Changes to the Topic Group

- The group was called: Energetic Particles, Heating & Current Drive and Steady State operation
- The group is now entitled:
- **Steady State and Energetic Particles**
  - Still validate Heating & Current Drive,
  - Do not include general discharge control (TG MHD)
  - But include the active tools needed for current and plasma control (pellets as well if needed).
  - ***Will emphasize integrated steady state scenario preparation***

Scope of the Group

The general scope is to further develop the physics basis for burning plasma experiments and to focus international collaborations in the area of steady-state operation and energetic particle behaviour. In particular the group will :

- Encourage international collaboration on experiments, code developments and modelling activities.
- Identify and formulate Research Priorities for Physics R&D.
- Evaluate and document the scientific progress and provide an annual written report to the ITPA Coordinating Committee.
- Promote publications and presentations.

Task Definitions

- Explore potential for integrated steady state operation in a burning plasma experiment, with particular attention to the role of fast particle phenomena and the effectiveness and compatibility of methods for current generation and control.

- Evaluate validity of numerical models of heating and current generation against present experimental data.

- Evaluation of the impact of energetic particle phenomena on the performance of plasma operating regimes

Report on TG meetings

- The second meeting of the ITPA TG was done in Cadarache 21 to 23 October following a meeting in Naka in February 2002
- In fact First meeting with new definition
  - 25 participants
  - Joint session with Transport & ITB TG
  - Joint session with Data modelling TG
  - Discussions with Diagnostic TG
    - nomination of liaison officers for Collective modes,Heating and current drive and Steady state control (mainly input to actuators)

Participants

- EU
  - C Gormezano,A Jaun,A Becoulet,
  - G Hobirk,G Giruzzi, B Lloyd, F Imbeaux,
  - E Barbato (partly), P Bosia (partly)
- Japan
  - S Ide, U Takase, F Fukuyama, N Nakamura, S Shinohara
- US
  - C Phillips, T Luce, P Bonoli, D Batchelor, R Perkins,

  C Forrest
- RF
  - V Zvonkov, V Vdovin

High Priority Research Areas 2002 (1)

Steady state plasma operation in existing devices:

- Define proper figures of merit for high fusion gain, high bootstrap fraction plasmas
  - $H x \beta_N / q_{95}^2$ (notion of high bootstrap not yet included)
- Investigate full current drive plasmas with significant bootstrap current including real time current profile control.
  - DIIID domain areas for candidate steady state scenarios: q_{min},ITB width,pressure peaking,…
  - substantial progress on several experiments
    - DIIID steady state and hybrid scenarios
    - JET steady state
    - JT-60U steady-state
    - AUG hybrid scenarios
  - JET active ITB and current profile controlat high fusion yield

High Priority Research Areas 2002 (2)

- Compare model predictions with experimental data for heating and current drive.
  - Study ECCD off-axis beyond r/a~0.4
    - ECCD in JT60 up to 0.6, being analysed
    - NTM stabilisation of 2/1 mode at r/a=0.66 done in DIIID
  - Assess off-axis NBCD localisation
    - Further experiments and analysis in progress (part of discrepancy due orbit effects)
    - Experiments planned on JET
  - Optimise ICRH coupling through experiments and models
    - Progress in modelling JET ICRH antennas
    - Modest improvements with CD4 (JET)

High Priority Research Areas 2002 (3)

Studies of fast particles collective modes in low and reversed magnetic shear configurations:

- Identify key parameters
  - Good progress: edge shear (JET), beta effects (JET), importance of q_{min} ,reversed shear effects (JT-60U)
- Use/Identify the necessary modelling code
  - Several developments (Frascati,Kyoto)including comparison with experiments, but still several codes in development fluid, gyro-kinetic, hybrid MHD kinetic

Highlights

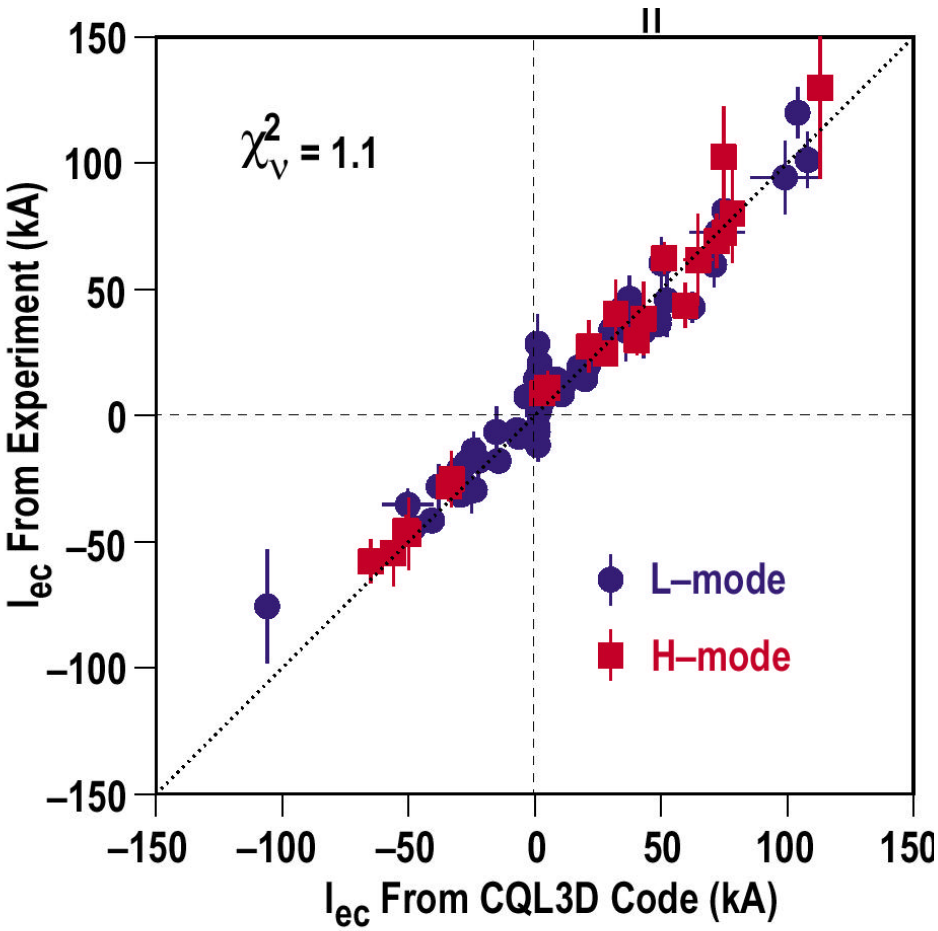
- Heating and Current Drive
- Energetic particles
- Steady State

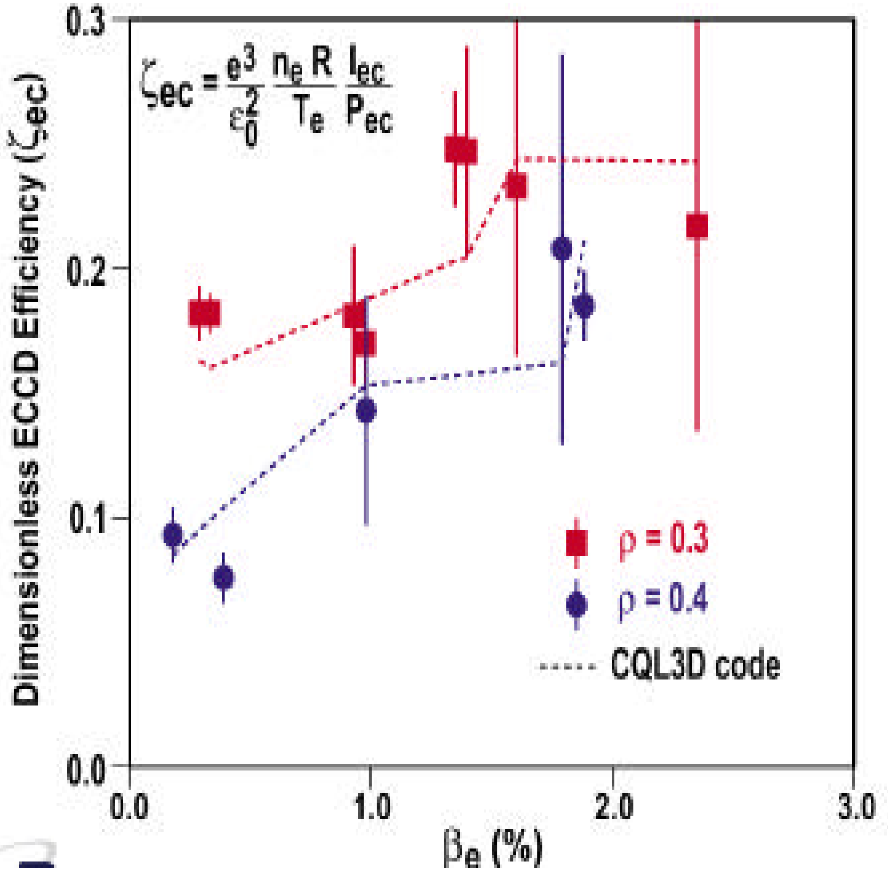
Highlights from Heating & Current Drive and Energetic Particles

