S1/2

EX/S, EX/D, EX/W

S1/2

- EX/S - Magnetic Confinement Experiments: Stability
  - 47 papers
- EX/W - Magnetic Confinement Experiments: Wave–plasma interactions, current drive & heating, energetic particles
  - 58 papers
- EX/D - Magnetic Confinement Experiments: Plasma–material interactions – divertors, limiters, SOL
  - 50 papers

156 papers

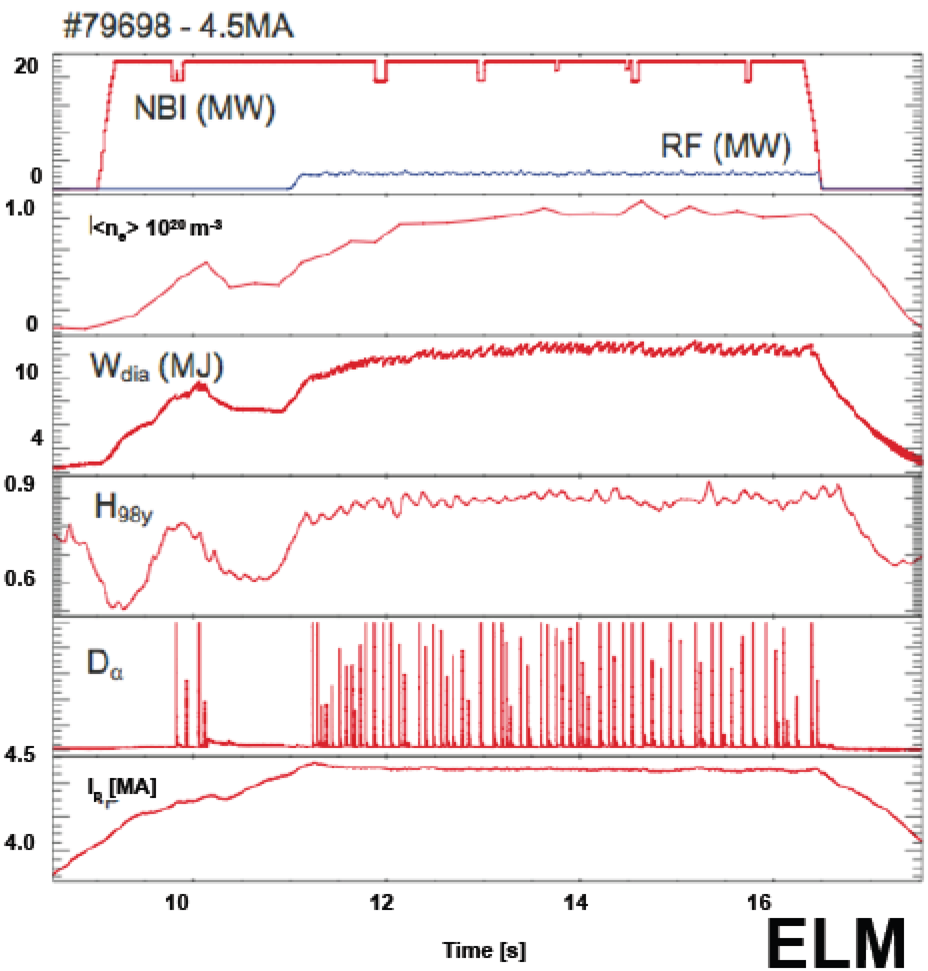
Apologies: non exhaustive “issue driven” report

Write to jean.jacquinot@cea.fr for suggestions to be included on the written summary

Stability

- Issues
  - ELM’s, RWM etc: occurrence – strength – understanding – mitigation
  - Disruption and runaway electrons
  - Fast particles: AE’s etc.
  - Real time control

The ELM ISSUE



ITER divertor will not tolerate "classical" type 1 ELMs:

Extrapolated frequency to be increased by > 30 or elimination altogether

ELM (

for di

also f... high confinement

see Nunes, EXC/P8-03

Elm issue

- **2 different approaches:**
  - Beat them: 2 “Quiescent” regimes proposed for ITER **(see S1/1)**
    - **Alcator I-mode**
    - **DIII-D quiescent modes**
    - **Both with good confinement without ELMs**
      - Seem ideal but scaling to ITER?
  - Join them:
    - **Several methods of mitigation and pacing**

ELM mitigation by perturbations

A wealth of results from JET, Mast, NSTX, JT 60 …

- Density perturbations in the pedestal
  - Pellets: OK but only Fx5 ➔ reliability?
- Fast particles
  - Mitigation by fast particle driven RWM (JT60-U)
- Pacing with vertical jogs
  - OK but only F ~ x 5; AC losses in supraconductors?
- Using 3D magnetic perturbations
  - Total stabilisation "proof of existence" from DIII-D with RMP n=3 m~11 coils, new results from JET (n=1,2; m?) and Mast but only partial stabilisation
  - Reliable pacing with fast pulses of n=3 coils m? (NSTX)

ELM mitigation by perturbations

- **Mitigation may well come with a price to pay**
  - On confinement quality
  - On threshold power (observed on RMP, n=3)
  - On rotation breaking with non resonant fields (disruption)
  - See also the new concern (R. Buttery) on the **error field threshold to trigger 2/1 modes** falls with proximity to tearing β limit

Understanding:

- Pellet pacing
  - Well accounted for by MHD simulations (Huysman)
- Effect magnetic perturbations
  - See excellent review by J. Callen at this conference
  - The RMP case of DIII-D is driven by ergodisation of magnetic fields in the pedestal. Right value of Chirikov parameter but uncertainty on the plasma response ➔ predictability??
    - **Requires good alignment (range of q possible with optimized coil as proposed for ITER)**
  - Understanding of non resonant case? Resonance with precursor?

