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EDGE STABILITY AND PERFORMANCE OF THE ELM-FREE QUIESCENT H-MODE AND THE QUIESCENT DOUBLE BARRIER MODE ON DIII-D

W.P. WEST, K.H. BURRELL, T.A. CASPER,[1] E.J. DOYLE,[2] P.B. SNYDER,
P. GOHIL, L.L. LAO, C.J. LASNIER,[1] A.W. LEONARD, M.F.F NAVE,[3]
T.H. OSBORNE, D.M. THOMAS, G. WANG,[2] and L. ZENG[2]

General Atomics
San Diego, California 92186-5608
United States of America

[1]Lawrence Livermore National Laboratory, Livermore, California, USA
[2]University of California, Los Angeles, California, USA
[3]Associacao Euratom/IST, Instituto Superior Tecnico, Lisbon, Portugal

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QUIESCENT H MODE: AN ELM-FREE, HIGH CONFINEMENT MODE IN TOKAMAKS

Near stationary state operation at $H_{89} \sim 2$ with no ELMs for $\tau_{DURATION}/\tau_E > 30$ ($\tau_{DURATION}/\tau_R > 2$).

No ELMs $\Rightarrow$ no impulsive divertor heating.

Edge transport barrier and pedestal pressure similar to ELMing H-mode

Edge particle transport sufficient to allow control of the edge density with divertor pumping without ELMs

Combines with an internal transport barrier to form the high-performance, long-pulse “Quiescent Double Barrier” mode.

Accompanied by MHD activity, usually the Edge Harmonic Oscillation (EHO).

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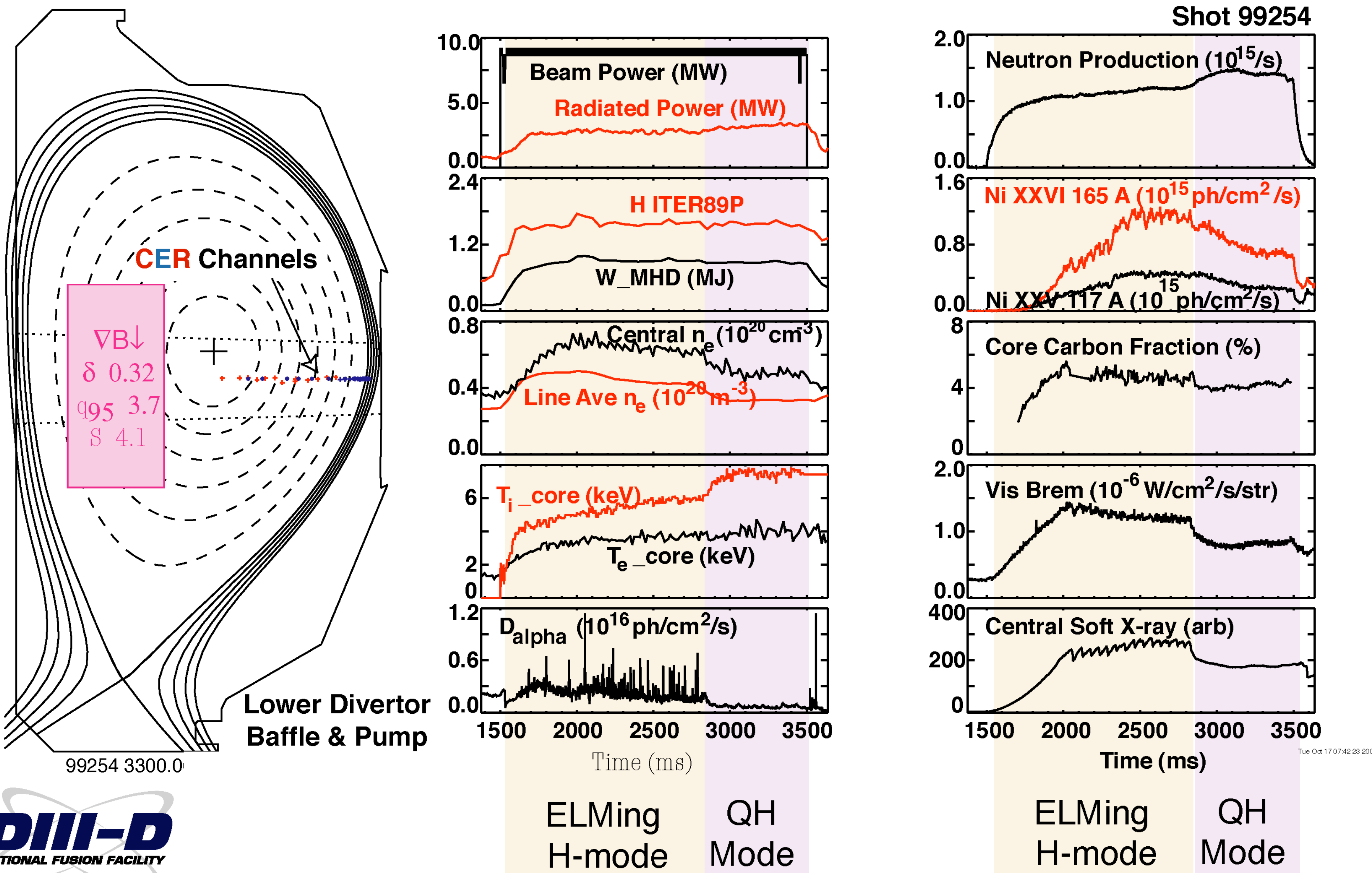
ELMING TO QH TRANSITION FEATURES: LOWER DENSITY, INCREASED T_I AND LOWER IMPURITIES