- ECCD
  - 0.74 MA of ECCD on JT-60U (3 MW)
  - Extensive off-axis ECCD data:DIIID, JT-60U, TCV,AUG
  - NTM stabilisation including 2/1 mode (DIIID)
- ICRH
  - Heating in LHD
  - Rotation profiles (JET, C-MOD)
- LHCD
  - Full CD at high density (FTU)
  - Extensive use of LHCD in Reversed Shear plasmas
  - 4 minutes 3 MW LHCD (JET)
- Energetic Particles
  - Reversed Shear AE modes (in JT-60U avoid $2.4<q_{min}<2.7$)
  - Hybrid code MHD kinetic modes
  - New antennas for TAE modes damping measurements
  - Ferritic inserts in JFT-2M

ECCD in DIIID

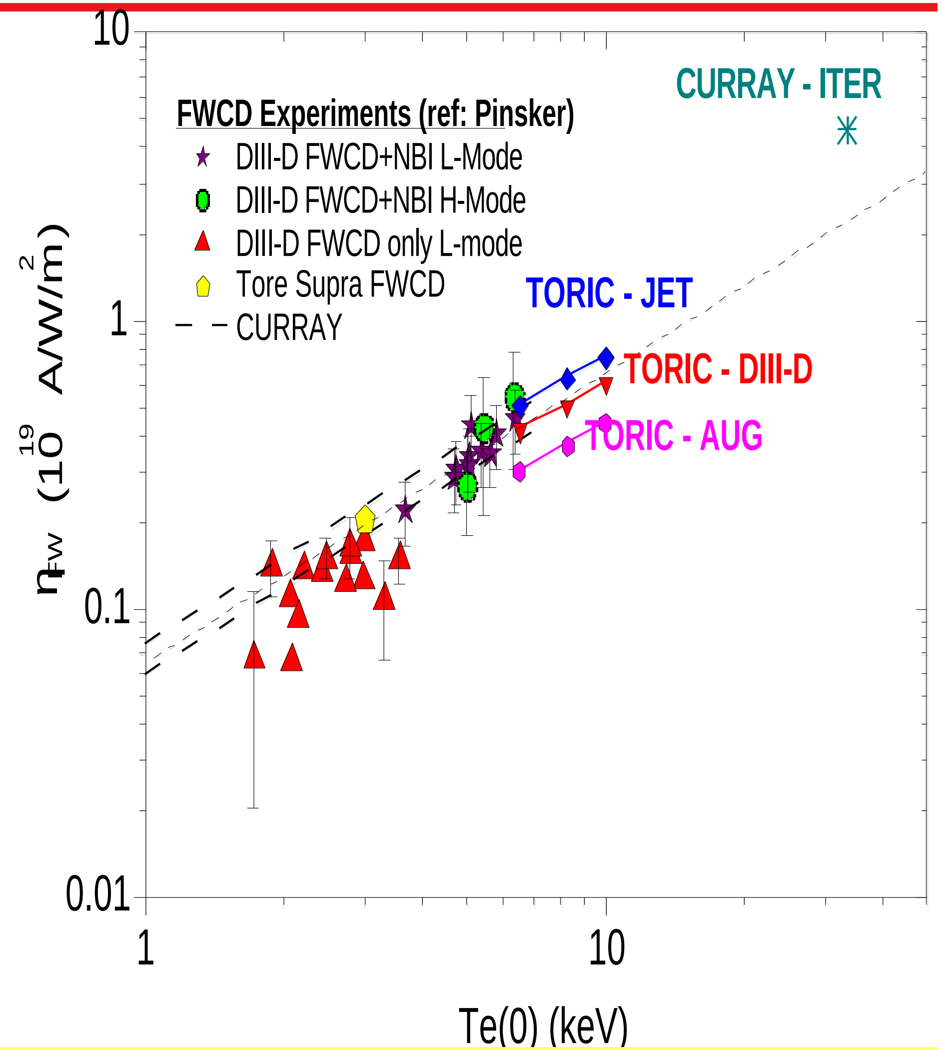
- Very good agreement between data and code calculations





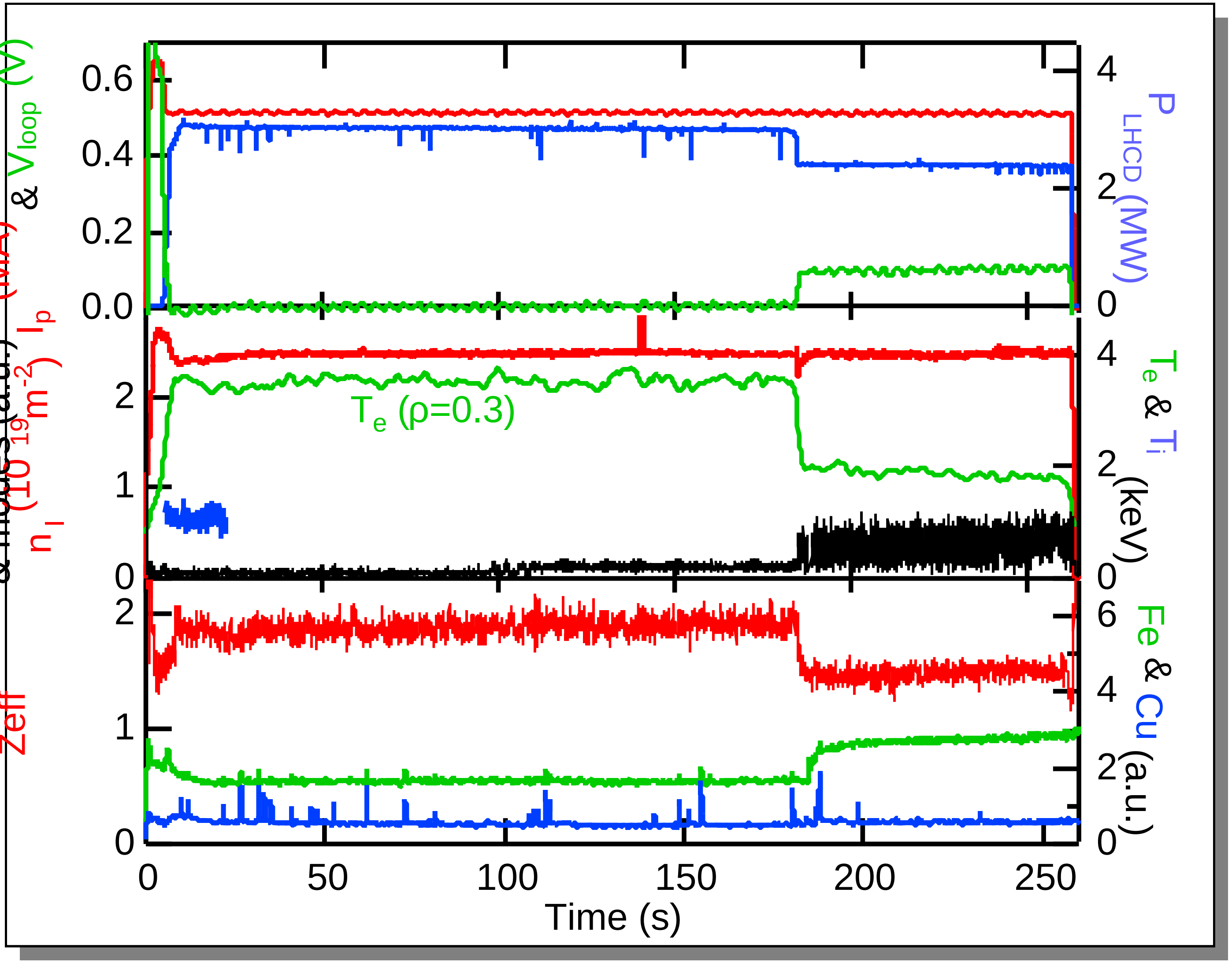
ICRH rotation in JET and FWCD

- Rotation profiles measured in JET with on and off-axis RF, weaker than in C-MOD and similar with high and low field side resonance. More experiments foreseen in 2002
- Note that rotation profiles with ECRH being analysed (DIIID, JT-60U)



FWCD data being compared with exp. data. Recent NSTX data in agreement

LHCD in Tore Supra Shot #30414: 4mn 25 & 0.75 GJ



I_p = 0.52 MA

P_{LHCD} = 3 MW

V_{loop} < 0.01V

82% LHCD

14% bootst.

