Vertical Launch Third Harmonic ECRH of H-mode on TCV and Access to Quasi-Stationary ELM-free H-mode

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&

THE TCV TEAM

OVERVIEW

- Introduction & Motivation
- X3 system
- X3 heating of H-mode
- Quasi-Stationary ELM-free H-mode (QSEFHM) regime
- Summary & Conclusions

INTRODUCTION

- TCV is a medium sized tokamak

  $I_p \leq 1$ MA
  $B_{tor} < 1.54$ T (1.45 T typical)
  $a \approx 25$ cm ; R = 0.88 m
  $\kappa \leq 2.8$ *(extreme elongation)*

- 6 Gyrotrons at 82.7 GHz for ECRH/ECCD

  current profile control
  e-ITB
  fully non-inductive operation
  $n_{e,max} < 4.2 \times 10^{19}$ m^{-3}

- Electron Bernstein Wave Heating (EBW)

  $n_{e,max} > 20 \times 10^{19}$ m^{-3}
  Mück A. et al PRL **98** 175004 (2007)

- ***One of the main goals of TCV is to study plasma near the β-limit***

- Heat H-mode at high density

X3 SYSTEM

- 3, 118GHz, 480kW gyrotrons; top launch to maximise path along X3 resonance and increase absorption

- Pulse length 2.0sec, limited by the power supplies

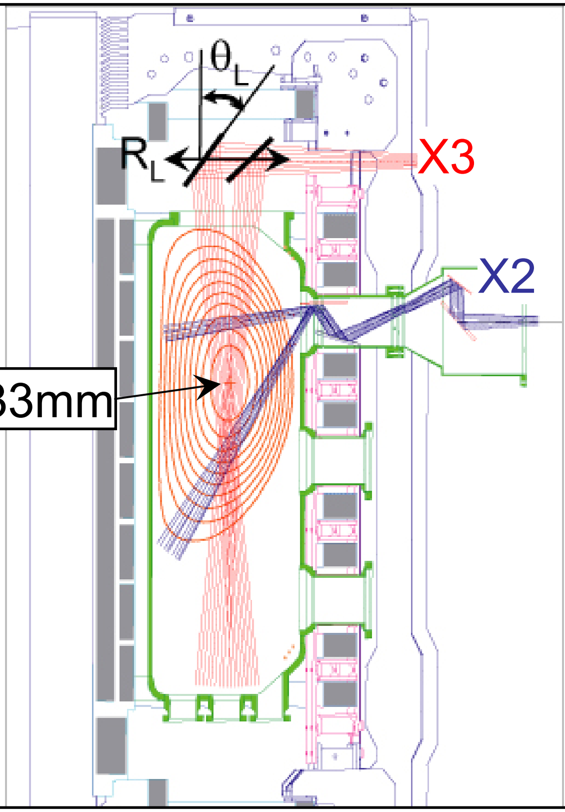
- *Liquid N2 cooled sapphire output window*
  window is limiting factor for output power
  CVD diamond window installed in one gyrotron
  → ***increase power***

- Gyrotron power can be modulated but power ramps difficult

- Launch X-mode
  Matching Optics Unit (MOU) → arbitrary polarisation

- Transmission line is ≈95 % efficient so ≈1.37 MW available at the plasma

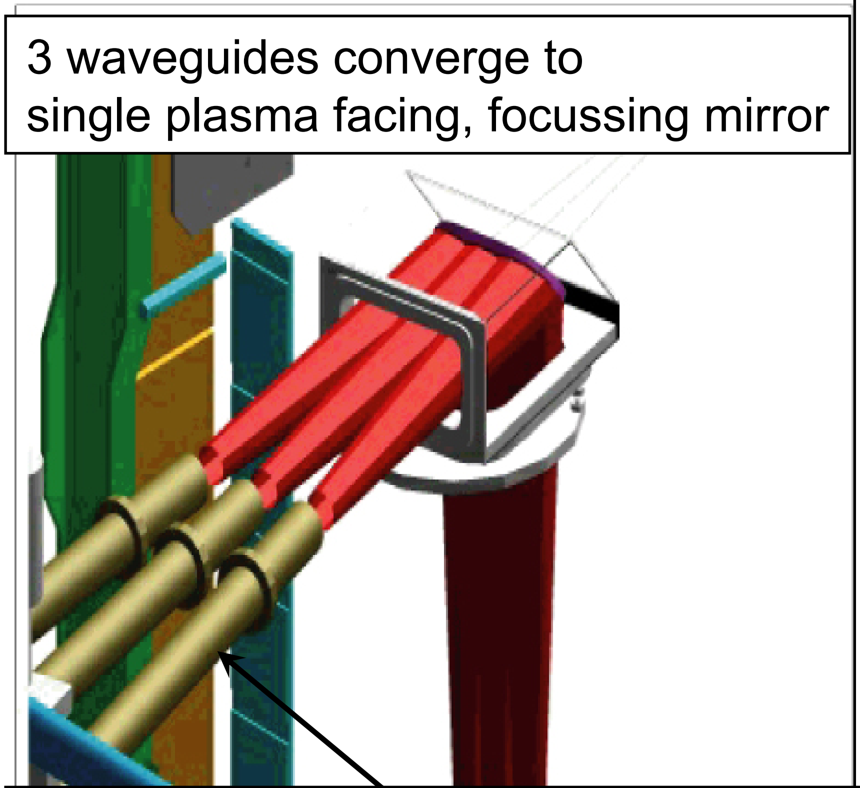
X3 SYSTEM : LAUNCHER



Spot size ≈ 33mm

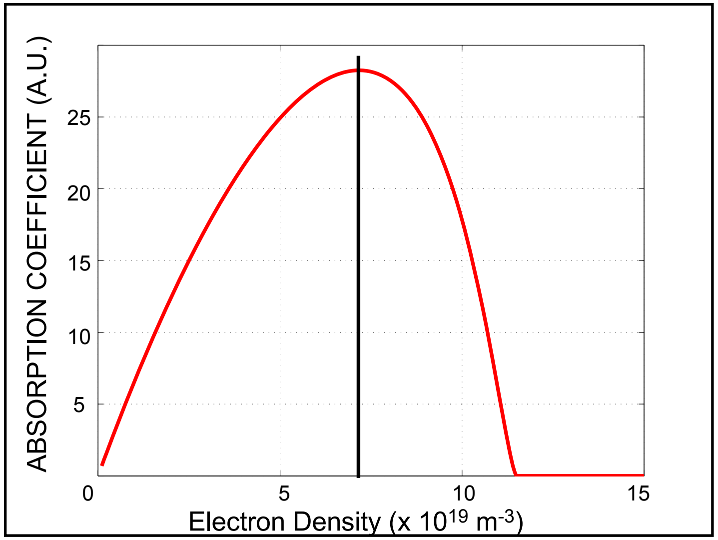
Mirror scanned
$80cm \leq R_L \leq 96cm$ between pulses
$40^o \leq \theta_L \leq 50^o$ during pulse