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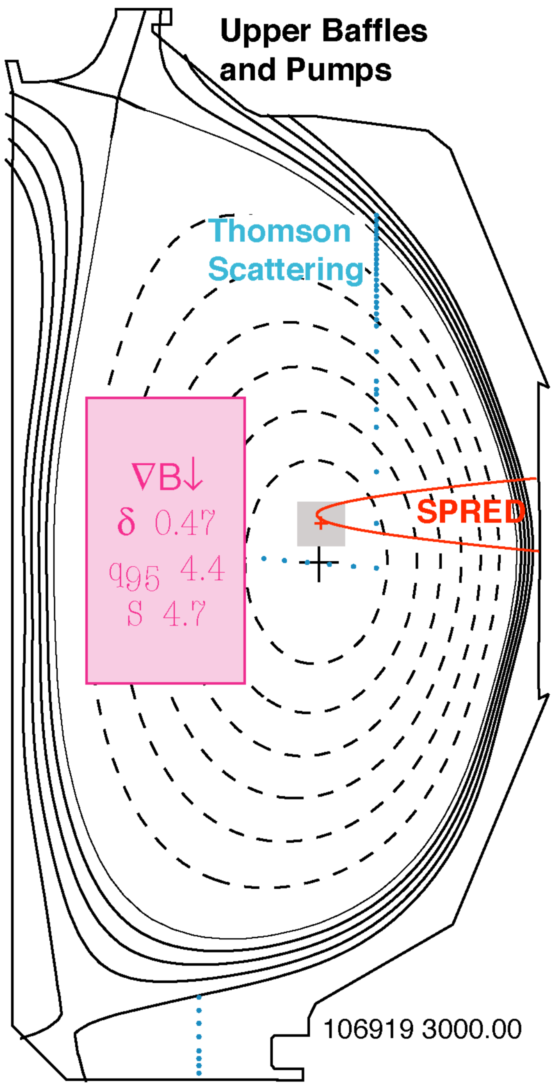