4% ohmic

Flux limited

n_{l0}=2.5$10^{19}$$m^{-3}$

T_{e0} = 4.8 keV

T_{i0} = 1.3 keV

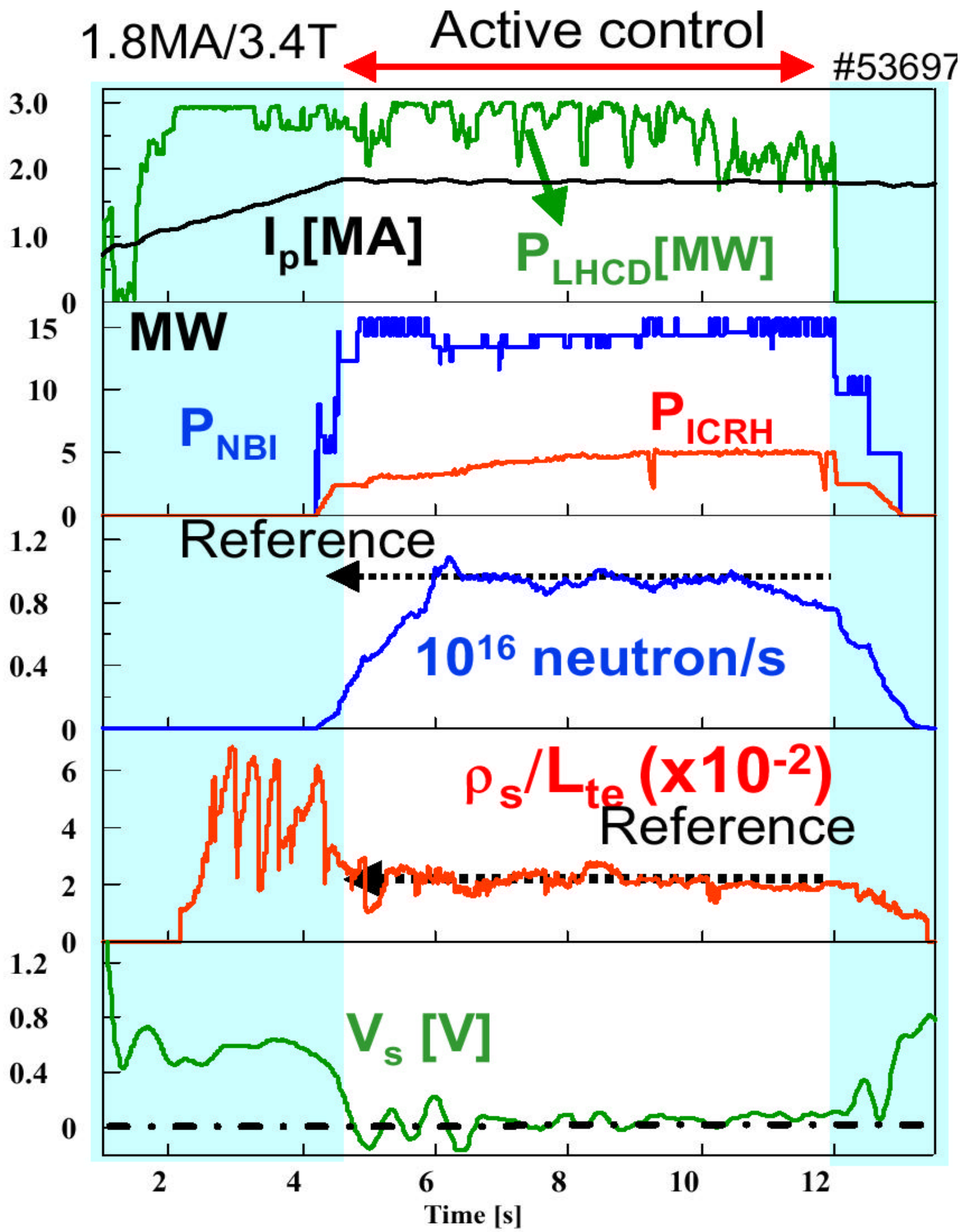
β_p = 0.5

β_N = 0.4

Work. gas D_2

Z_{eff} < 2

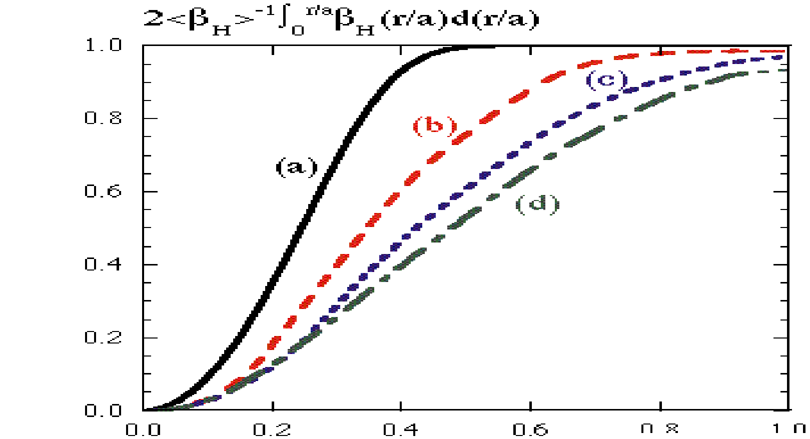
Real Time Control in JET ITB High Fusion Yield



- ITB is controlled during 7.5s at V_s 0V with 100% of non - inductive current
- P_{LHCD} to slow down q(r,t)
- P_{NBI} controlled by Neutron
- P_{ICRH} controlled by ρ_s/L_{Te} at the ITB location

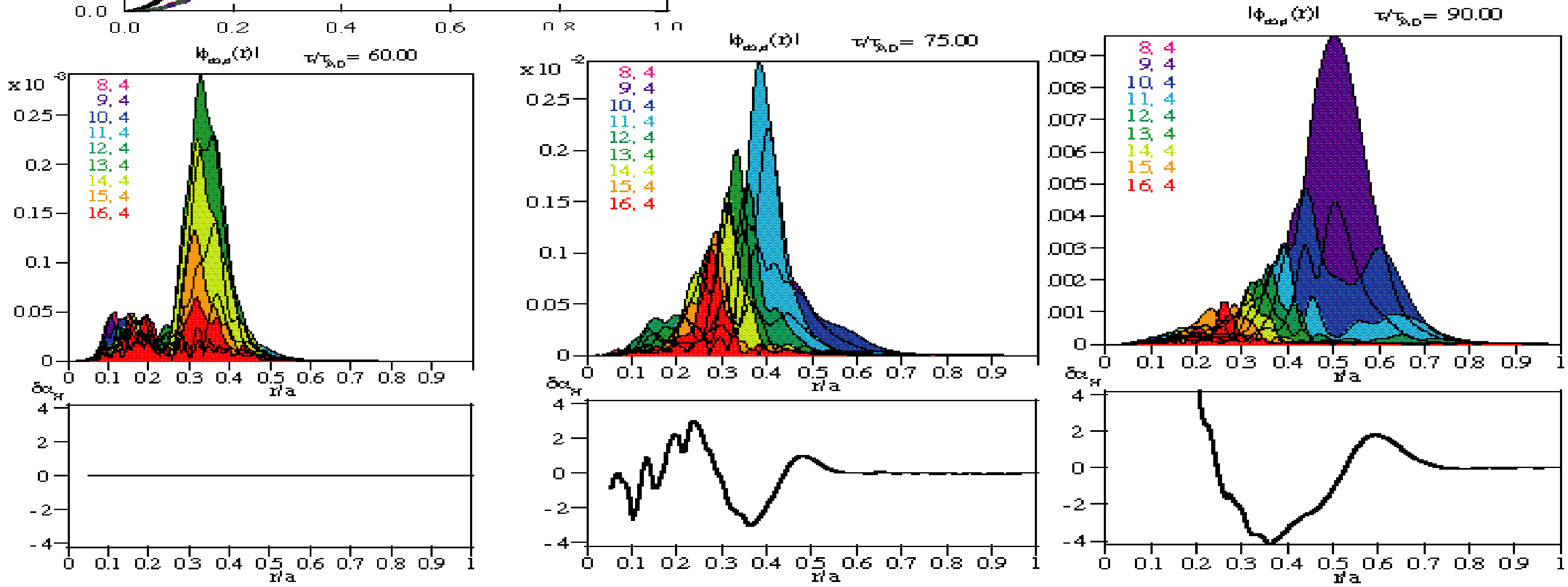
> ➢ Active use of LHCD for real time control of AT scenarios

