× normal H-mode
- Energetic particle effects near the barrier
- EHO/HFO necessary features

EX/1-4 AUG Suttrop
QH-MODE IN JT-60U

- Pedestal parameters almost constant during QH phase

$T_e$ (keV)

$\bar{n}_e (10^{19} \text{ m}^{-3})$

$T_i^{\text{ped}}$ (keV)

$n_e^{\text{ped}} (10^{19} \text{ m}^{-3})$

$P_{\text{inj}}$ (MW)

$P_{\text{abs}} \approx 7 \text{ MW}$

$Prad$ (MW)

$D\alpha$ (a.u.)

$QH$ (low $\delta$)

- $T_i^{\text{ped}}$ also smaller in QH phase

EX/2-1 JT-60U Oyama

$\sim 18\%$
ELM AMPLITUDE AND FREQUENCY CAN BE CHANGED BY TOROIDAL ROTATION

- Larger counter rotation leads to smaller ELM and higher frequency.
- New parameter for access to grassy ELM regime. 
  
  *Absolute value? or Sign?*

- No edge fluctuations were observed even in larger counter rotation phase.

**Toroidal rotation profile**

- **Small CTR-V**
- **Top of Ti**
- **Large CTR-V**

**Standard scenario**
ELITE STABILITY MODELING: QH MODE IS MARGINALLY STABLE TO CURRENT DRIVEN PEELING/BALLOONING MODES

ELITE Stability Diagram from the experimental case, $x$, and perturbed equilibria, $x$

---

**Upward $I_p$ ramps during QH operation induce ELMS, supporting the ELITE result of marginal stability to current driven modes.**
EDGE FIELD PERTURBATION CAN SUPPRESS ELMS WITHOUT DEGRADING CONFINEMENT

- Several isolated ELM-like events remain
- ELMs return after I-coil pulse turns off
DIII-D/JET pedestal similarity experiments show importance of neutral penetration

- Matched shapes and \((\beta, \nu^*, \rho^*, q)\) at top of pedestal
- Neutral penetration physics dominates in setting the density width
  - Mahdavi-Wagner model reproduces differences in DIII-D vs JET profiles
- Plasma physics dominates in setting the transport barrier
  - \(T_e\) width \(\propto a\)

**Graphs:**
- Neutrals scaled to DIII-D: \(n_e \propto a^{-2}\)
- Temperature scaled to DIII-D: \(T_e \propto a^{-1/2} A^{5/4}\)
M3D: Sheared-flow reduces growth rate by factor of 2-3

• Possible because $\gamma_{\text{shear}} \sim \Omega_{\text{rotation}}$ can be of $> \gamma_{\text{linear}}$

In experiment, the NBI power is held roughly fixed

In M3D, with a fixed momentum source rate, the $v_\phi$ and $p$ profiles flatten inside the island, reconnection still occurs (saturated state rare)
PLASMAS THAT VIOLATE THE MERCIER CRITERION DO NOT SUPPORT AN ELECTRON PRESSURE GRADIENT

Indented Plasmas:
- Mercier limit occurs at q<1
- Local electron heating results in strongly increased gradient

Oval Plasmas:
- Mercier limit occurs at q>1
- Local electron heating results in almost no change in gradient
V- Preparing for Burning Plasma Experiments

‘Monster’ sawtooth control

core +90° phasing ICRH to make fast particles and large sawteeth (period up to 0.4s)

q=1 -90° phasing ICRH for current drive sawtooth destabilisation

Essential technique for ITER to control fast alphas stabilised sawteeth

R.Buttery, EX/7-1

LG.Eriksson et al PRL92 (2004)235004
EC Effects on Sawtooth Period
EX-P/5-16 TEXTOR Westerhof
Locked mode threshold has weak size scaling

- Set of external non-axisymmetric control coils installed.
- Allow determination of intrinsic error field and mode locking threshold.
- Dimensionless identity experiments performed w/JET, DIII-D.
- Weak size scaling found.
- Locked modes should not be worse for ITER than for current machines.
- Coils allowed suppression of locked modes, 2 MA operation.
Study on MHD stability limit of high beta plasma

Role and Function of Boundary

\[ \gamma = 1.22 \]
\[ (\gamma = n/m \cdot a_c/R = \kappa \varepsilon) \]

\[ T_e(T_i): \text{Thomson} \]
\[ n_e: \text{FIR} \]

- $\beta$ values achieved significantly exceeds the Mercier limit and increases up to $m/n=1/1$ ideal MHD limit

Achieved beta is close to the $m/n=1/1$ ideal mode limit

Achieved beta significantly exceeds the Mercier limit

kinetic beta gradients at $\rho=0.9$ ($\nu/2\pi = 1$) in $<\beta>-d\beta/d\rho$ diagram.
Degradation of Equilibrium May set $\beta$ Limit

- PIES equilibrium calculations indicate that fraction of good surfaces drops with $\beta$

- Drop occurs at higher $\beta$ for higher $I_{CC} / I_M$

- Experimental $b$ value correlates with loss of $\sim 35\%$ of minor radius to stochastic fields or islands