➔ A strong case for pellet and internal coils but more work needed

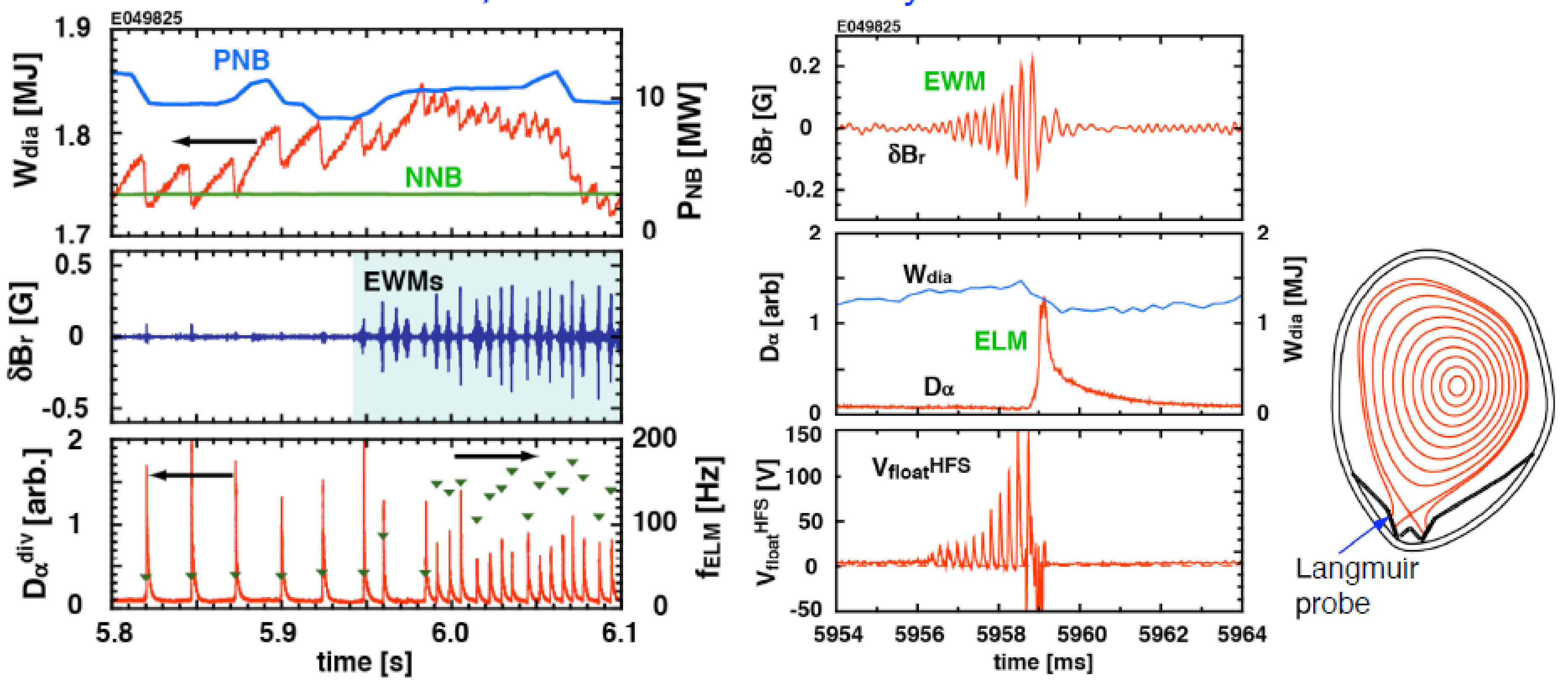
Energetic particle driven Wall Mode triggers ELM with decreasing ELM amplitude

Matsunaga, EXS/5-3 (Thu/PM)

JT60-U

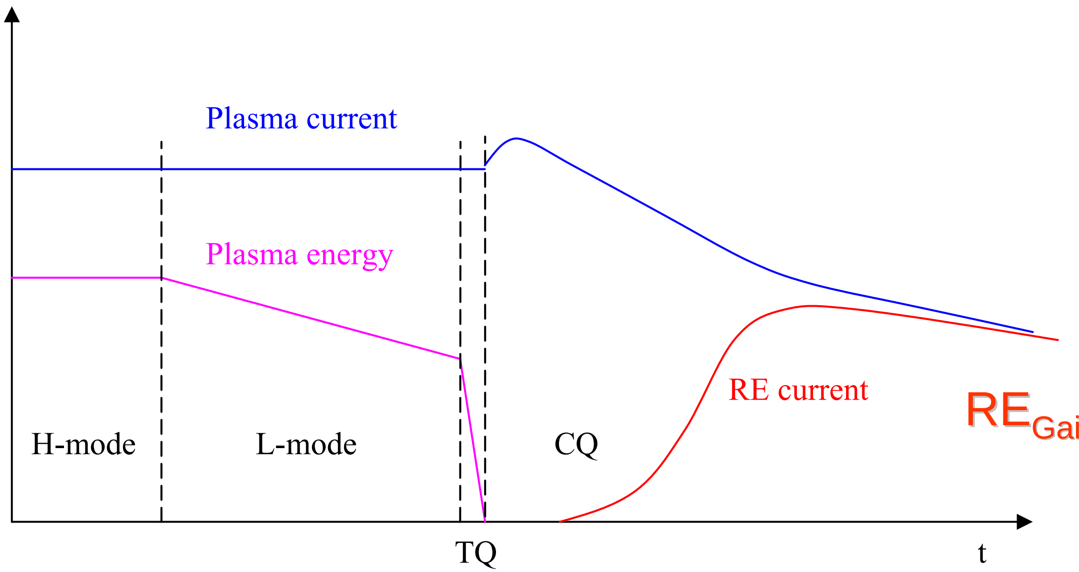
- EWM (Energetic particle driven Wall Mode): destabilized at $\beta_N > \beta_N^{no\text{-}wall}$, around q=2 ($\rho$~0.6)
- EWM-triggered ELM: f_{ELM} ↗ and ΔW_{dia} ↘ → ELM loss by half
- Divertor diagnostics: oscillations in synchronization with EWM → ion loss → increase in ∇p_{edge} → ELM trigger

Effect of fast-ion component on ELM stability



Disruption and Runaways

- ITER requirements for full scale operation:
  - 90% of plasma radiation during the thermal quench
  - < 1 MA of runaway electrons



$RE_{Gain} \sim Exp\{2.5 I_p(MA)\}$

Events during plasma disruption. S. Putvinski

Collisional RE dissipation requires exceeding a critical density given by Rosembluth-Putvinski theory. It is very high for ITER ~ $10^{22} m^{-3}$
Also MHD is not likely to deconfine REs in ITER (Izzo)

Disruption and RE (2)

- New results from Asdex-U, Tore Supra, DIII-D, C-mod, JET
  - Massive gas injection with mixtures of He, Ar
    - **> 50% radiated; <2% of RE left; forces on VV small**
    - **Uniform radiation would required 4 systems with large orifices**
  - J. Wesley suggests maintaining the equilibrium of the RE beam to dissipate it slowly. Multiple injection suggested by Putvinsky.