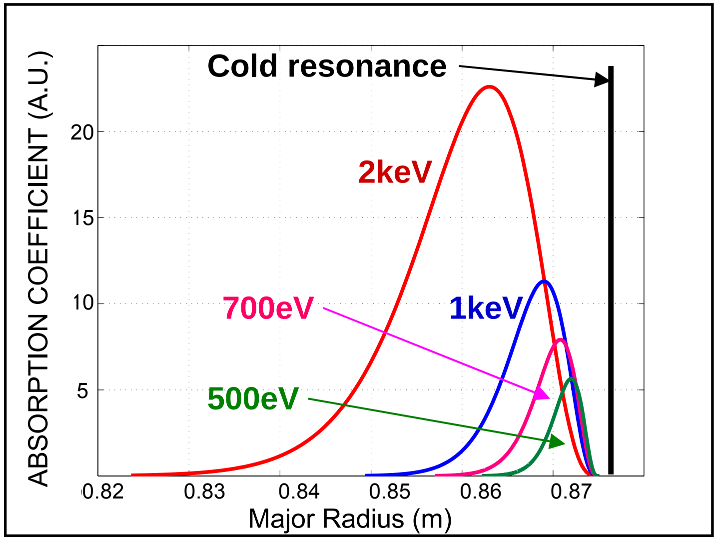
3 waveguides converge to single plasma facing, focussing mirror



63.5mm diameter corrugated waveguide transmission line

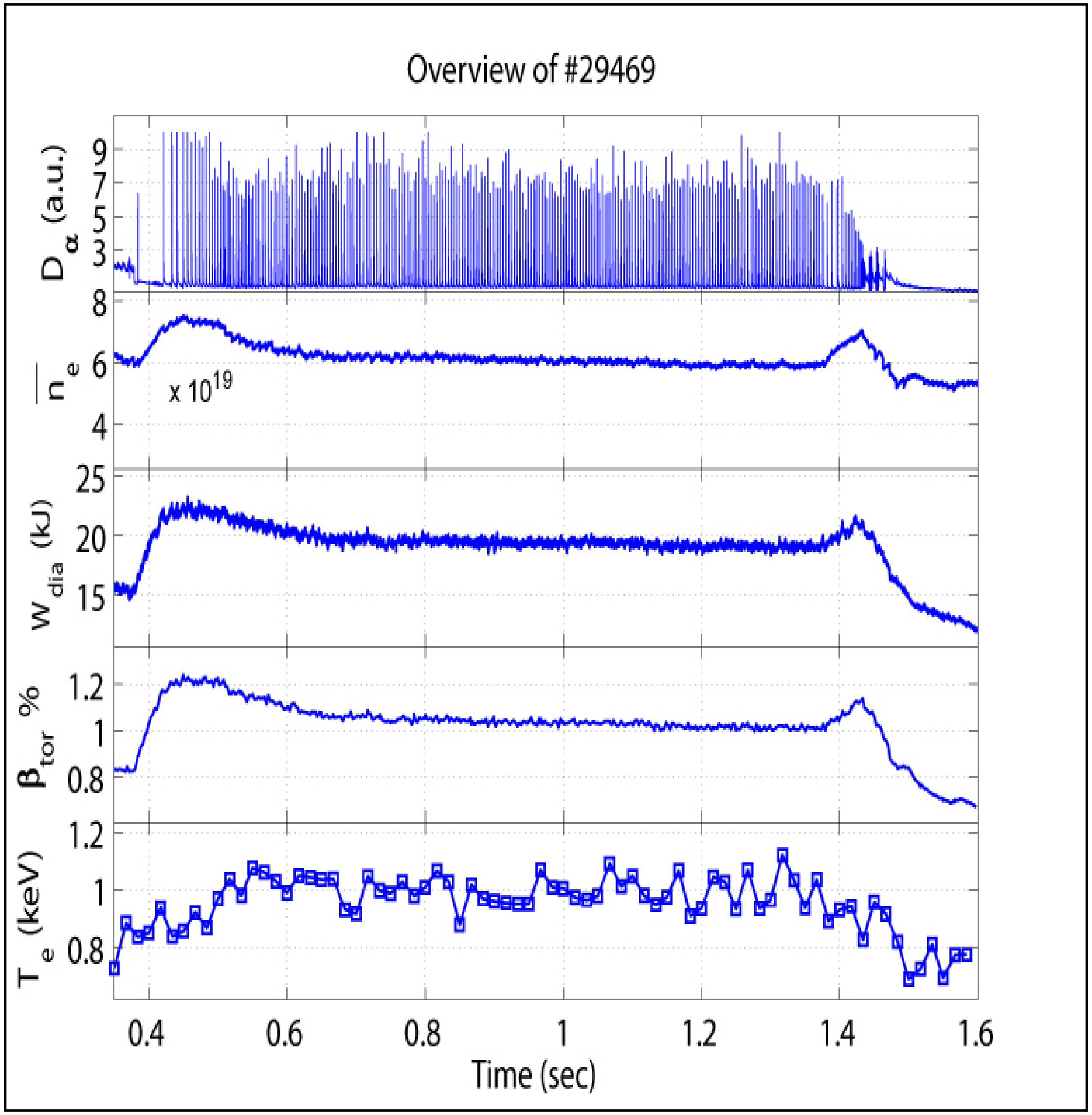
X3 HEATING OF H-MODE





- $n_e \approx 7.1 \times 10^{19} m^{-3}$ for best absorption
  - Work typically at $n_e \approx 6 \times 10^{19}$ m^{-3}
- $\alpha_{X3,vertical} \propto T_e$ so if we couple X3 well enough the absorption increases quickly
- relativistic broadening
- At T_e > 2keV not sensitive density perturbations (ELMs for example) & first pass absorption > 75%