Hybrid code MHD kinetic modes: radial expansion of fast ions



(a) Equilibrium
(b) =0.025, q profile (a); 1.3% loss
(c) =0.05, q profile (a); 3.1% loss
(d) =0.025, q profile (b); 6.6% loss

Fast ion transport is mainly associated with radial redistributions with sufficiently hollow q-profile



Evidence of radial propagation of an unstable front

Avalanches: Relay-Runner Model for EPMs

ENEA-UCI

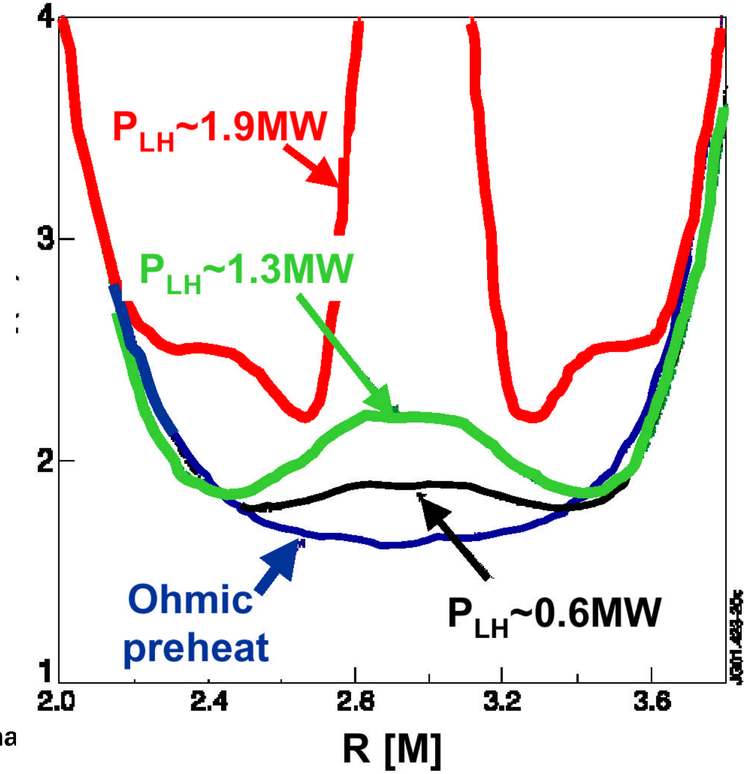
F. Zonca, S. Briguglio, L. Chen, G. Fogaccia, G. Vlad

Steady state scenarios and Current Profile

- So far, one of the main tool in the present development of possible steady state scenarios is the plasma current profile
- Most scenarios use Heating and/or Current drive during the low beta phase in the current ramp-up phase to freeze profile
- A large variety of current profiles can be generated using either operational tools or non-inductive current drive or other effects such as fishbones

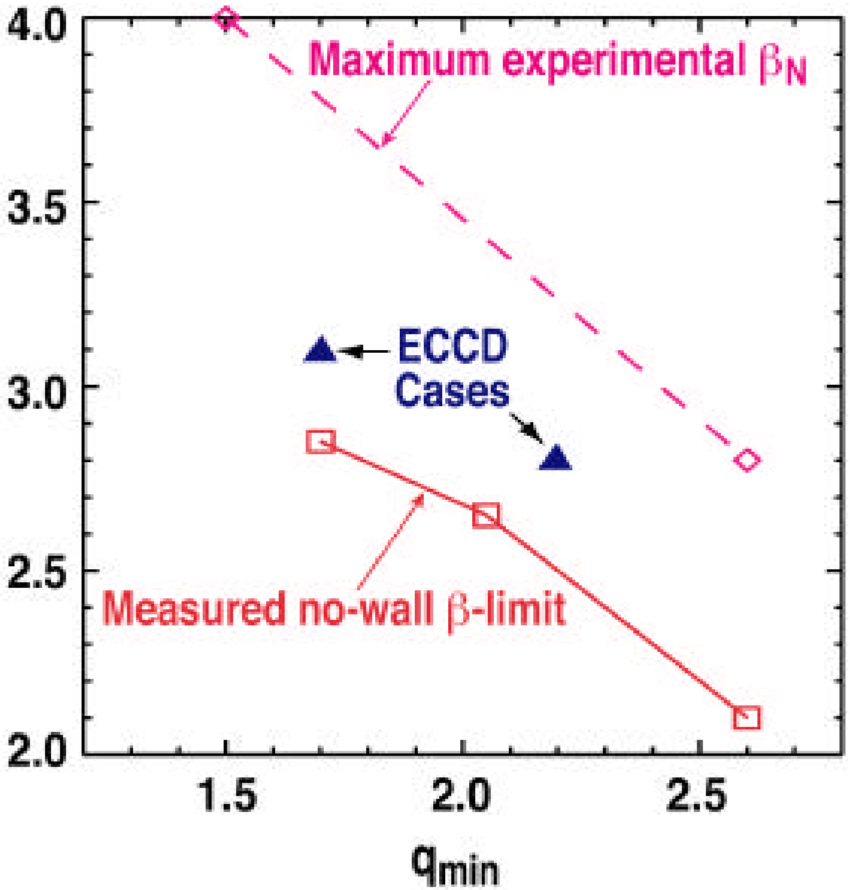
➢All candidate steady state scenarios have q_0 equal or above one, i.e. no sawteeth

Use of LHCD in JET prelude phase allows a variety of current profiles to be achieved

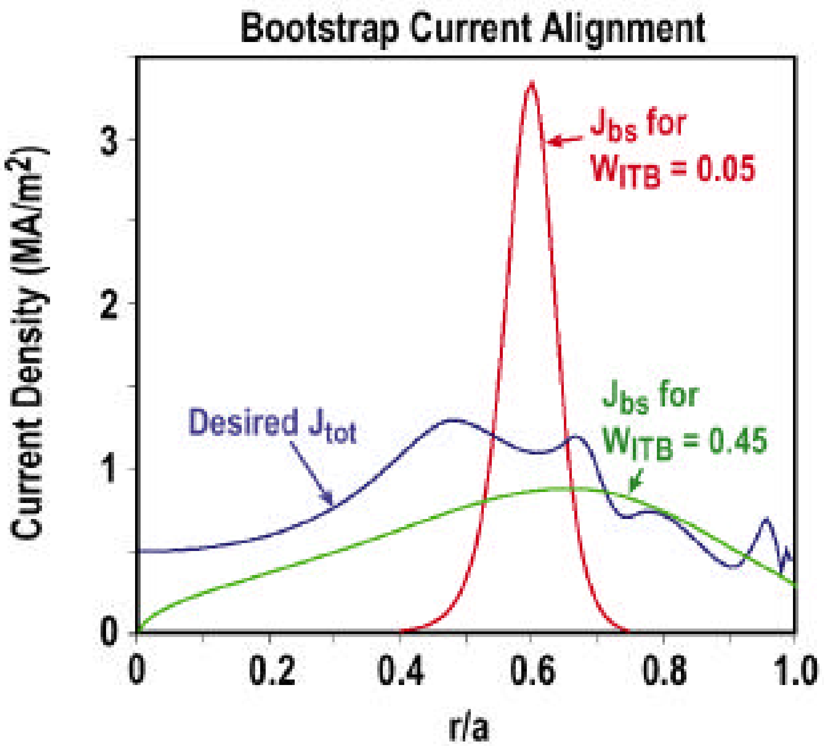


Alignment of bootstrap current and pressure profiles as well as q_{min} are key features of steady state scenarios