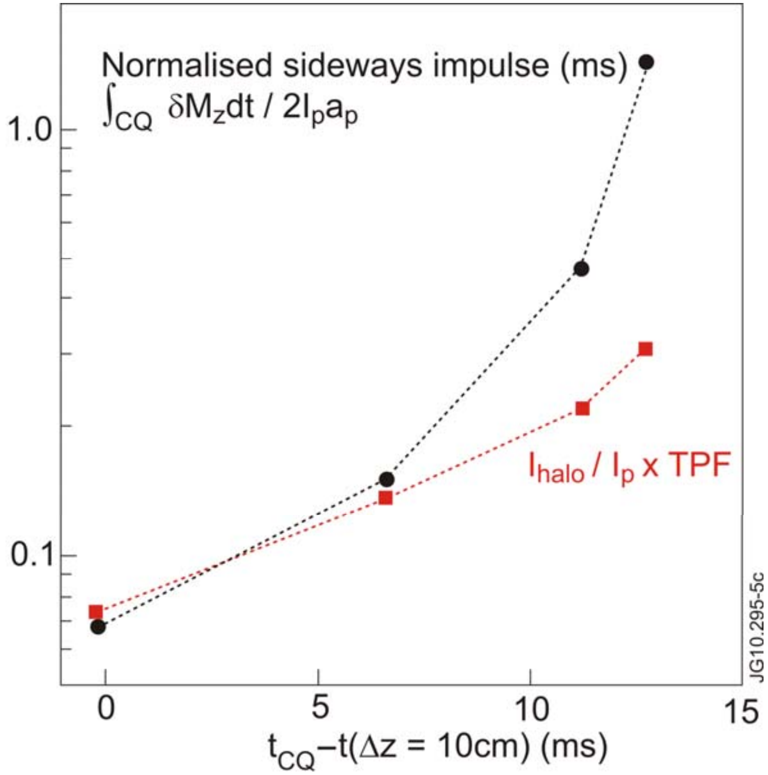
    ➔Good progress but ITER radiation requirements not met yet
- And a much broader basis:
  - Diffusive model for halo width growth during VDE
  - Survey of JET disruption occurred in the last 10 years (T. Hender): causes, forces asymmetries and extrapolation to ITER (40MN). Rather good news but also a warning: “Runaway electrons are found to be lost to small wetted areas determined by small tile misalignments/irregularities”

Disruption mitigation by massive gas injection

M. Lehnen

halo currents / sideways forces

Ar/D_2 injection during VDE



Forces

- halo currents reduced by factor of 4
- sideways forces reduced by factor of 10
- both achieved for current quench times above the ITER eddy current limit

Heat loads

- more than 50% of thermal energy is radiated
- strong radiation peaking during pre-TQ (conservative estimate suggest that 4 injection ports are needed to prevent from Be melting by local radiation in ITER)

Runaways

- safely avoided for Ar or Ne mixed with 90% D_2
- reached only 2 % of critical density for avalanche suppression, which is essential for ITER
- pure Ar or Ne injection generates runaways