X3 HEATING OF H-MODE ; TARGET



Single null diverted plasma

Ion grad-B drift away from the X-point

390 kA $\leq I_p \leq$ 420 kA

B_{tor} = 1.45 T

$n_{e,max} \approx 6.5\times10^{19} m^{-3}$ (25% $n_{e,G}$)

$\delta_{95} \approx 0.36$

$\kappa_{95} \approx 1.65$

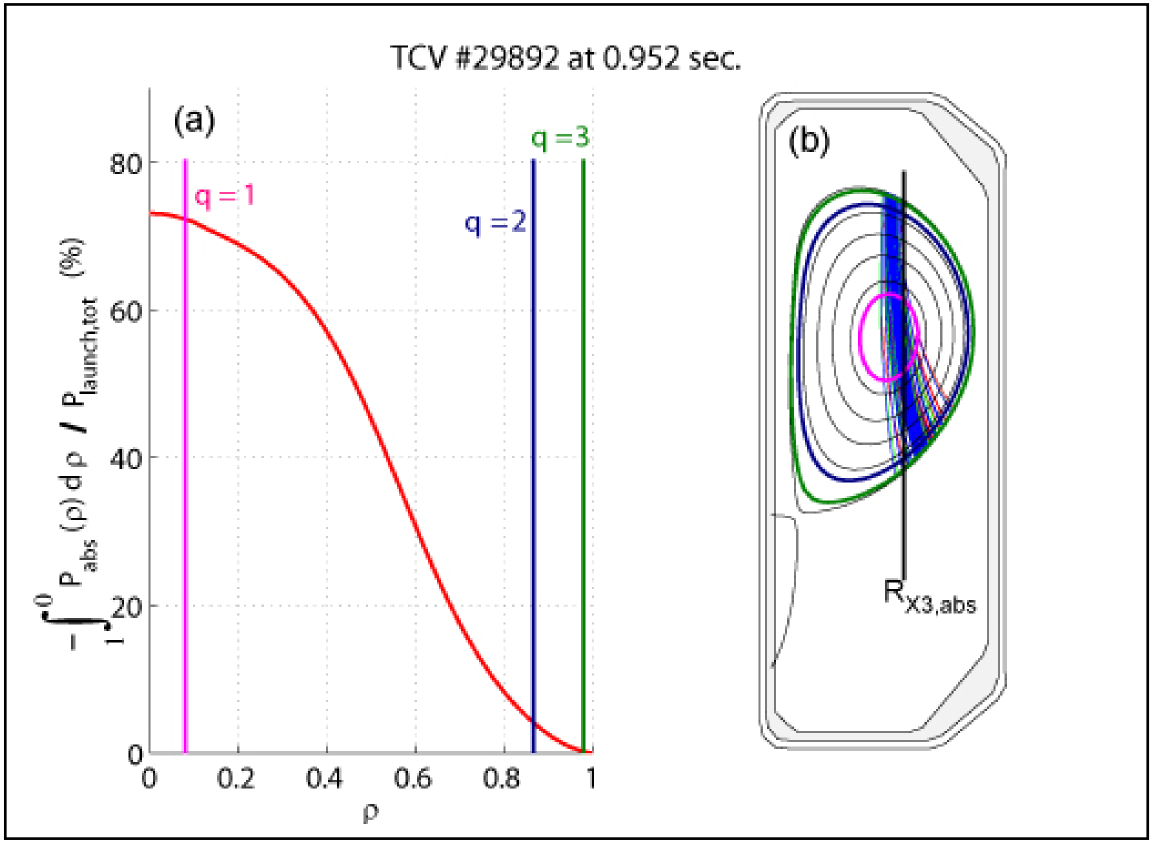
$q_{95} \approx 2.4$

$d_{inner} \approx$ 3cm

$\delta W_{DIA,ELM} / W_{DIA} \approx 4\%$

IPB98(y,2) describes confinement

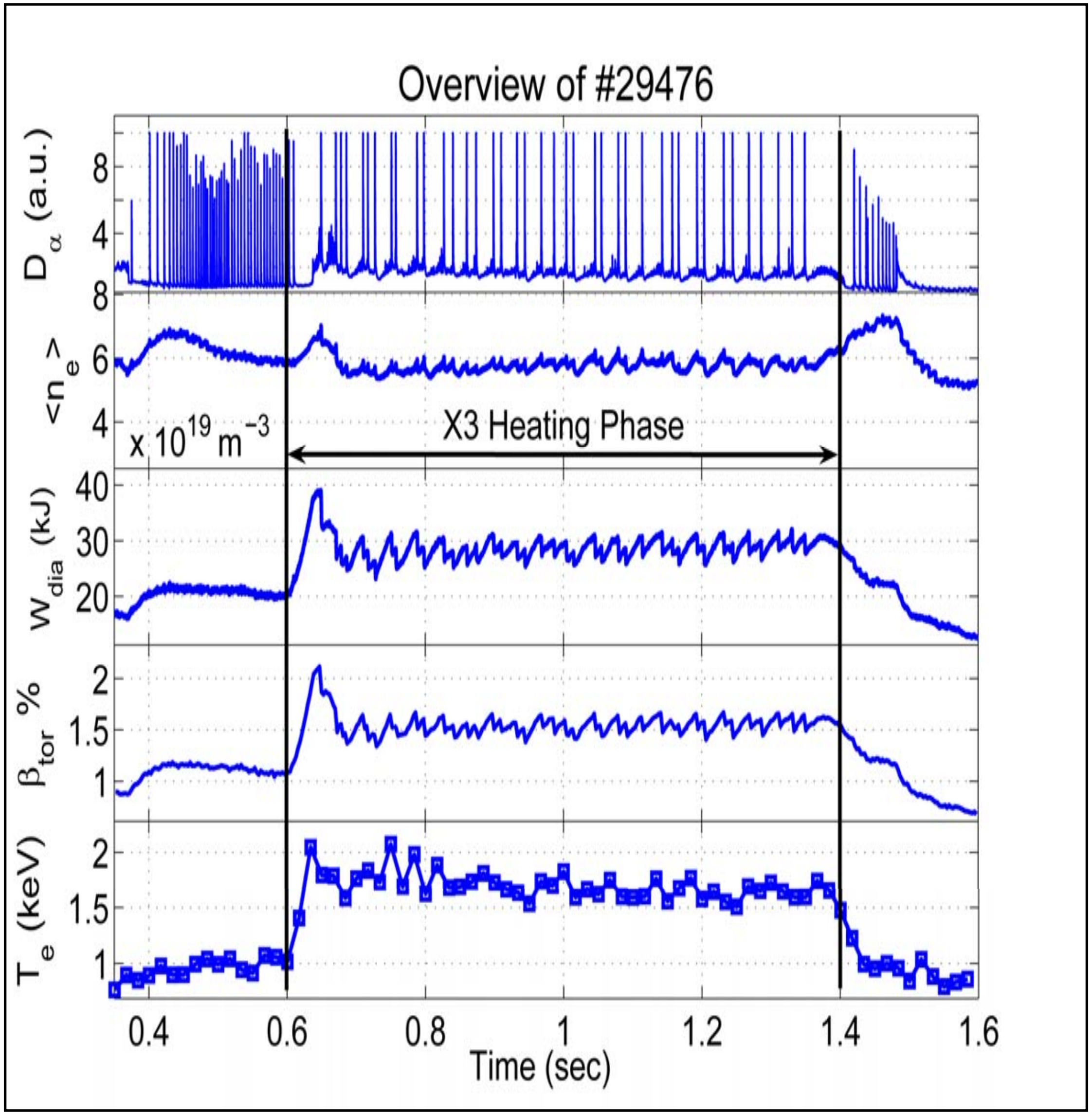