From DIIID domain studies, β_N decreases when q_{min} increases



Steep, localised pressure gradients not consistent with high β_N and well aligned bootstrap current: wide ITBs required for high β_N

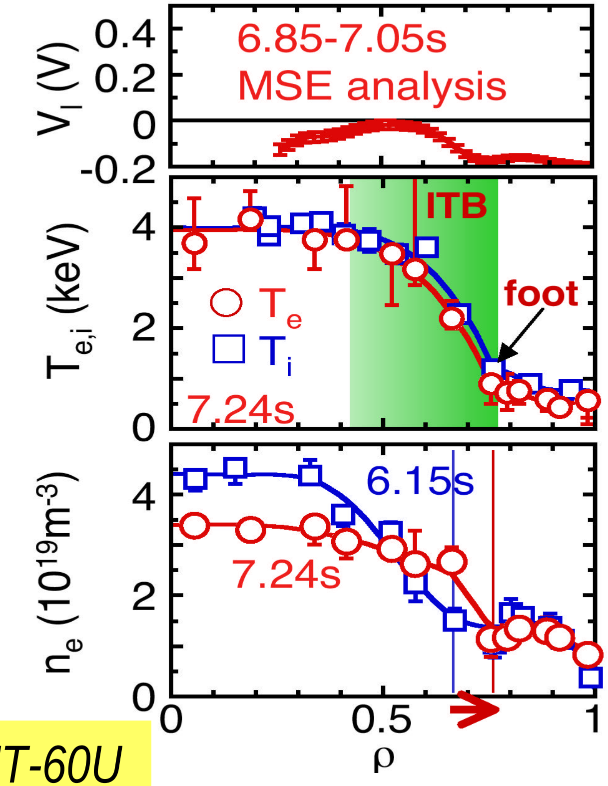


Current profiles and candidate steady state scenarios

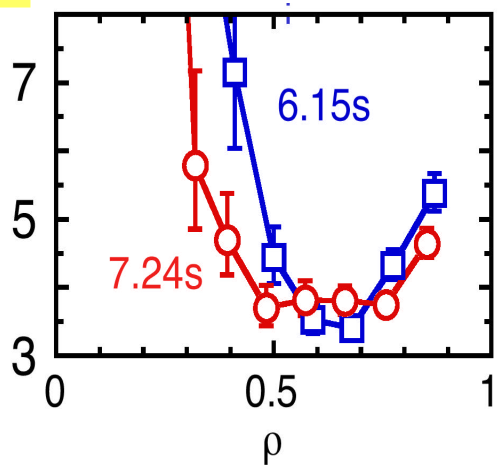
- Constant and impressive progress is made on the road to steady state operation
- So far, one of the main tool in the present development of possible steady state scenarios is the plasma current profile
  - All variety of current profiles seem to have been used (but for strong reversed shear at q=1), all giving interesting developments
- Some schemes can now be considered as potential candidates for steady state scenario on ITER
- Other schemes need some more developments for ITER application
  - Very strong shear reversal
  - QDB modes
  - Full boostrap current

Very strong shear reversal

- Impressive physics results: long steady high performance achieved with almost no current at center (JT-60U, JET, DIIID).But, for steady state, major problems:
  - limited to low beta
  - Bootstrap current will peak just inside the current sheet shrinking ITB
  - Impurity accumulation
  - Confinement of alphas and other energetic particles will be very low within the ITB
  - increased diffusion due to collective modes if q_0>3
- Can be best used, so far, for scenario development



JT-60U

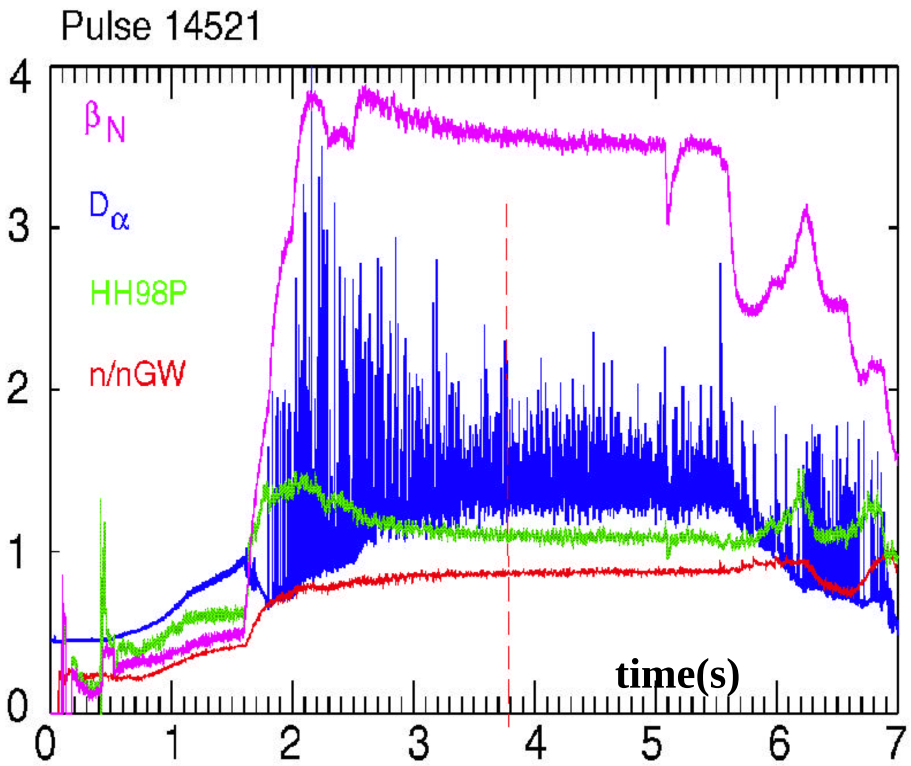


Best Candidates for Steady State Scenarios

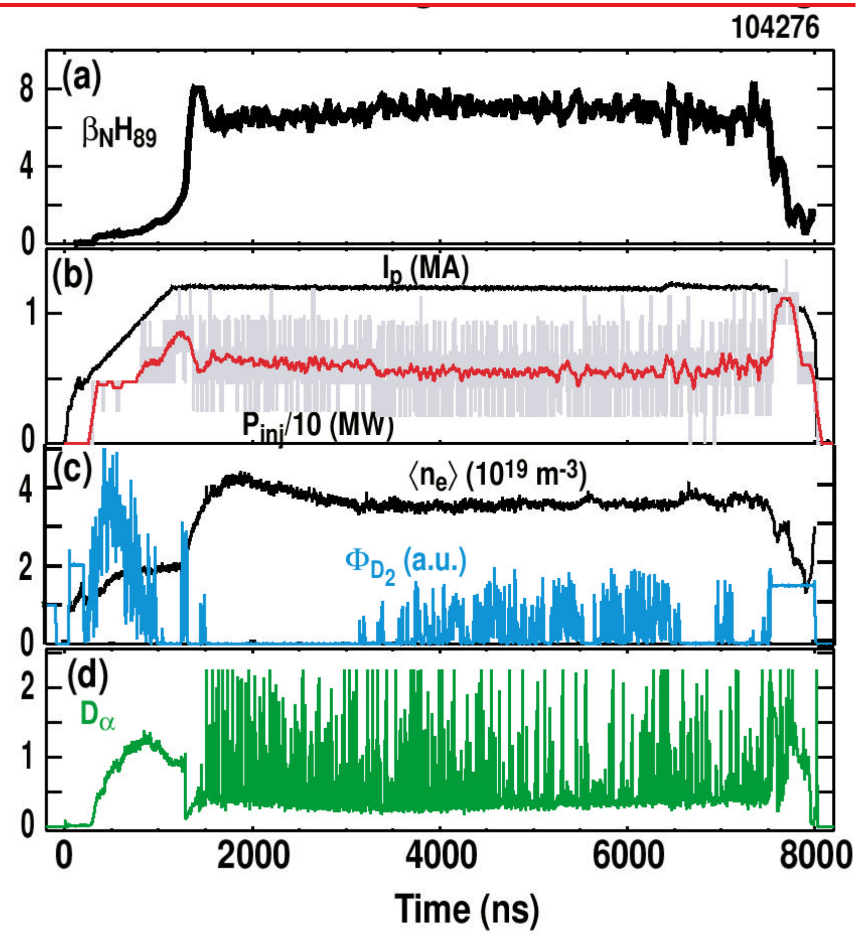
Candidates mean: not yet perfect, but a good basis for development