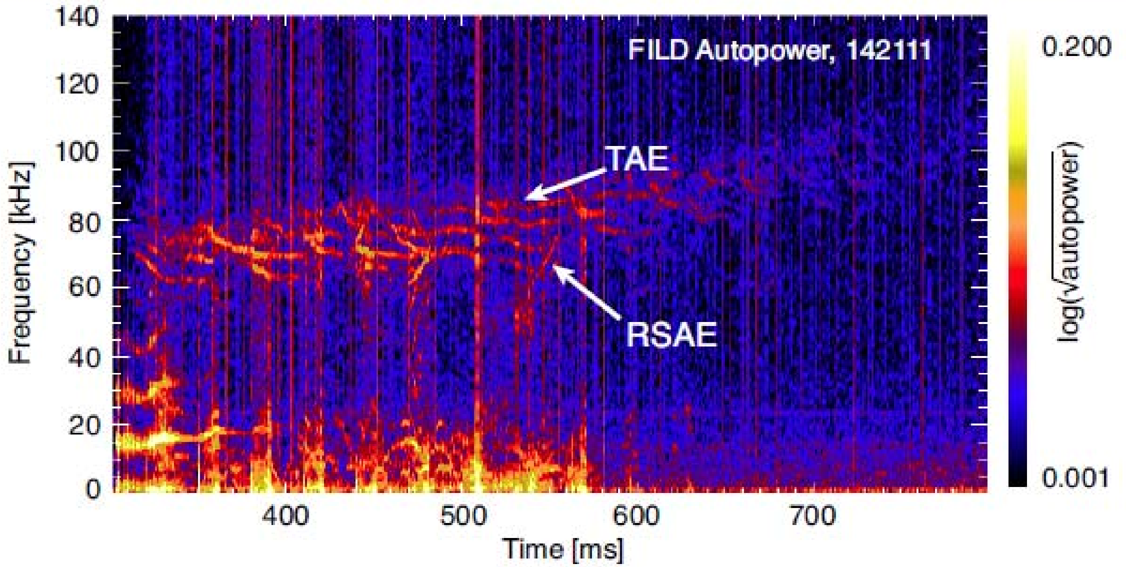
Fast particle Issues

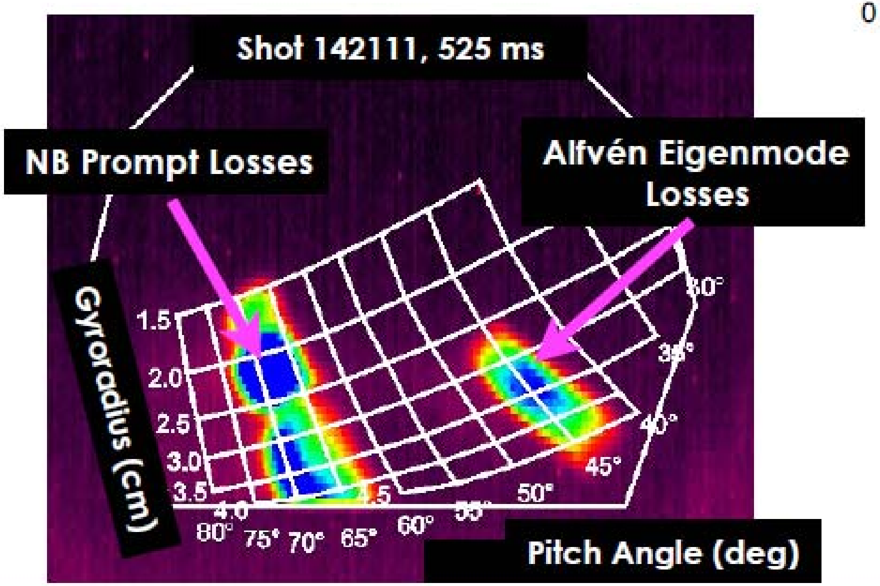
- Requirements: avoid excessive losses of fast particles potentially dangerous for the machine and for the performance.
  - Sources: fusion born α's or heating systems
  - Drive: microturbulence, sawteeth, Alfvén eigenmodes
  - ITER reference scenario estimated safe; advanced scenarios, in particular reverse shear are in danger.
- Results:
  - New powerful diagnostics (e. g. FIDA, HIBP, ..)
  - Results from DIII-D, LHD, HL-2A
    - **1st observation of e-BAE**
    - **Detailed results on GAM, Sawteeth, TAE, KAE**
- Need for integrated predictions for ITER and reactor
  - Requires the nonlinear superposition of many modes
  - An urgent task for ITER!

Energetic Ion Losses are Observed at Frequencies Corresponding to Both Toroidal and Reversed-Shear Alfvén Eigenmodes

D. Pace

- Majority of the loss activity appears at TAE frequencies; clear observation of some RSAE activity





- Neutral beam prompt losses are accounted for in analysis
- Losses at the TAE frequency are observed in a narrow region of phase-space
  - pitch angle: 42° ≤ α ≤ 48° (± 5°)
  - energy corresponds to full energy of neutral beam injection: 80 keV

Ido, Todo

Geodesic acoustic mode (GAM) - background -

Geodesic acoustic mode (GAM): a branch of zonal flow

Turbulence-driven GAM

Nonlinear coupling of micro-turbulence

$$\tilde{\phi}, \tilde{v}_p, \tilde{n}_e$$

Energetic-particle driven GAM

Velocity space anisotropy

in the energetic particle distribution function.

Global GAM (GGAM) -MHD-

(JET: Berk H et al 2006 Nucl. Fusion ***46****, S888,*
Boswell CJ et al 2006 Phys. Lett. A , ***358****, 154)*

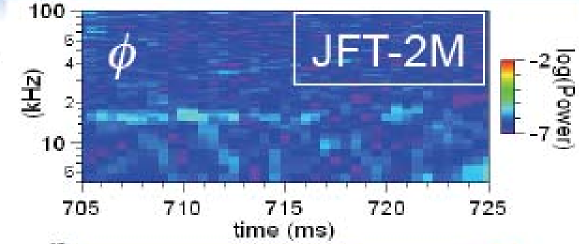
Energetic-particle-induced GAM (EGAM) -Kinetic-

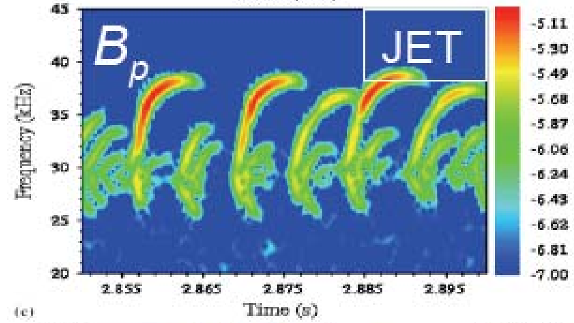
(DIII-D:Nazikian R et al 2008, Phys. Rev. Lett. 101, 185001.
Fu G 2008, Phys. Rev. Lett. ***101****, 185002.)*

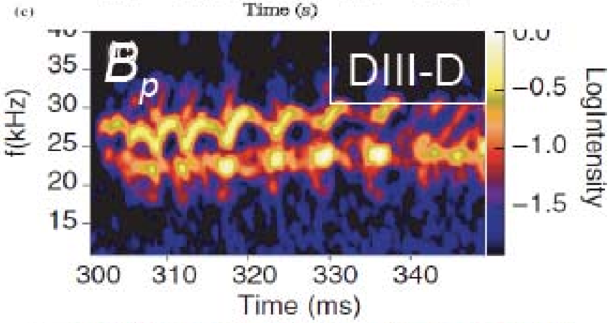
(LHD: Toi K et al, 22nd IAEA FEC, EX_P8-4)

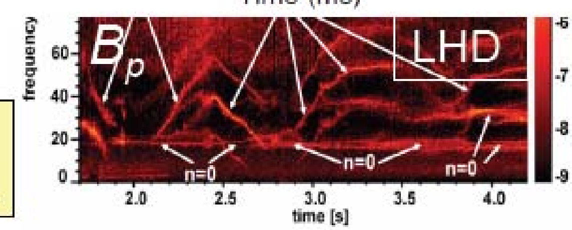
$$\tilde{B}_p, \tilde{n}_e, \tilde{T}_e$$

⇨ In this study, $\tilde{\phi}$ is measured locally and directly using a heavy ion beam probe in the LHD plasmas.