X3 HEATING OF H-MODE ON TCV



- Estimates of X3 absorption obtained using TORAY-GA
- Arnoux et al[1] have validated TORAY-GA use in H-mode → *good agreement between TORAY_GA & measures using modulated ECH & the response of a diamagnetic loop*
- These plasmas are thermal
- Absorption not localised & most heating takes place in a region $0.1 < \rho < 0.8$

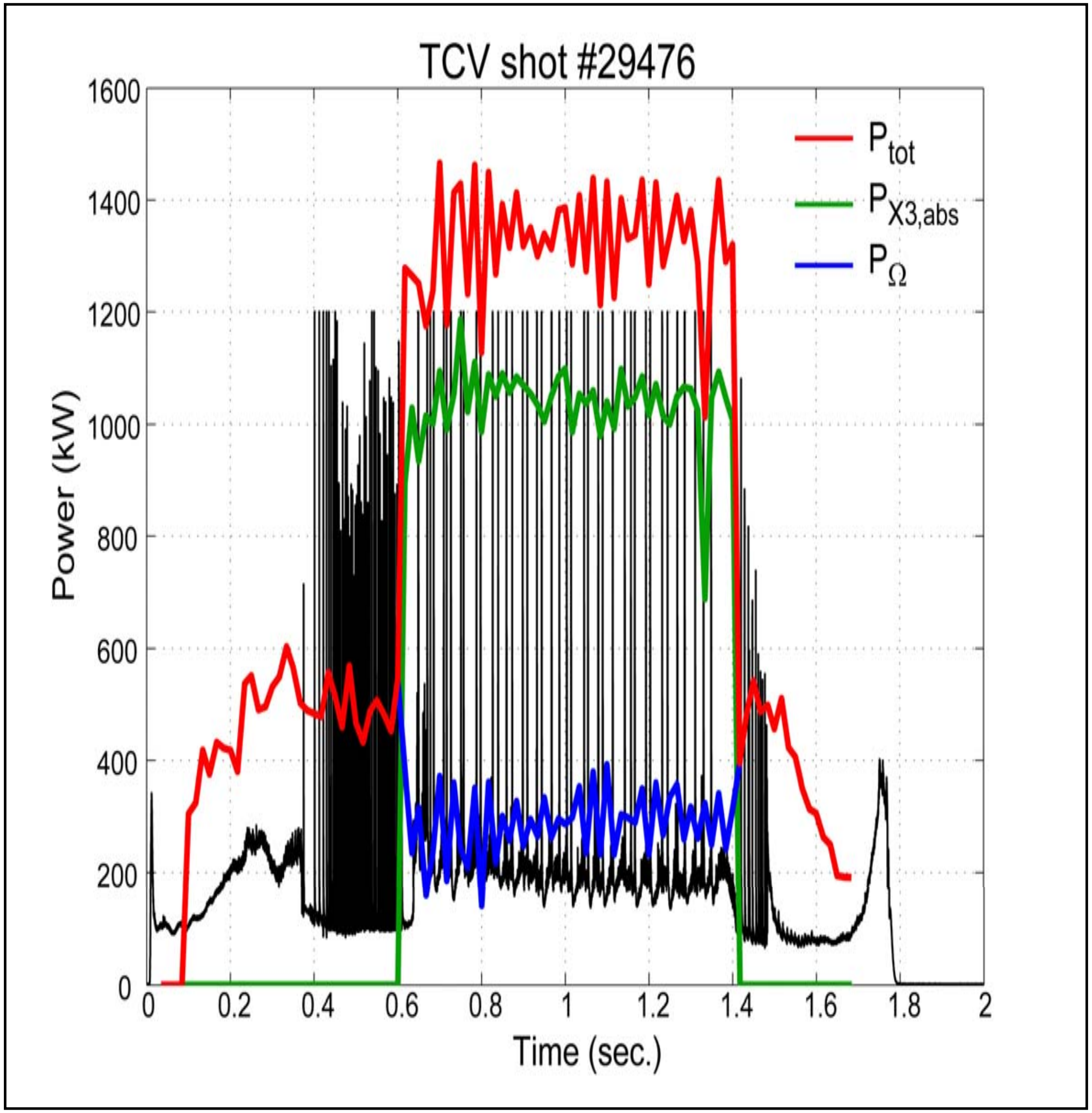
[1] Arnoux, G, PhD thesis EPFL #3401 (2005) & Plasma Phys. Control. Fusion **47**, 295 (2005)