- Very long high fusion yield pulses in ITER (hybrid scenarios: high beta,high confinement, high bootstrap, steady current profile)
  - Shallow shear at q_0 =1 (AUG,DIIID)
- Steady state scenario for ITER (high confinement, high beta f_{BS}=50%, full current drive)
  - Shallow shear at q_{min} around 2 (DIIID,JET,JT-60U)
- Real advanced scenario (high confinement, high beta f_{BS}=80%, full current drive)
  - Progress to be made

Shallow shear reversal at q_0 around 1: high fusion yield hybrid ITER scenarios



In AUG with NBI +off-axis NBCD high β_N at q_{95}=3.6, H_{98}=1.3, n/n_G ~1, I_{BS} /I_P~0.6 and type II ELMS



DIIID: High performance sustained for 35 τ_E (t_{relax}=1.8s)

In both machines: no sawteeth. Question:

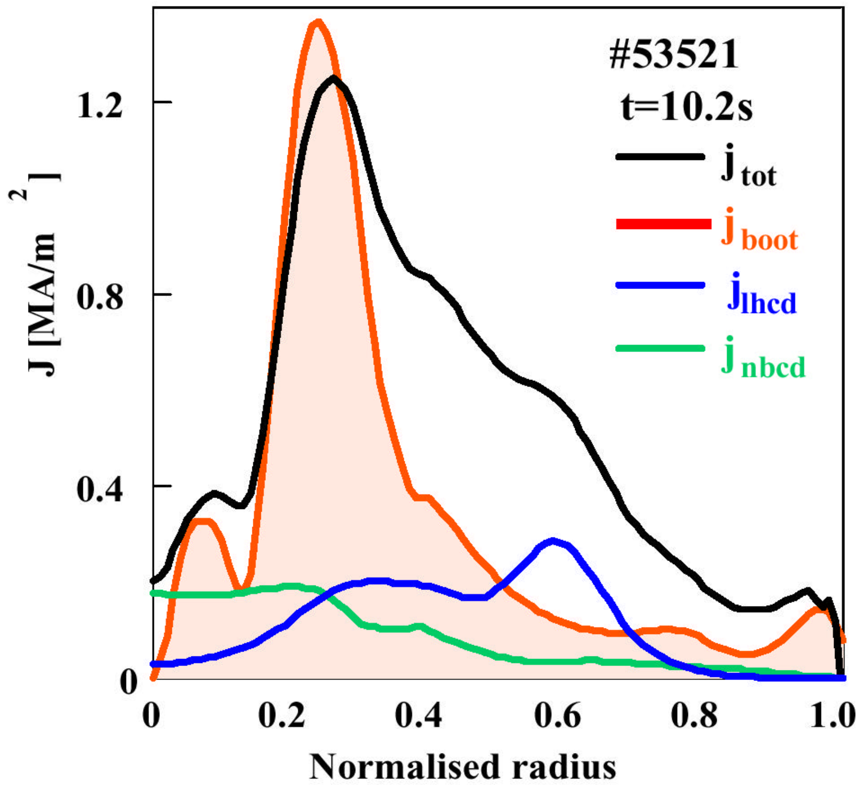
How to maintain q_0 very close to 1:Are fishbones(AUG) or mild tearing modes (DIIID) accceptable in a BPX?

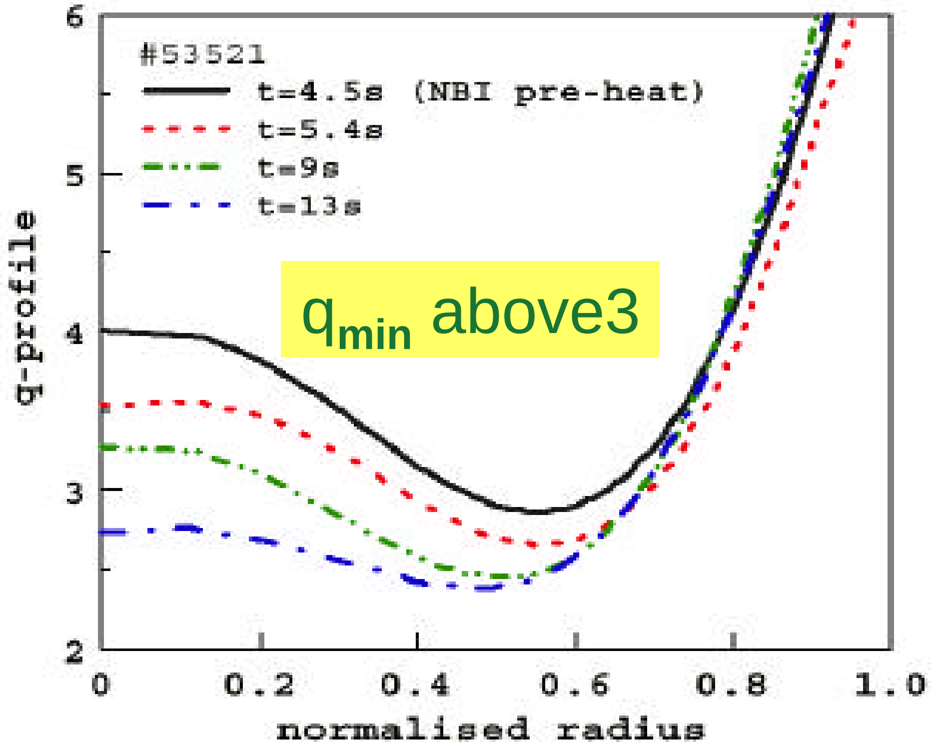
Shallow shear reversal at q_{min} around 2: ITER steady state scenarios

- Very impressive (quasi) steady steady state plasmas achieved in JET,JT-60U, DIIID.
  - High bootstrap fraction
  - High beta limits due to flatter q profiles, hence broad pressure profiles
  - Higher density, Some hope for pellet fuelling (JT-60U)
  - Possibly acceptable ELMs
  - Acceptable alpha confinement and collective modes losses
- Still, developments to be made, among them:
  - Simultaneous high β_N and β_P difficult
  - impurity accumulation is a problem in some scenario: control with electron heating (ECRH, alphas)
  - More Current Drive to be used