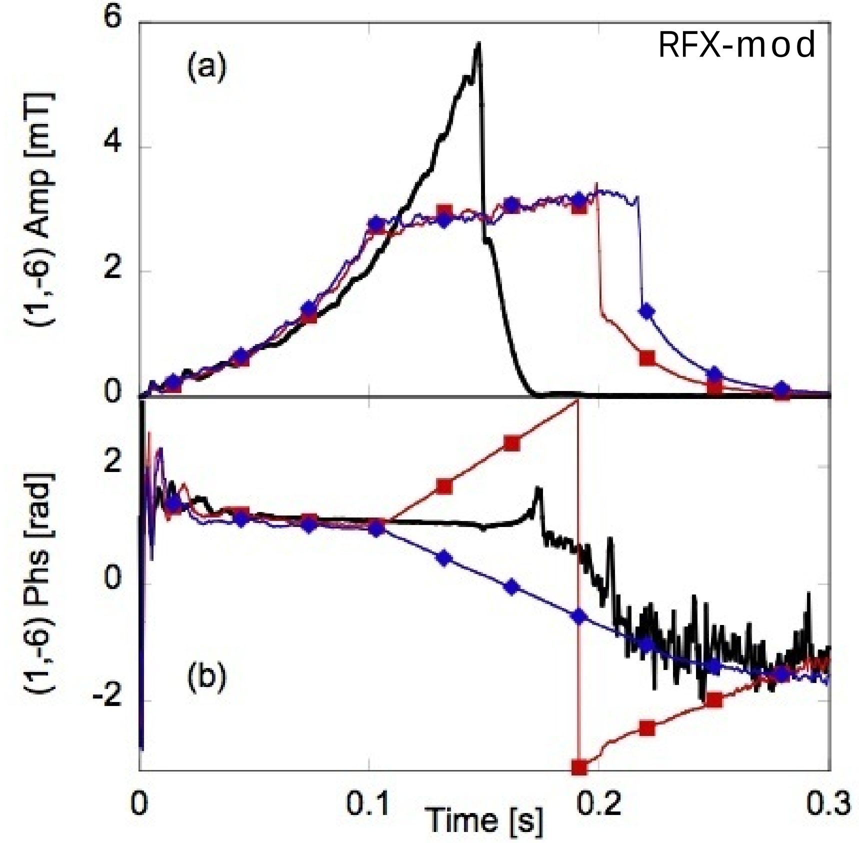
Sensors, actuators, real time control

- **Issue:**
  - Simultaneously control profiles, stabilize an increasing number of modes and maintain suitable plasma regime
- **Progress:**
  - Multi actuator MHD control; Extrap, RFX, MST + many
  - Example of diagnostics: 2D Te ECE imaging systems: 400 channels on KSTAR, results from yesterday (Park)
  - NTM control with ECRH: 7 real time controllable launchers on TCV + …
  - “State Space controller” for RWM stabilisation (Sabbagh)
  - Profile control of Advanced Tokamak (Moreau)

MHD feedback control

RFX-mod and EXTRAP T2R are equipped with a most comprehensive system of active coils

BOLZONELLA EXS/P5-01



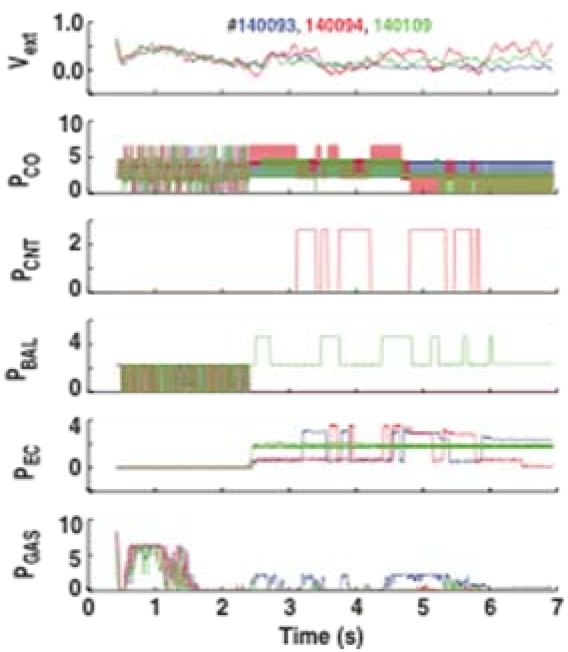
RWM amplitude

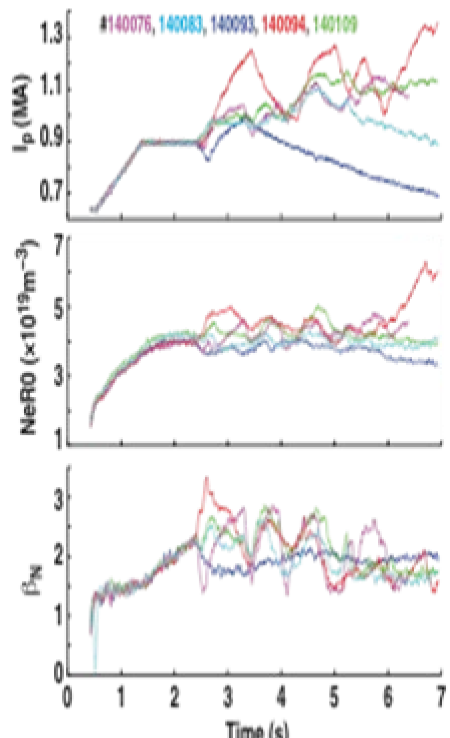
RWM phase

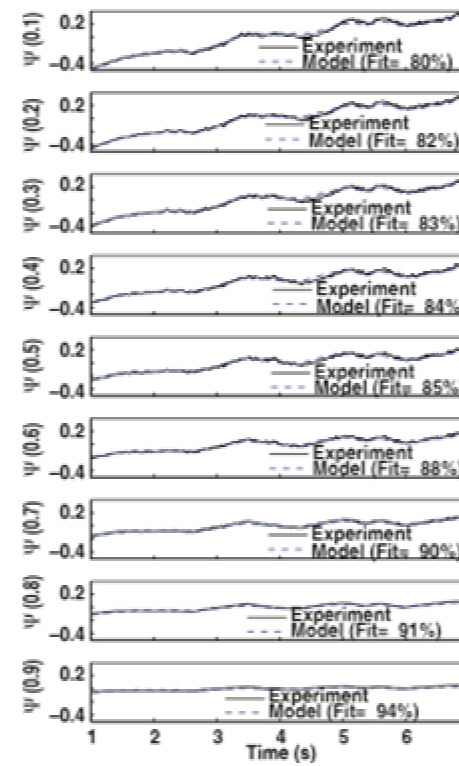
REAL-TIME CONTROL OF ADVANCED TOKAMAK SCENARIOS

D. Moreau

- Control-oriented response models for profile control obtained from actuator modulation experiments (ITPA-IOS Joint exp. 6.1)
- Shown on JET (2008) and now on JT-60U and DIII-D (e.g. Ψ + Vtor + Ti)
- The missing link for closed-loop magneto-kinetic control on advanced scenarios and control simulations on ITER.