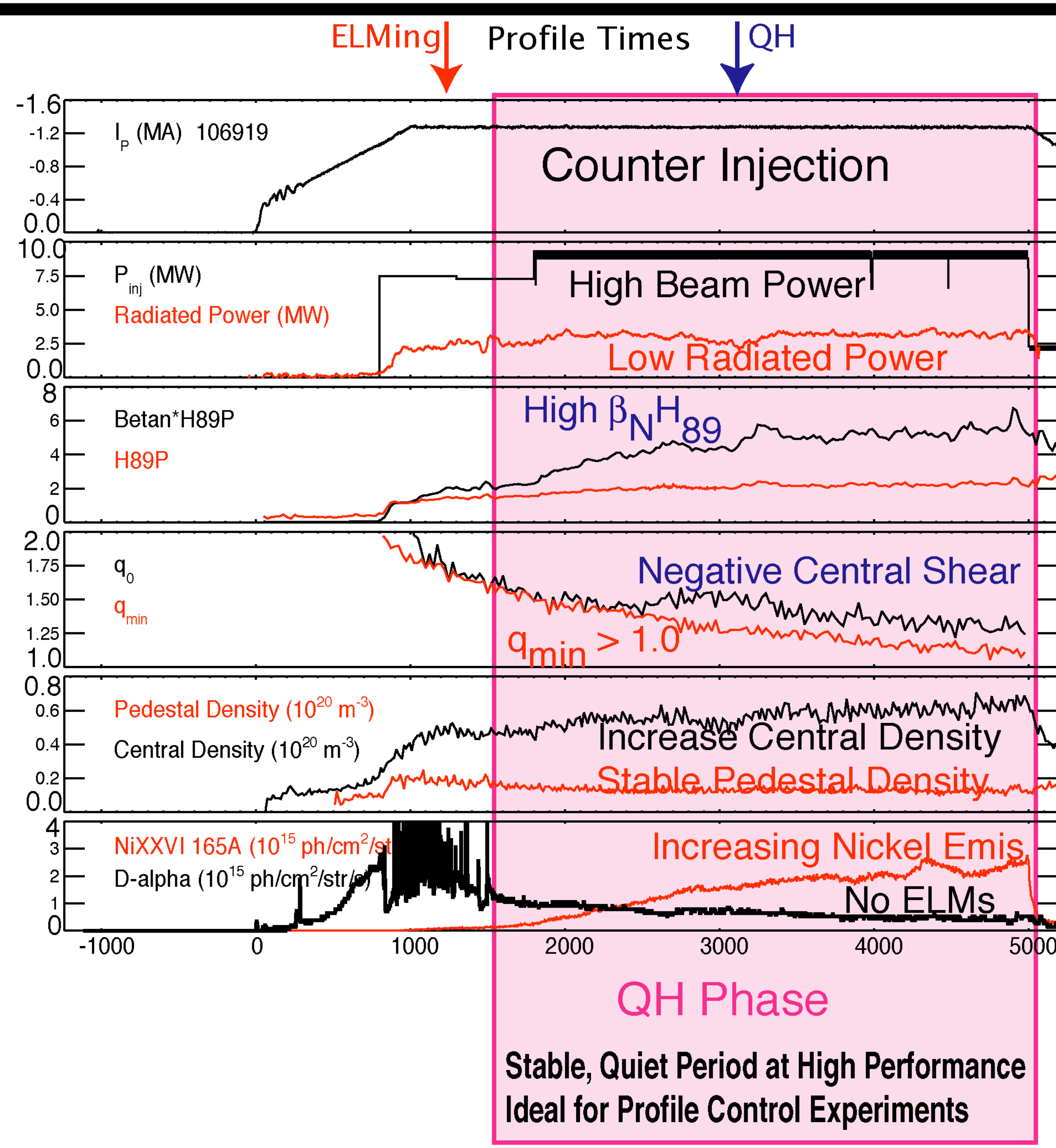
QDB DISCHARGES, QH + ITB
LONG PULSE, HIGH PERFORMANCE, NO ELMS