- Loss of flux surfaces to islands and stochastic regions should degrade confinement. May be mechanism causing variation of $\beta$.
Other Stability Results

• EX-P/5-8 CT-6B Khorshid - Limiter Biasing Affects Rotation Which Affects MHD Stability
• EX-P/5-12 HL-1M Liu - Snake Perturbations Excited by Pellet Injection and During LHCD
• EX-P/9-6Rb HANBIT Jhang - Interchange Stability Window with Strong RF
ALFVEN EIGENMODES

Alfvén cascades excited by $^4$He ions in JET reversed-shear discharge EX/5-2 Sharapov

TAE modes in low density ICRH heated discharges in ASDEX-Upgrade EX-P/4-37 Borba
MHD Spectroscopy and the Evolution of $q_{\text{min}}$ in the Current Rise of Alcator C-MOD

EX/5-1 Nazikian

- MHD spectroscopy useful when MSE is challenging
- Higher-$n$ gives higher $q_{\text{min}}$ resolution
- Core fluctuations measurements access higher-$n$
Application of MHD Spectroscopy: Onset of ITB Triggered by Integer $q_{\text{min}}$ Crossing on JET

- What role do Cascades play in ITB triggering?
Breakthrough: Interferometer Measurements Reveal Many Hidden Modes in Reverse Shear Plasmas on JET

- Interferometer $n > 16$
- Reflectometer $\bar{B}/B \approx 1.5 \times 10^{-4}$ for $n=3$
- Fast ion loss not observed

S.E. Sharapov et al., PRL 93 (2004) 165001

EX/5-1 Nazikian
EX/5-2 Ra Sharapov
A “Sea of Alfvén Eigenmodes” Observed in DIII-D Plasmas Driven by 80 keV Neutral Beams

- Bands of modes \( m=n+l, l=0, 1, 2, \ldots \): \( w_{n+1} - w_n \approx w_{\text{rot}} \) (CER)
- Neutral beam injection opposite to plasma current: \( V_{||} \approx 0.3V_A \)
- \( 8 < n < 40, k_q \) up to 2.0 cm\(^{-1}\) (Turbulent scale length !!)
TAE can cause significant losses at both low and high aspect ratio,

- Largest losses occur with multiple unstable modes.

On NSTX:
- TAEs most virulent in low-shear, \( q(0) \approx 2 \) regime*.
  - TAE seen at toroidal \( b \)'s greater than 20%.
  - Observed growth rates in good agreement with NOVA estimates.
  - Up to 15% drops in DD neutron rate from TAE.
- With higher shear, TAE not bursting
  - no enhanced fast ion loss

EX/5-3 Frederickson

Confinement of energetic ions at ALE

• In a JT-60U weak shear plasma, N-NB drives bursting mode in the TAE freq. range.
  => Abrupt Large Event (ALE)

• How are energetic ions affected?

  Only ions in limited energy are affected.
  =>Agrees with AE resonant condition
  =>Contribution to theory/modeling towards burning experiments.

E43014, Ip=0.6MA Bt=1.2T
P\textsubscript{NNB}~ 4.8MW, ENNB~387keV

<neutron emission>

<energy distribution of neutral particle>
Configuration Dependence of Energetic Ion Driven Alfvén Eigenmodes in the Large Helical Device

S. Yamamoto¹, K. Toi², N. Nakajima², et. al.,
1) Institute of Advanced Energy, Kyoto University, Uji, Japan
2) National Institute for Fusion Science, Toki, Japan

◆ Motivation

It is important to clarify the configuration dependence of Alfvén eigenmodes (AEs) because the existence and stability of them sensitively depend on the profiles of the rotational transform \( j / 2p \) and magnetic shear \( s \).

⇒ We have experimentally studied the AEs in various magnetic configurations (high, middle and low \( s \)).

◆ Conclusion

Continuum damping, of which damping rate is related to the magnetic shear and toroidal mode number \( n \) (\( \gamma_c \sim n^{3/2} \) and \( \sim s \)), would be the most important damping mechanism in the LHD plasma.
EPM activity reduces with $\beta$ on MAST

For $\beta > 5\%$ TAE and EAE activity become dominated by non perturbative down-frequency chirping modes
The **amplitude of these modes falls sharply with increasing** $\beta$, vanishing for $\beta > 15\%$

$\Rightarrow$ AE activity likely to be absent in a future ST device where $\beta$ on axis would approach 100%

See S. Sharapov EX/5-2Ra
Validation of key ICRF scenarios for ITER are being carried out

(³He)H used on JET for pre-activation experiments in ITER

(³He)H 3.6T / 2MA, 37 MHz
- Pulse No 63312: dipoole
- Pulse No 63313: +90°
- Pulse No 63314: -90°