D. Moreau, et al., IAEA FEC Daejeon 2010, EXW-P2-07

Limiter and divertor issues

- Snow flake divertor
  - An idea of Ryutov first tried on TCV ➔ increased flux expansion, low frequency ELM's
  - Upgrades foreseen for NXTX and MAST
- Low recycling with Lithium with improved performance
  - Liquid lithium limiter on FTU (ETG stabilisation)
  - NSTX, TJ-II
  - Compatibility with impurity seeding

The “snowflake” divertor

- 2nd
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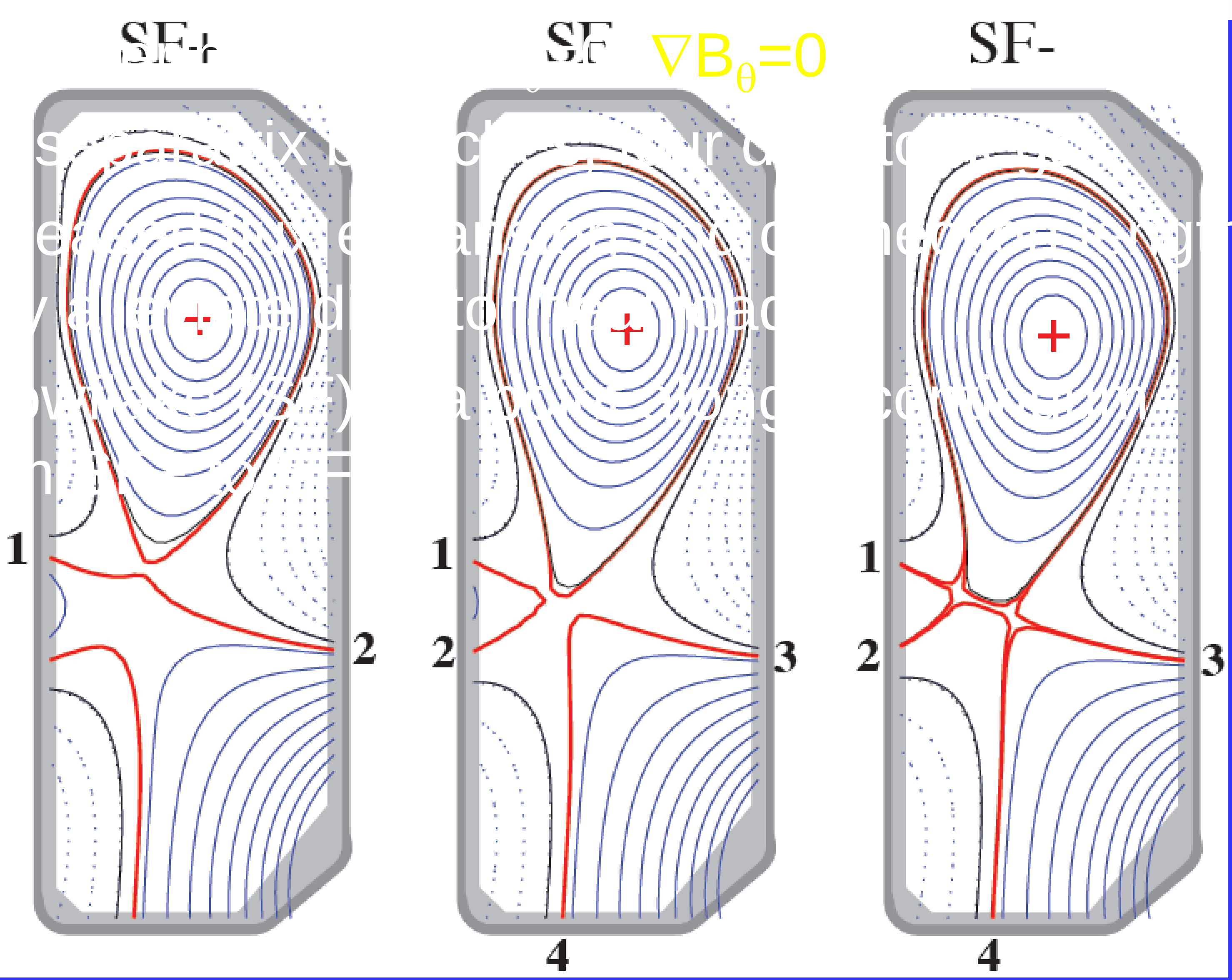


W pollution, dust, gas inventory

- Tungsten issue
  - W coated walls (Asdex-U)
    - Dominant W source is during ELMs but ELM flushing and divertor screening are effective. For ITER OK if F_{elm}>5Hz
    - N2 seeding ➔ 70% radiation, improved confinement, ΔZ moderate
    - JET tests in preparation
  - W splashes if melted (Coenen, Textor) ➔ reduced power handling, core contamination
- Dust transport in JT60-U
  - Low penetration in the plasma but hides under the divertor!
- Gas inventory (C walls in DIII-D)
  - **No** retention during the H phase, 20% during start-up (L phase)
  - Good recovery using thermo oxidation (20% O2; 80%)

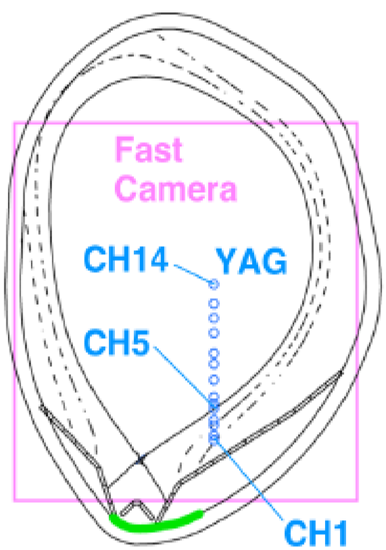
➔ **Reconcile this with other studies, well conditioned graphite?**

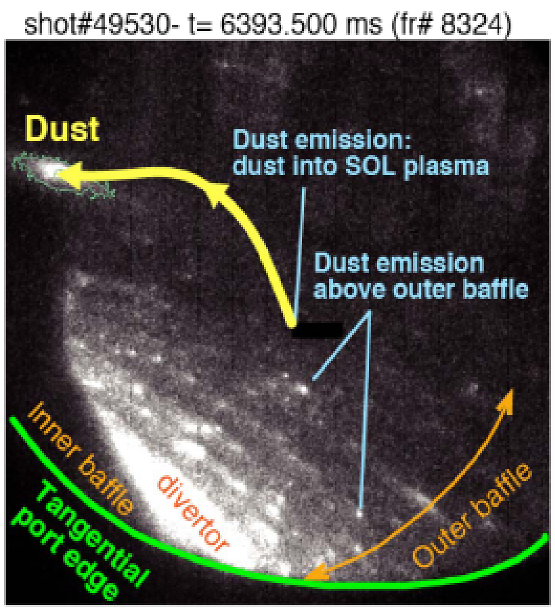
Dust transport during discharges and dust deposition in vacuum vessel have been clarified.