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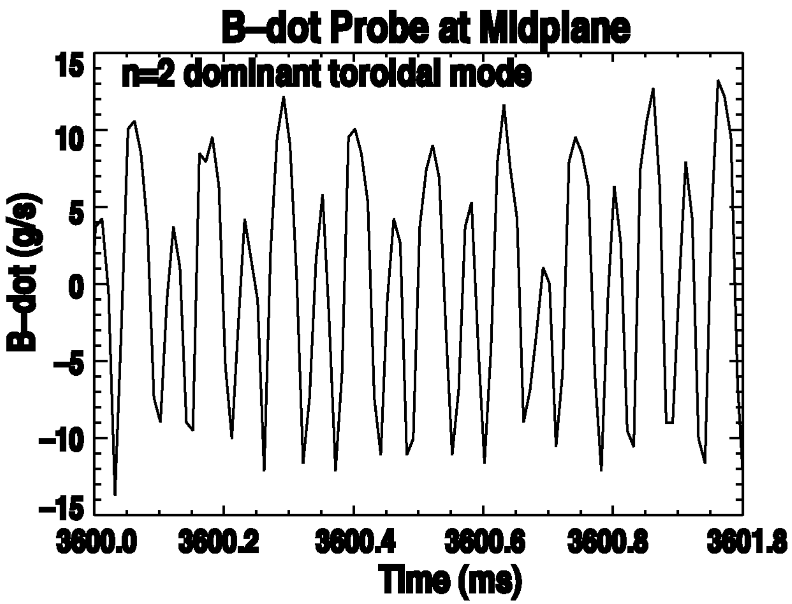
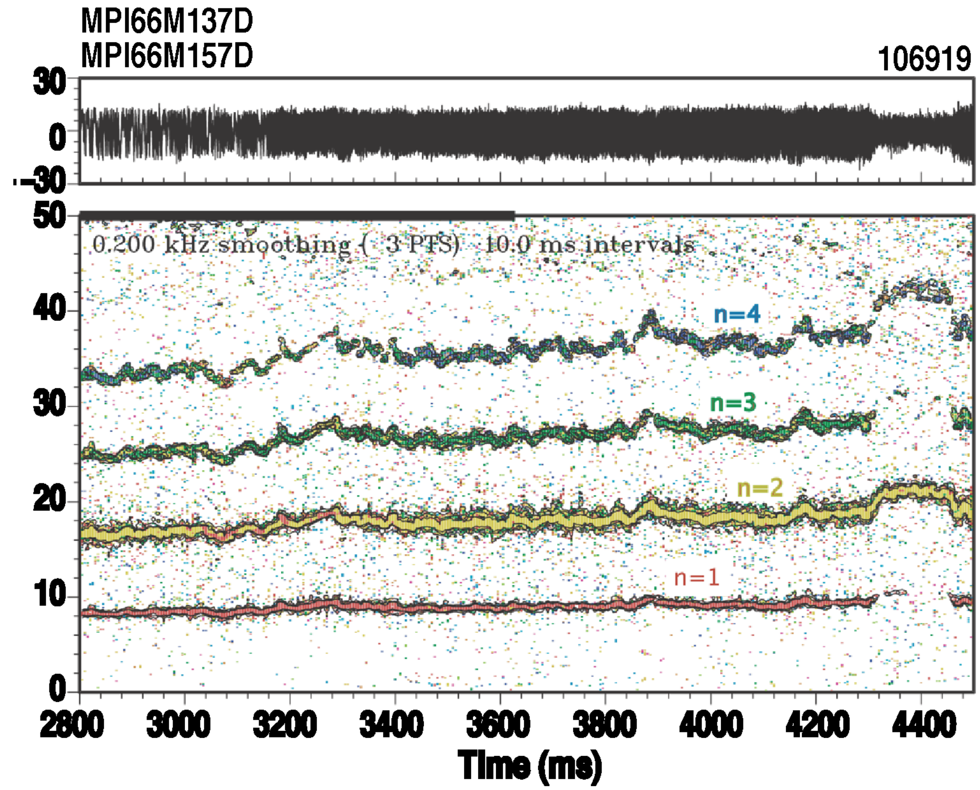
EHO CROSS–POWER SPECTRUM FROM MIDPLANE MAGNETIC PROBES