+90 deg phasing more efficient due to improved ion orbits

(T)D used when T experiments begin

D-T neutron yield

- P_{RF}
- P_{PND(D)}

Strong increase in reactivity observed with 1.4 MW ICRF

EX/P4-26 Lamalle
ICRF is useful in experimental applications

Mode conversion current drive

- Direct launch IBW in FTU (OV/4-6 Gormezano)
- Heating from ICRF (H)D found in Globus-M (EX/P4-24 Gusev)
- Fundamental heating of H found in T-11M (EX/P4-29 Maltsev)
- FWCD for heating on NSTX, but edge absorption a problem (OV2-3 Kaye)

sawtooth control found in Alcator C-Mod

EX/P4-32 Porkolab; TH/P4-35 Wright
ITER relevant coupling of Lower Hybrid Waves

D injection improves LH coupling over large gap

Successful use of PAM obtained in FTU

3 MW coupled, but D affects ELMs Doesn’t affect ITB

Efficiency of PAM equal that of other antennas (EX5/5 Pericoli)

Multijunction antenna with improved directionality successfully used in HT-7 (EX/P4-19 Ding)

EX/P4-28 Mailloux
LHCD is useful in present experiments

- Control of CD location by phase control found on JT-60U

- 6.5 minute discharge sustained by LHCD on Tore Supra

- 5.6 hour discharge sustained by LHCD on TRIAM-1M

- H-mode by off-axis LHCD in HT-7 (OV-1Rb, Wan)

- Current profile by LHCD used on HL-2A to generate RS

EX/P4-21 Gao
Synergy between RF waves can increase current drive efficiency

Synergy when LH and EC waves absorbed at same location
ECH predictability is addressing the extremes

Third-harmonic, top-launch, ECRH experiments on TCV Tokamak

Theory and experiment are well coordinated
Feedback system successfully used

EX/P4-17 Alberti
Toroidal Current Generated Without a Solenoid

Non-solenoidal current generation/sustainment essential in future ST

1) PF-only startup
   - 20 kA generated

Goal is to maintain plasma on outside where $V_{\text{loop}}$ is high

2) Transient Co-Axial Helicity Injection
   - $I_p$ up to 140 kA, $I_p/I_{\text{injector}}$ up to 40

Goal is to extend $I_p$ beyond duration of $I_{\text{injector}}$
Alternative start-up schemes investigated

One such scheme is being developed in association with ENEA. Double-null merging (DNM) involves breakdown at a quadrupole null between pairs of poloidal coils in upper and lower divertor. Modelling predicts merging of plasma rings as current in coils ramped to zero. DNM is compatible with future ST design.

OV/2-4 MAST Counsell
Transformerless Startup by ECH and Bv in LATE EX-P/4-27 Maekawa

(1) $t < 0.5$ s  Vacuum

(2) $t = 0.75$ s  Interferometer Chords

(3) $t = 4.35$ s

$\Phi_c$  Flux Loops

$R (\omega=2\Omega_e) = 27.4$ cm

$IP = 3.2kA$

$A \sim 1.35$

$\kappa \sim 1.34$

$2^{nd}$ Harmonic EC

Heating by EBW

SX CT Image
Completely CS-less Start-up in JT-60U

100 kA maintained for 0.2 sec

- Start-up with VR and VT\textsubscript{out} only (VT\textsubscript{in} coil not used)
- With strong enough EC ionization, Ip starts up with Bv in the negative direction (no field null)

EX/P4-34 Y. Takase, et al.
How is the dynamo current generated in the RFP?

\[
\langle E \rangle + \langle \tilde{v} \times \tilde{B} \rangle - \frac{\langle \tilde{j} \times \tilde{B} \rangle}{ne} = \eta \langle j \rangle
\]

MHD dynamo

Hall dynamo, two-fluid effect

The standard model

significant in quasilinear theory

j and B measured by Laser Faraday Rotation (UCLA)

OV/4-2 MST Prager
Transformer Recharging by Excess Non-Inductive Current Drive

LHCD OV/5-1Rb HT-7
Wan

Bootstrap Overdrive EX-P/4-34 JT-60U Takase
The desired steady-state operating point may not be a stationary solution to the coupled fluid equations. If not, active control is required.

Inductive control of the plasma current may be desirable \(\Rightarrow\) non-inductive overdrive will be required.

At high safety factor \((q_{95}\sim10)\) and high \(q_{\text{min}}\) \((\sim3)\), the bootstrap current fraction is \(>80\%\).
Nonlinear interplay between transport and current profile at the onset of the core ITB

\[ \Rightarrow \text{RT control of current profile required (for ex, ECCD)} \]

See also 150 second PWI related oscillations in TRIAM-1M OV/5-2 Zushi
SUMMARY CONCLUSIONS

**RWM** – Progress in fundamental understanding and direct feedback with low rotation.

**NTM** - ECCD suppression becoming an application.

**Disruptions** – Massive Gas Injection mitigates all consequences.

**ELMS** – Peeling-Ballooning Model Converging. Many avenues of approach to tolerable ELMS.
Stability - Stellarator Beta limit studies beginning.

Alfven – Internal plasma diagnostics show modes more pervasive than was thought.

Waves - Synergy between waves can increase current drive efficiency.

Current Drive – Long pulse, transformerless operation challenging for the future.