Full non-inductive CD in mild RS configuration in JET

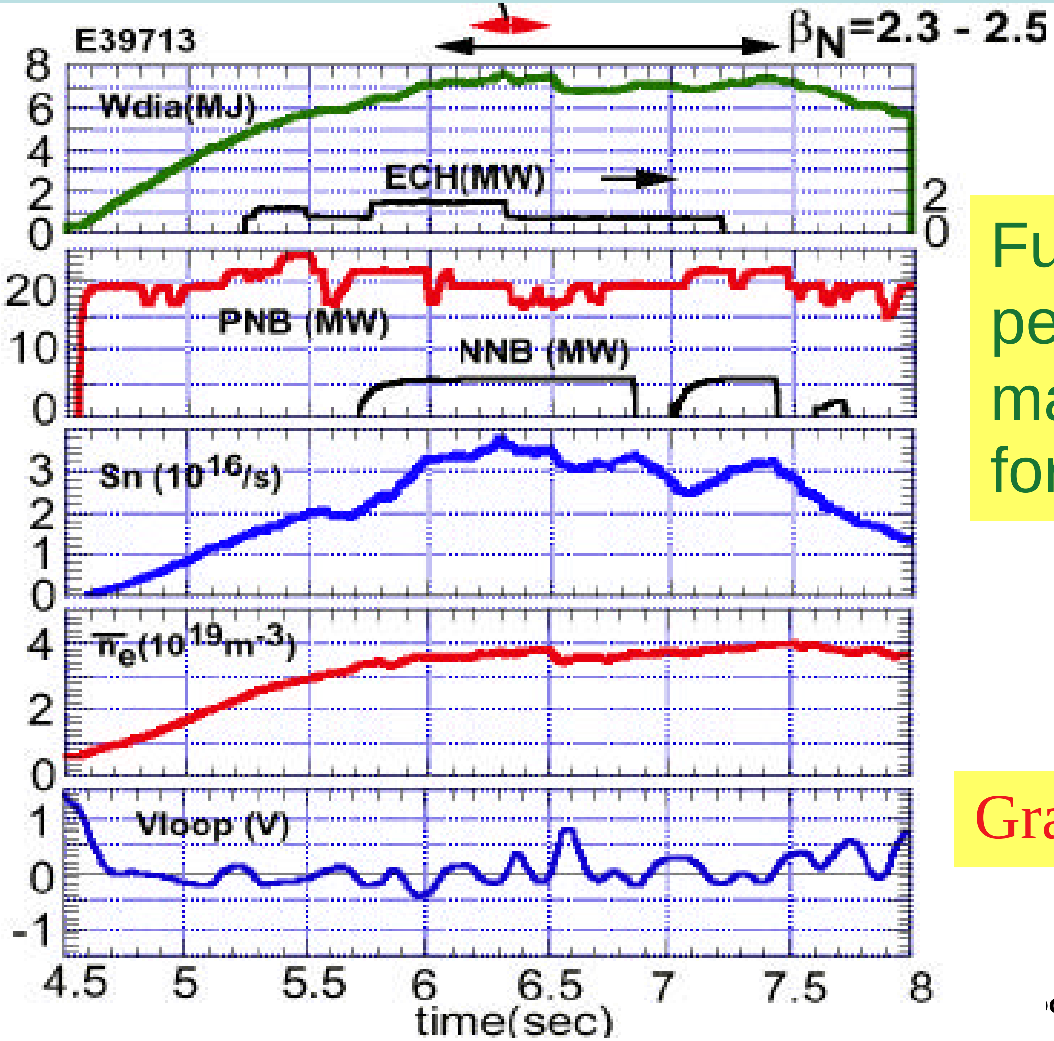
- Full NICD with NBI+LHCD+ICRH at 2MA/3.4T maintained for 7 sec, about 23 τ_E
- ITBs produced in low shear region
- I_{BS}=1 MA, f_{BS}=50%, but not yet full alignment
- Type III ELMs,   Impurity accumulation problem





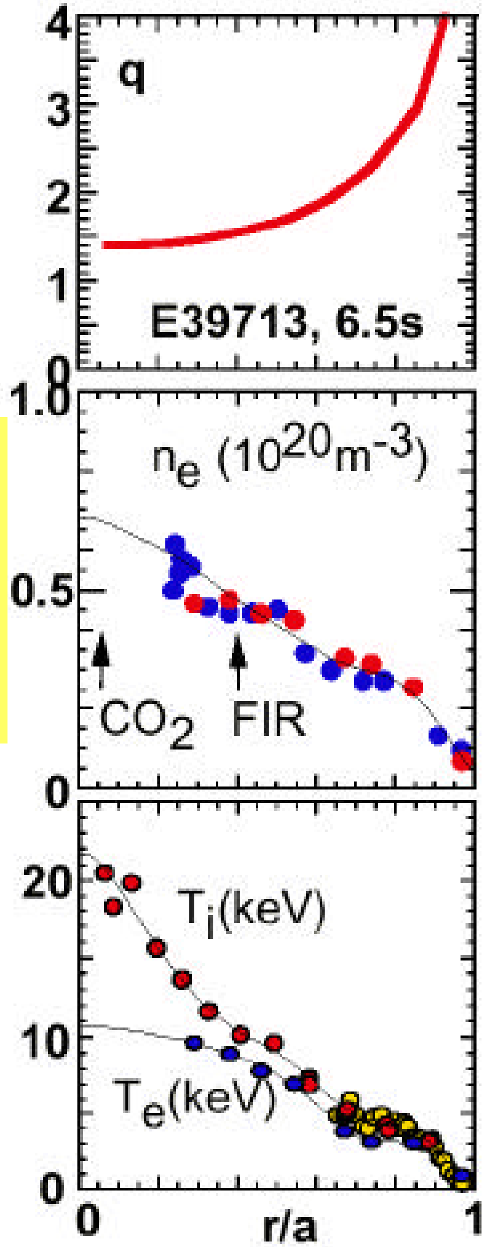
Full NICD with shallow shear q_0~2 in JT-60U: highβ_N

With NBI+N-NBI+ECH 1.8MA 4.1T q_{95}=4.1 H_{98}=1.2 β_N=2.4,β_P=1.7 f_{BS}=0.5. Full CD



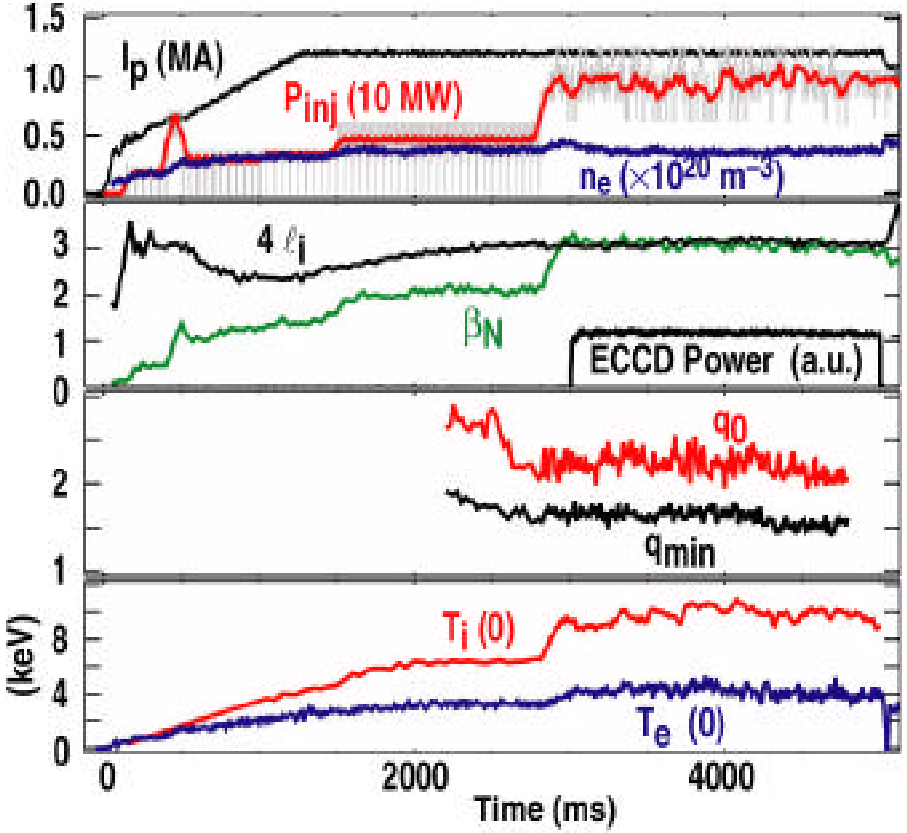
Full CD+High performances maintained for 6τ_E