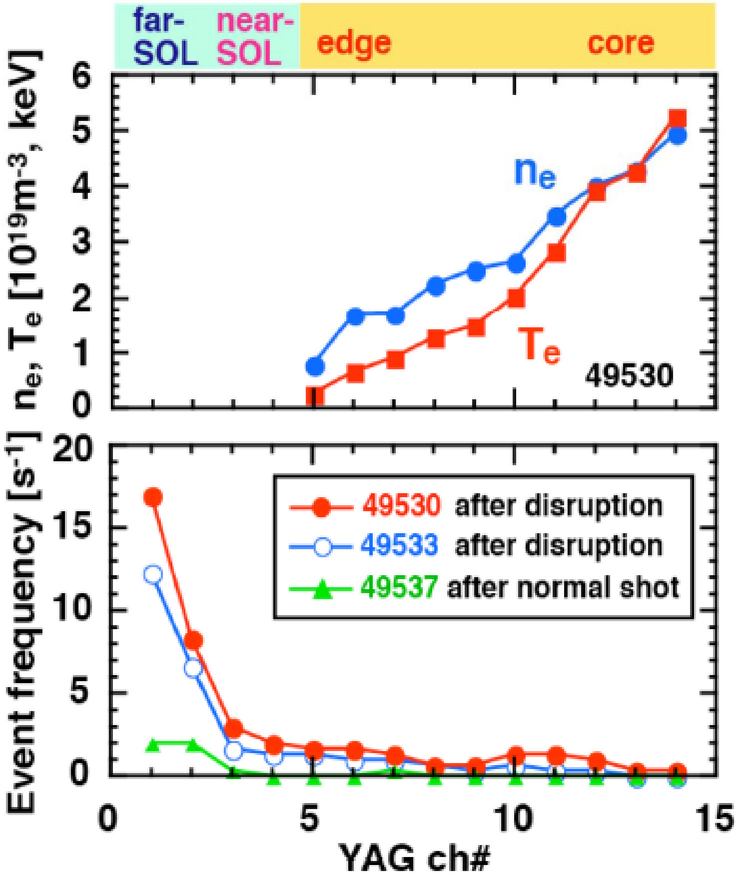
- Dust transport measurement by fast camera
- Dust distribution measurement by Mie scattering using YAG laser
  - Dust ejection/transport from divertor and outer baffle tiles
  - Distribution peak in far-SOL

  ⇒ No significant penetration into the edge and core plasma
- Dust collection: Dominant accumulation in shadow area particularly under divertor

Asakura, EXD/P3-02 (Wed/AM)





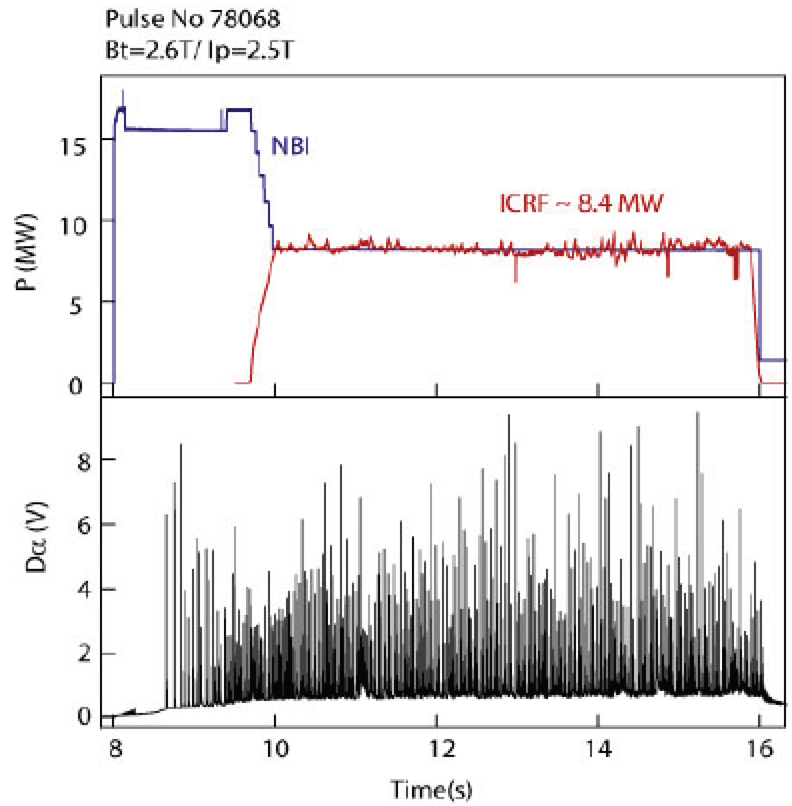


Heating, wave coupling

See S/2-2 for ITER hardware and heating mix (Wagner)

- ECRH
  - Disruption avoidance at high Beta N + modelling (Esposito)
- LHCD:
  - PAM launcher ➔ match resiliency, active cooling, remote coupling (Tore-Supra) ➔ suitable for ITER long pulse
  - Plans for SSO in EAST, KSTAR, HL etc.
- ICRH
  - Use of Elm resiliency schemes and compact antenna (JET)
  - Impurities with high Z walls ➔ contradictory results from Asdex-U and Alcator-C mod. Sources or confinement??
  - Routine wall cleaning with field on (KSTAR, EAST, TS)
  - Large core rotation with MCFD (mode conversion flow drive)