Also seen in:

- Beam emission spectroscopy
- Reflectometry
- Divertor Langmuir probes
- Tile current array
- Thomson scattering
- Electron Cyclotron Emission

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QH MODE EXISTS OVER A WIDE RANGE OF OPERATING PARAMETERS

To date, QH mode has been found only in discharges with counter injection.

Upper and lower single null and double null configurations With ion Bx∇B drift away and toward the active x-point.

High and low triangularity	$0.15 < \delta_{AVG} < 0.8$
Elongation	$1.64 < \kappa < 2.1$
Safety Factor	$3.1 < q_{95} < 5.8$
Low Pedestal Density	$.07 < n_{ePED}/n_{GW} < 0.48$
Not a clear power threshold	Typically $P_{INJ} > 5$ MW

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PEDESTAL PROPERTIES IN QH MODE DISCHARGES

The QH-mode pressure pedestal is similar in the QH and ELMing phases of the same discharge

The pedestal density height and gradient are smaller in the QH phase, while electron and ion pedestal temperature height are corresponding larger.

The edge current is suspected to have a significant role in the edge peeling/ballooning mode stability.

Deep, narrow Radial Electric Field Well observed just inside separatrix

Higher δ, double null QH discharges have higher pedestal density, and pressure-- reach β_{PED} and $\nu_i{}^*{}_{PED}$ values ~ ITER.

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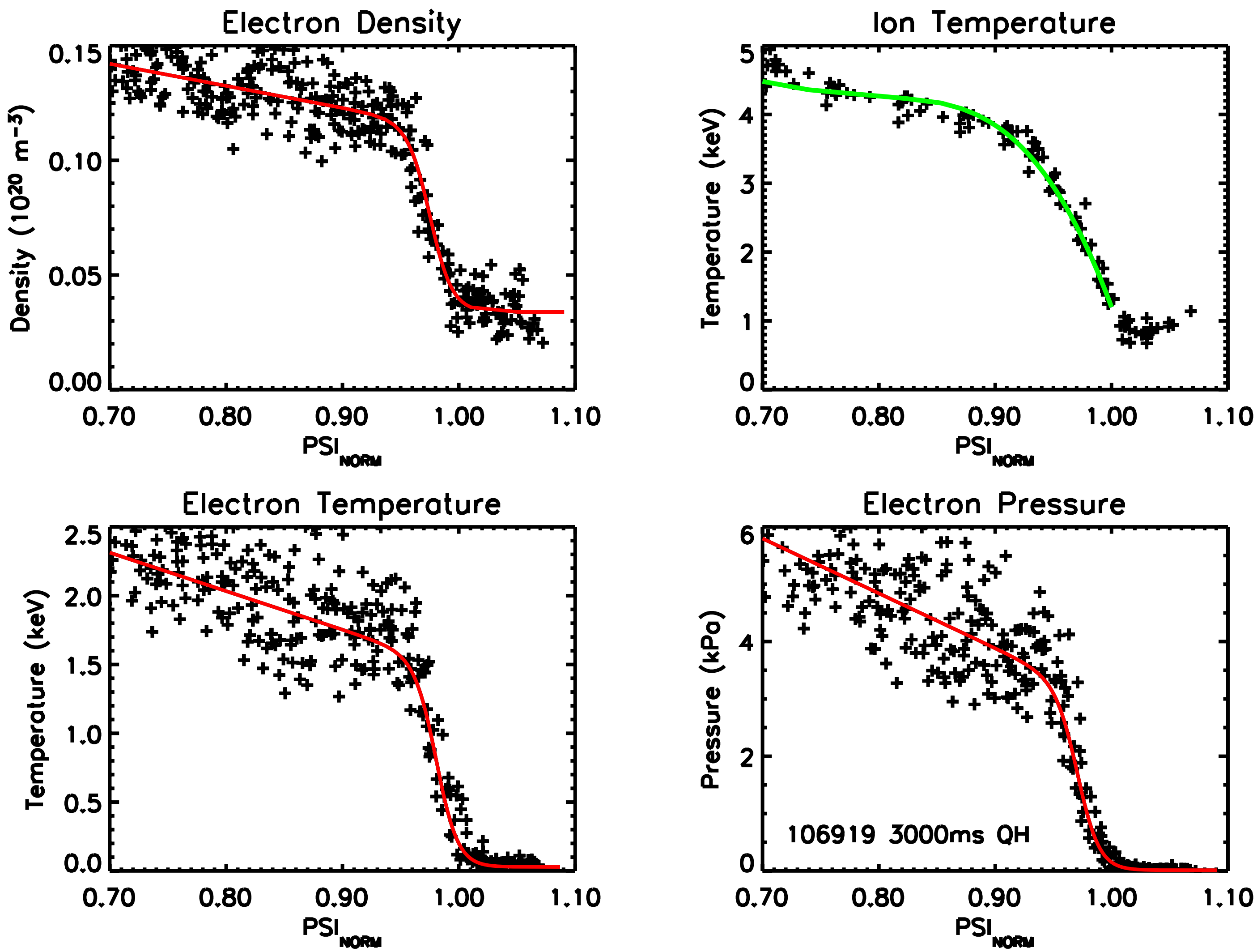
THE DIII-D EDGE THOMSON AND CER DATA SHOW THE H-MODE EDGE BARRIER