X3 HEATING OF H-MODE IS 'ROBUST'



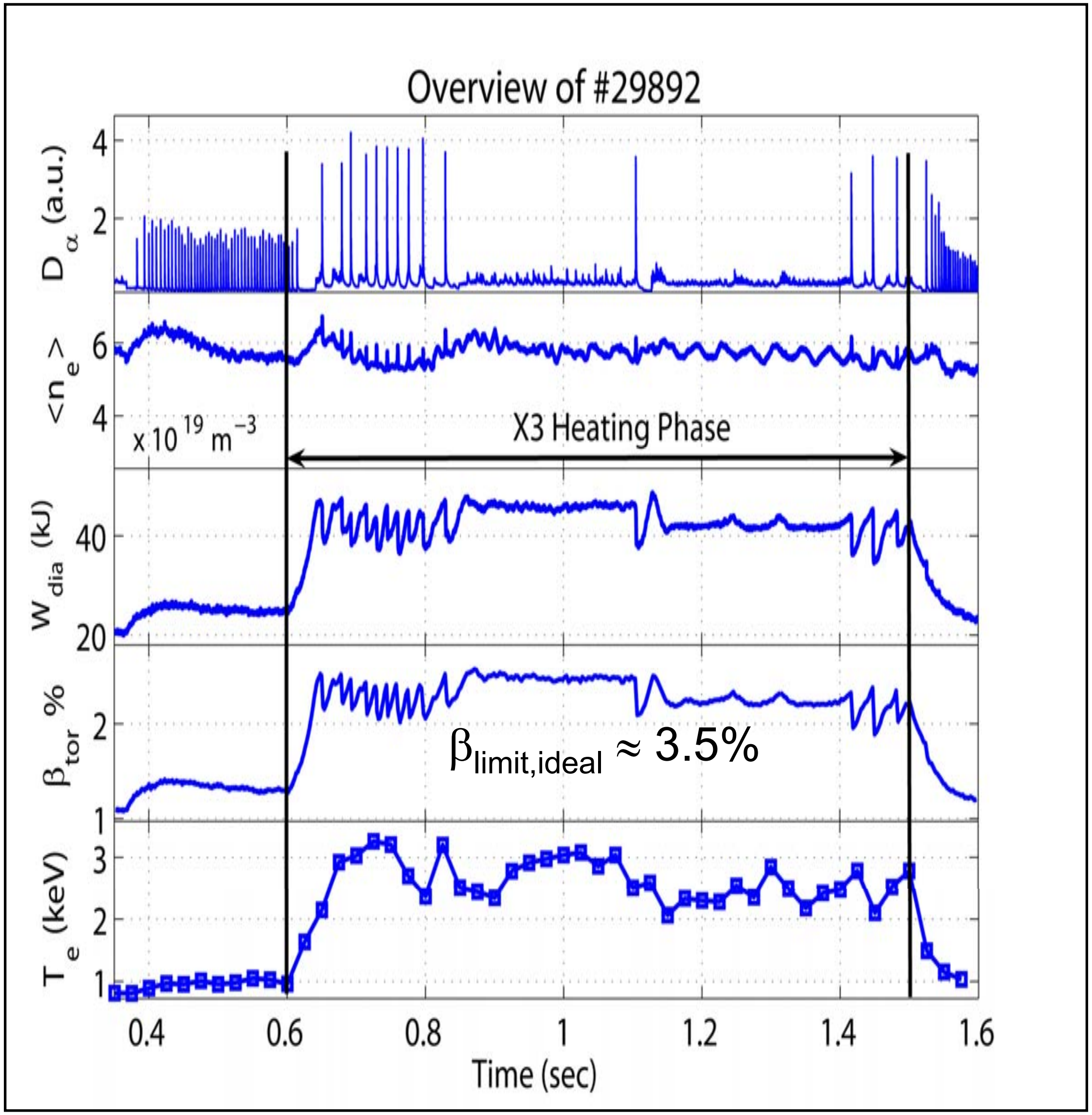
- ELMy H-mode successfully heated using vertical X3 ECRH
- $\delta<n_e> / <n_e> \approx 0.07$; ELMs do not degrade the X3 heating performance
- In this case X3 coupled fraction was ≈ 70% (960 kW)

X3 HEATING OF H-MODE IS 'ROBUST'