ICRH ITER relevant systems



NBI vs. high ICRF fraction H-modes ➔ 8.4MW coupled on Type-I ELMs

~ 3MW from 3dBs

~ 4 MW from ECT

~ 1.4MW from ILA

Mailloux

Three different ICRH matching system tested on JET in 2008-09

- ITER-like antenna

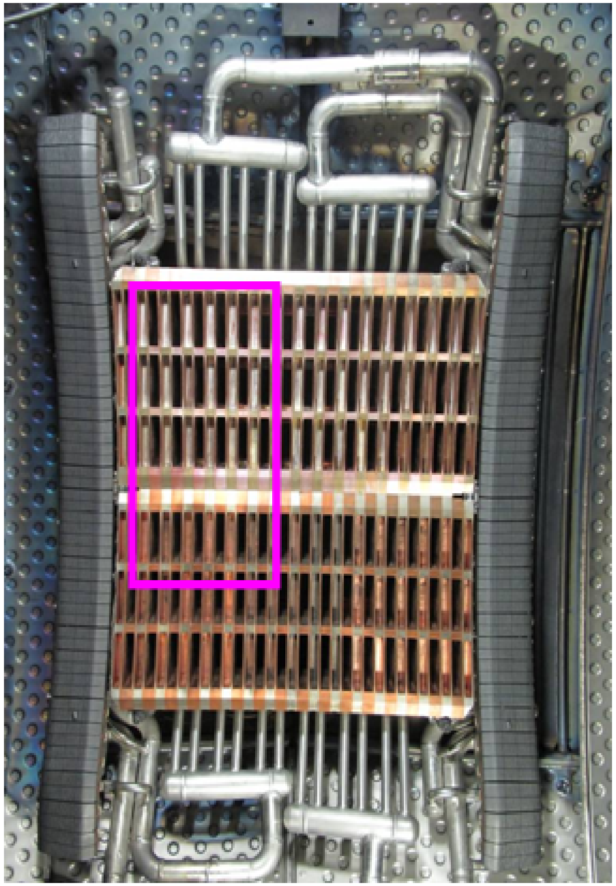
- External Conjugate T between antennas C & D

- 3dB hybrid couplers between antennas A & B

see Durodié, EXW/P7-04, Sartori, EXC/P8-12

Characterization of the properties of the PAM LHCD launcher

- New launcher built in the frame of the LHCD system upgrade
- Based on the Passive Active Multijunction (PAM) concept created for providing efficient cooling of the launcher in the ITER environment (neutron load)

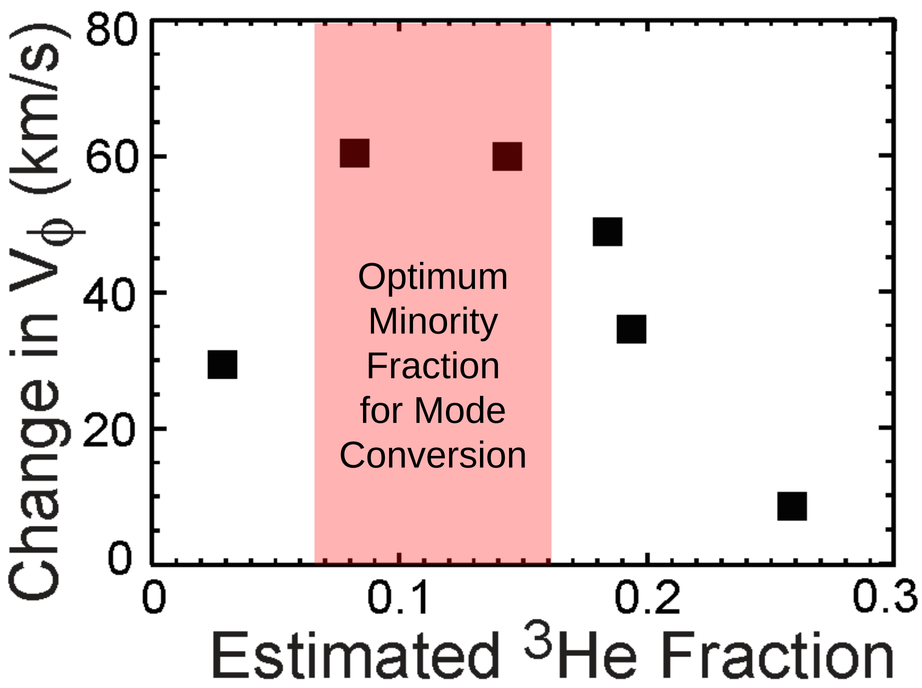


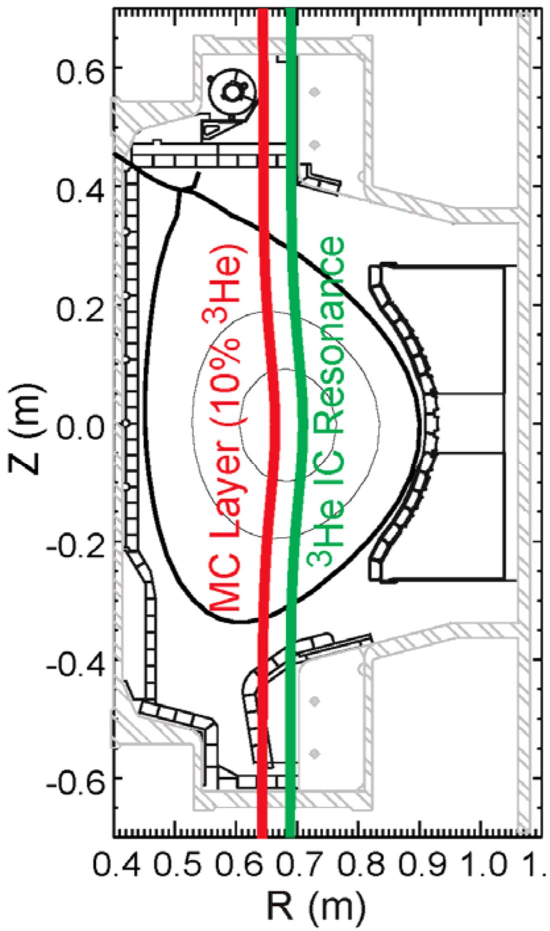
- ITER requirements:
  - Efficient cooling
  - Long distance coupling
  - ELMs resilience
  - Power density 33 MWm^{-2} at 5 GHz
  - Long pulse capability

ICRF Mode Conversion Flow Drive Demonstrated on C-Mod

Yijun Lin C-mod

- Strong toroidal flow with significant flow shear
- Favorable scaling with power and plasma current
- Also in JET (~ ½ NBI rotation) T. Tala





Concluding remarks

- Impressive depth of physics and results
  - Diagnostics – experimental procedures – theoretical basis
  - Integrated physics multimode approach
- Revival of runaway, disruption and material studies
  - Important and urgent for ITER
- 3 D magnetic field perturbations
  - Wealth of results and good prospect for more
  - A “star” in this summary but not a mature subject yet

  ➔ **requires more studies**

Finally, lots of thanks to our host and IAEA for a great conference