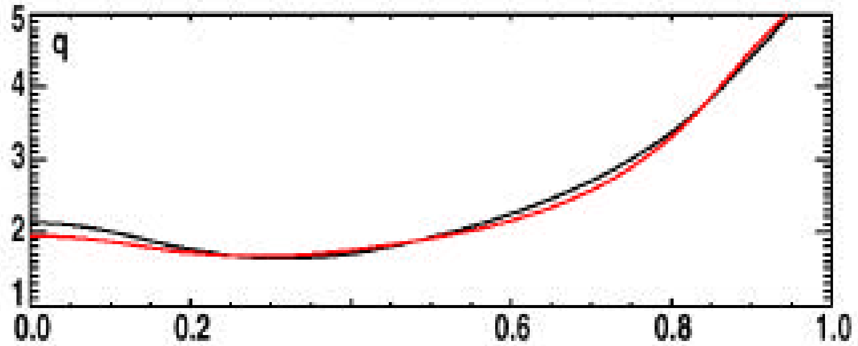
Grassy ELMs

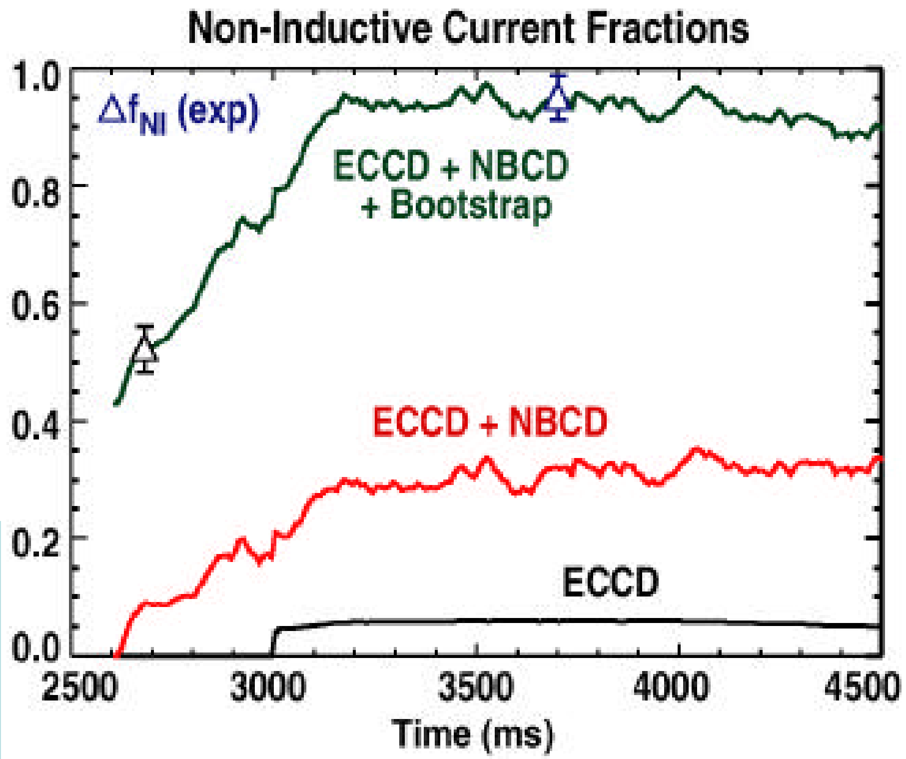


Recent results from DIIID: high bootstrap at q_{min}~1.5

β_N=3.1, β=3.3%,H_{89}=2.4







- With off-axis ECCD, up to 95% NI current drive at the no-wall beta limit with β_N=3 and H_{89}=2.5

Collaboration within IEA Large Tokamak framework (1)

- Two promising advanced scenarios have been identified for further investigation
  - one compatible with hybrid operation (long inductive pulse at high fusion yield)
  - and one compatible with steady state (fully non-inductive) operation.
- Hybrid scenario is defined by a flat q profile with **q_{min} >~1.** The four largest divertor machines (JT-60U, JET, AUG, DIII-D) have operated at high normalized $\beta(>2.5)$ under these conditions for long pulses **(>20 τ_E).**
  - The high priority is to map the existence domain for this scenario for each machine and identify across the domain the mechanism by which the current is prevented from peaking (fishbones, tearing mode, etc.). Variations of performance (e.g., $\beta\tau_{th}$) with q_{95} and density at fixed field and shape are of high interest. Variations with shape (performance and ELM behavior) and T_e/T_i are also of interest.

Collaboration within IEA Large Tokamak framework (2)

- Steady state scenario is defined by specifications on the q profile: **$q_{95} = 4 - 5$, $q_{min} = 2 \pm 0.5$, $q(0)-q_{min} < 0.5$, $f_{BS}>50\%$, and $\beta_N>3$**. At the IAEA meeting,discharges in that range were shown with a q profile meeting these specifications.
  - High priority for this scenario is for the four large divertor machines to explore performance limits with this q profile and compare the results. Direct collaboration among the groups on the experiments could increase the productivity of this effort.
- On a longer time scale (> 1 year), these discharges can constitute the basis for integrated development: density limits, fuelling, impurity control (test central electron heating), edge compatibility, collective modes assessment,…
- Complementary role of each machine optimising hardware

Current drive code assessment (1)

- Validate current drive codes outside formal data base
- Step 0
  - Benchmark codes on given profiles: ITER profiles
- Step 1
  - Benchmark codes on single machine
- Step 2
  - Benchmark codes on multi-machine
- Step 3
  - Install code on steady state ITER scenario code(s) development

Actions and ROs have been identified for each system

Current drive code assessment (2)

- LHCD
  - Step 0: Compare the CQL3D -GENRAY test case with the predictions of the EU codes (DELPHINE, FRTC) using the ITER profiles
  - Step 1: Do current diffusion simulations to assess CD efficiency on a JET shot
  - Step 2:Benchmark DELPHINE+FRTC and CQL3D against JET pulse (JET, JT60 to provide data)
- NBCD
  - Step 0 and 1: done
  - Step 2:
    - Compare ASTRA,TRANSP,SINBAD and OFMC codes on AUG and JT-60U off-axis data,
    - On-axis CD Benchmark NBCD codes on N-NBI JT60U data

Current drive code assessment (3)

- FWCD
  - Step 0: Identify ITER case (CCFW) and compare TORIC (US), STELION (RF) and TASK (Japan)
- ECCD (0<r/a<0.5)
  - Step 0 and 1: done, step 2:almost done (remaining check JT-60U)
  - Optimisation study to increase domain of application lower (frequency): GA
- ECCD (0.7<r/a<0.8)
  - Step 0: done :Very sensitive to details of launching structure and boundaries
  - Step1 :is it possible?
  - Optimisation to increase efficiency (frequency and location): GA, CCEC,RF,Japan (ask ITER to provide equilibrium and profiles)

Steady state data base

- Start Data Base on steady state scenarios using Houlberg's group proposal
  - Steady state scenarios
    - JET #53521, JT-60U #E39713, DIIID #111221
  - Hybrid scenarios
    - AUG #14521, DIIID #104276
- Data providers from DIIID, AUG, JET, JT-60U identified
- Include progressively other discharges, including from other scenarios when they are mature
- Scenario development code: Cronos (Cadarache) candidate for such development. When data base will be ready, other codes will likely be candidates (ASTRA for instance).

High Priority Research Areas for 2003 (1)

- Steady State
  - Multi-machine assessment of candidate steady state and hybrid scenarios:
    - Map the existence domain for the hybrid scenario
    - Explore the performance limits(beta limits, confinement, integration: impurities, edge compatibility, fuelling,…) for the steady state scenario
  - Install steady state scenario development data base
  - Explore ad develop plasmas with very high bootstrap content
- Heating and current drive including comparing model predictions with experimental data
  - ICRH : ELMs resilience coupling techniques (3db junctions)
  - NBCD:Off axis NBCD on JET co-counter trace tritium
  - LHCD: Improve predictability of current drive efficiency
  - ECCD: evaluate ITER system for off-axis CD and NTM stab.

High Priority Research Areas for 2003 (2)

- Energetic Particles
  - Start assessment of reversed shear operational space: modelling codes, experiments including mainly quantitative measurements (JT-60U, JET)
  - Assess proposed q profiles for steady state and hybrid scenarios

Plans for for meetings and publications

- Next meeting following EPS in St Petersburg:
  - Mainly reports on action lists
  - Review of possible new steady state discharges
- Meeting in fall in the US
- Publications and conference presentations are foreseen: RF conference in May 2003, Steady state modelling at EPS,…

Medium Term Priorities

- Coordinated modelling of ITER scenarios (continuous updates as appropriate);
- Need to identify approach to estimate uncertainties in projecting H/CD systems to Burning Plasmas (Develop self-consistent integrated modelling capability for H/CD systems)
- . Evaluate ITERH/CD systems in terms of relevance to Standard operating scenarios and global Steady-State requirements
- Continue the assessment of ECCD and LHCD system both for NTM stabilization and current profile control
- Need to understand RF-driven rotation
- Assess energetic particles and H/CD diagnostics requested for ITER.
- Continue analysis of ripple induced losses in deeply reversed magnetic shear scenarios;
- Develop global non-perturbative gyro kinetic models for linear stability of MHD collective effects;