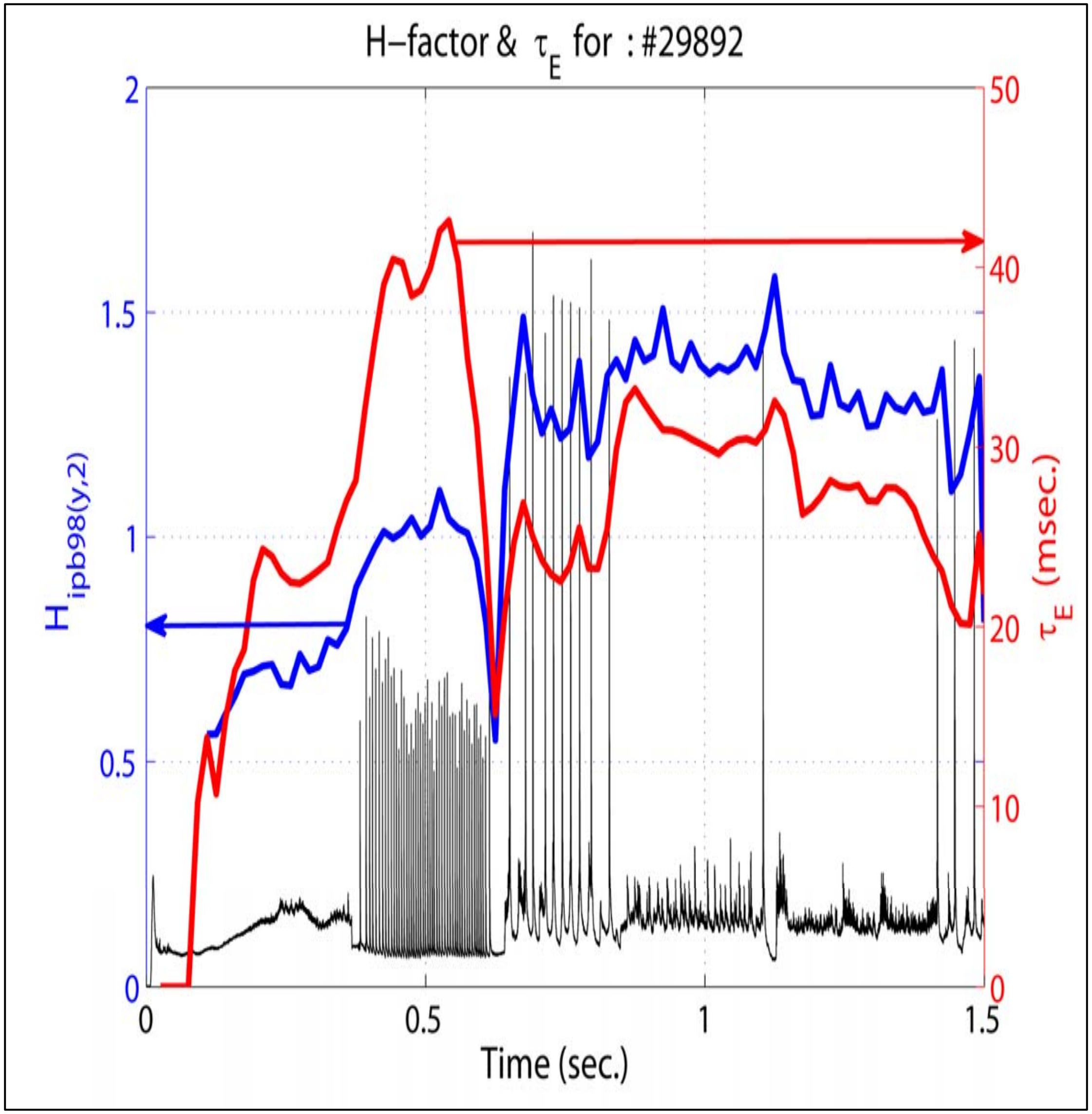
- $P_{\Omega} \approx$ 500kW falls to $\approx$ 300kW
- X3 absorption starts at 40% and quickly rises to its final 70%

QSEFHM : GENERAL



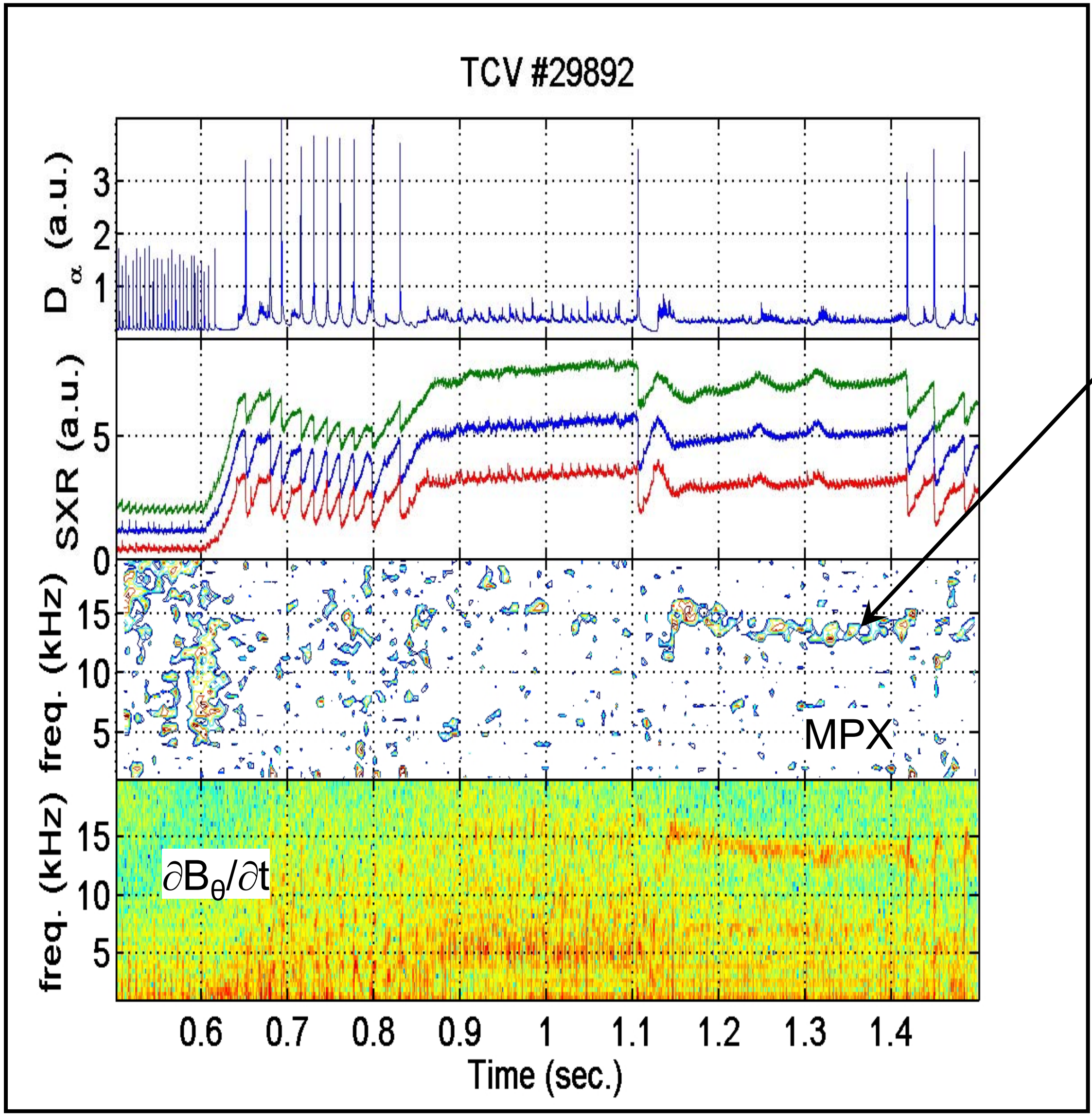
- Operating regime new to TCV
- Requires > 1.2 MW coupled X3 power
- The transition to QSEFHM is not yet understood
- High confinement
- Stationary density
- $Z_{eff} \approx 2.5$; $P_{rad} \approx 300$kW
- no impurity accumulation
- Discharge exhibits sawteeth
- Energy content doubles

QSEFHM: CONFINEMENT & MHD



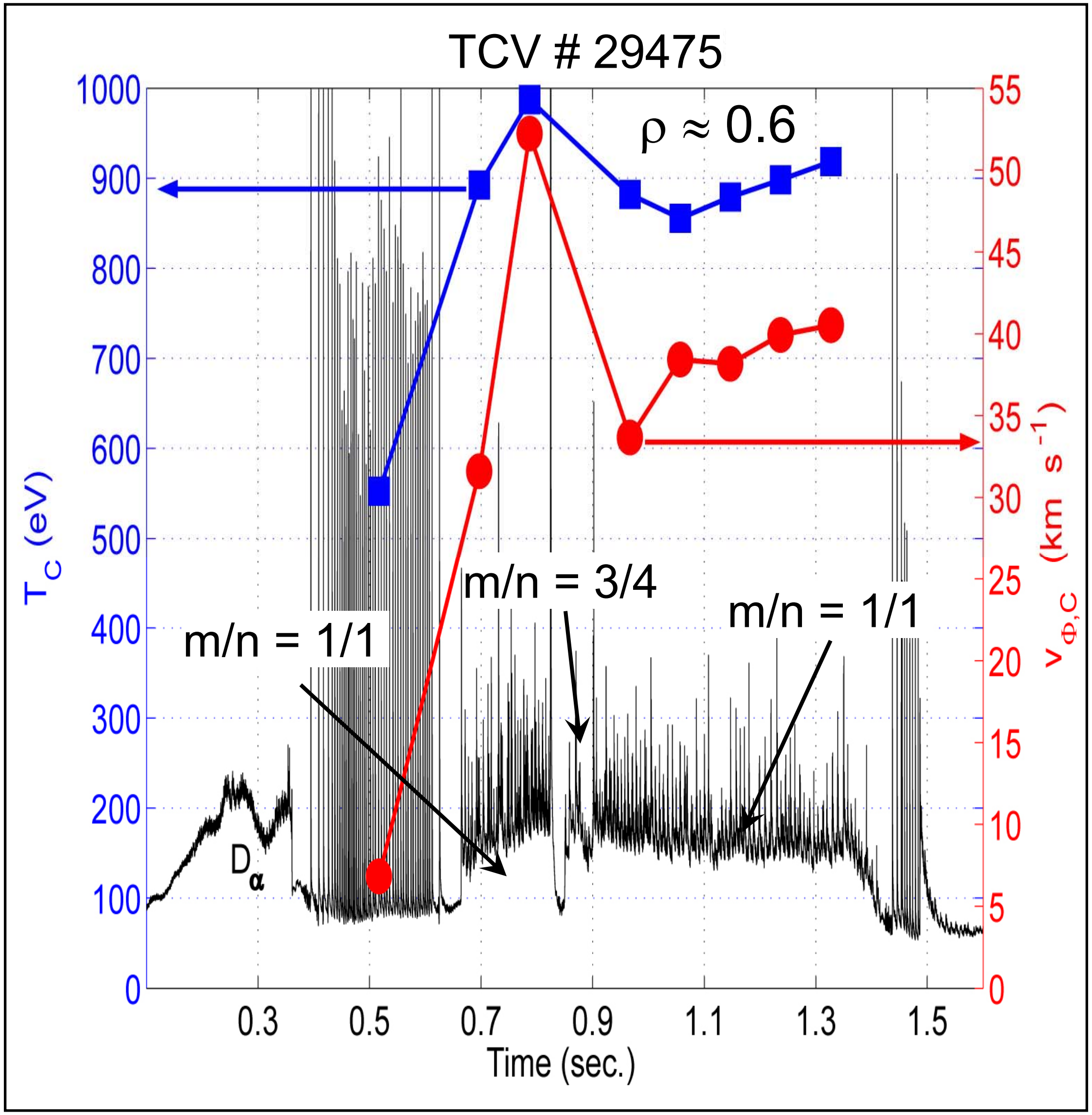
- $\tau_E \approx$ 27msec
- $H_{ipb98(y,2)} \approx 1.4$
- $n_{e,o}$ / $<n_e> \approx 1.5$
- Confinement degraded by the appearance of core MHD

QSEFHM: CONFINEMENT & MHD



- m/n = 1/1 modes dominate during the 'high performance' phase (SAWTEETH)
- m/n = 4/3 modes (NTMs ?) also appear and these degrade the confinement
- No mode similar to the EHO has been detected to date
- Density control not understood
- D_α light fluctuations strongly correlated with core MHD

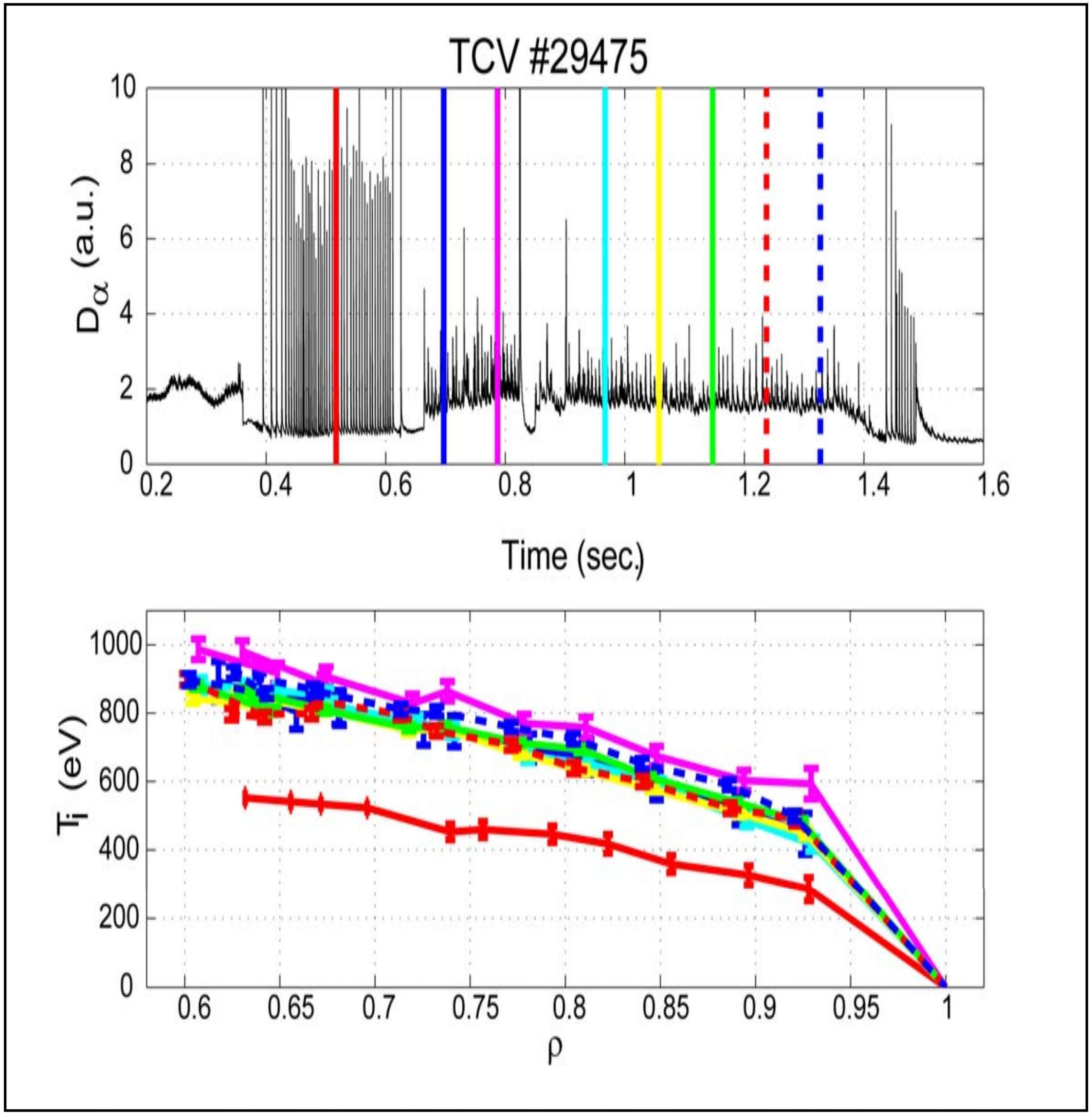
QSEFHM : ION BEHAVIOUR



- Shot similar to 29892
- CXRS measurements in unique conditions
- Significant collisional ion heating; T_i *doubles*
- $v_\Phi \uparrow$ at onset of QSEFHM
- $v_\Phi \propto T_i^{**}$ during the QSEFHM
- It is *not clear* that ion heating & toroidal rotation are features particular to QSEFHM
- MHD moderates T_i (confinement) and rotation

** Scarabosio et al : $v_\Phi \propto -T_i / I_p$ in L-mode : PPCF **48** (2006) 663-683

QSEFHM : ION BEHAVIOUR



- X3 goal → access high n_e
  → heat ions
- Achieved in these discharges
- $\rho \approx 0.6$ we have $T_i \approx$ 1keV
- $T_{i,\rho=0} \approx$1.0 keV (?) ASTRA
- $\tau_{e,I} \approx$ 90msec : ions heated on this time scale
- ≈ 18% coupled ECRH power to ions
- no sign of fast ions (NPA)
- first time on TCV
- door open to H-mode studies :
  massive electron heating
  indirect ion heating

QSEFHM : Unique ?

- It is our contention that the TCV QSEFHM is unique

- New mode does not resemble any other ELM–free high confinement regime seen elsewhere :

QH-mode (DIIID, JT-60U, JET, ASDEX) requires counter current NBI, cryo-pumping of divertor

EDA H-mode (ALCATOR) : $q_{95} > 3.7$, broadband, coherent fluctuations ($f_{fluc} \approx 100$kHz)

RI-Mode – high Z impurites, $n_e/n_G > 0.8$ and $\nu_{eff} > 1$

Type II ELMS – $q_{95} > 4.0$ required & $n_e/n_G > 0.8$ and $\nu_{eff} > 1$

QSEFHM : SUMMARY

- Require $P_{x3,coupled}$ > 1.2MW to access QSEFHM
- significant : ELM-free High Confinement Mode occurring at fusion relevant plasma parameters ($\beta_N \approx 2$, $\nu_{eff} \approx 0.4$ and $q_{95} \approx 2.5$)
- unique : differs in many respects to other very similar regimes found elsewhere
  opportunity to study rotation, in high power, high confinement regime with no external momentum input
- transition to quasi-stationary ELM free mode not yet understood
- energy confinement better than IPB98(y,2)
  modelling effort underway (Asp, Horton et al Sherwood meeting 2007)@
    ASTRA & GFL23 used to model confinement
    BOTH underestimate the energy confinement time
    GLF23 fails to predict the increase in τ_E at transition from ELMy to QSEFHM (29892)
- Stationary density has yet to be explained: no 'edge harmonic oscillation' observed to date; core MHD ? Fluctuation diagnostics (correlation ECE & phase contrast imaging) to be installed

@ work done in collaboration with the Institute for Fusion Studies, Univ. Texas, Austin

SUMMARY & CONCLUSIONS

- cryogenically cooled sapphire gyrotron windows → problematic
  - one has already been replaced by a CVD diamond window
  - increase gyrotron power output

- high harmonic (X3) ECRH has proven an effective heating method on TCV

- H-mode heating experiments have been very successful
  - collisional ion heating observed in an ECRH heated H-mode plasma
  - >80% first pass absorption obtained

- new quasi-stationary ELM-free H-mode regime obtained
  - Ion temperature doubles ; collisional ion heating
  - high energy confinement
  - massive toroidal rotation increase observed at the onset of X3 heating (no external momentum input)