Stationary QH Phase with Data from a 200ms Window

Red– Modified Tanh fit

Green– Spline Fit



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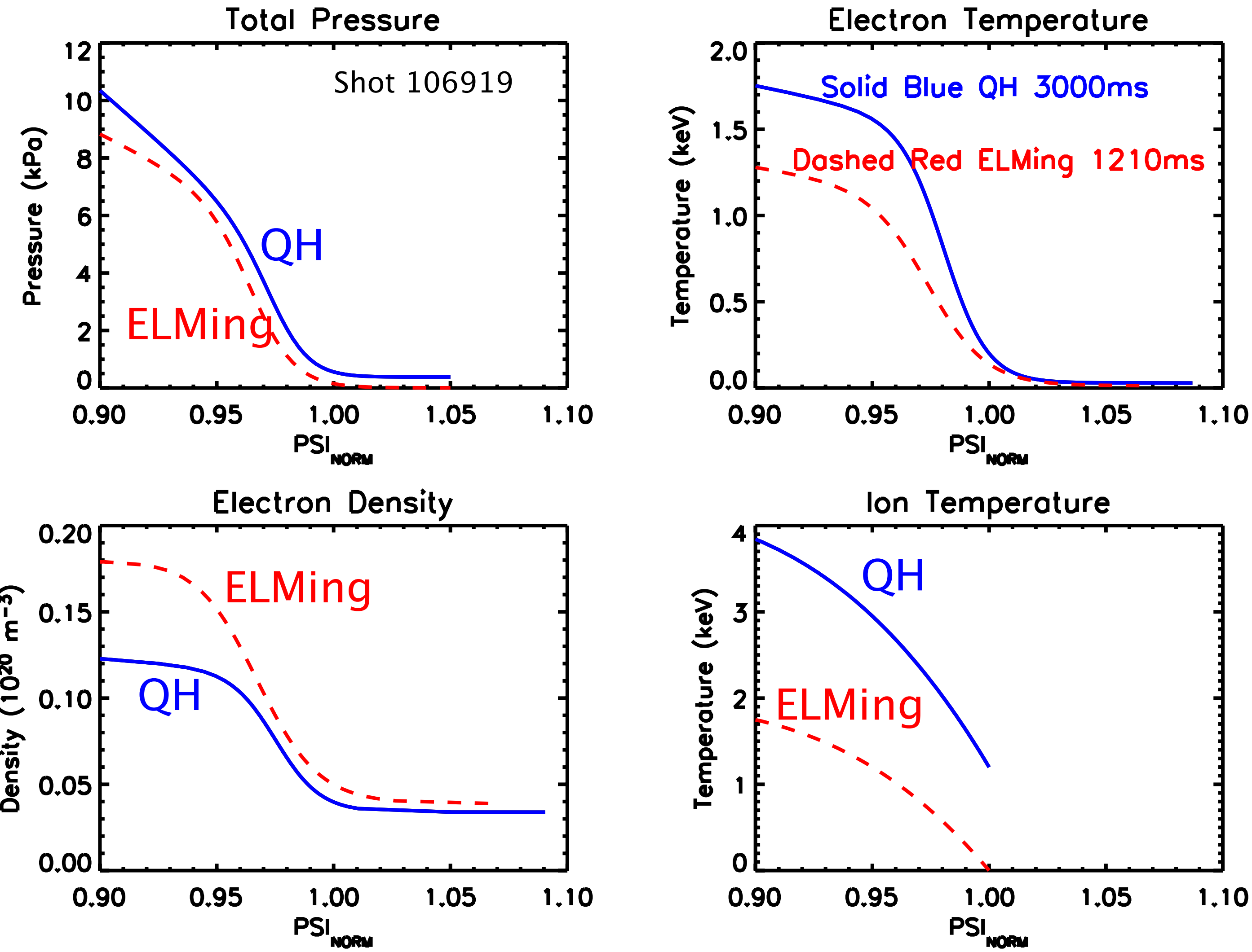
ELMING AND QH PHASES HAVE SIMILAR PEDESTAL PRESSURE PROFILES BUT VERY DIFFERENT DENSITY AND TEMPERATURE PROFILES

Pedestal Density is Higher in the ELMing Phase but Ion & Electron Temperatures are Lower



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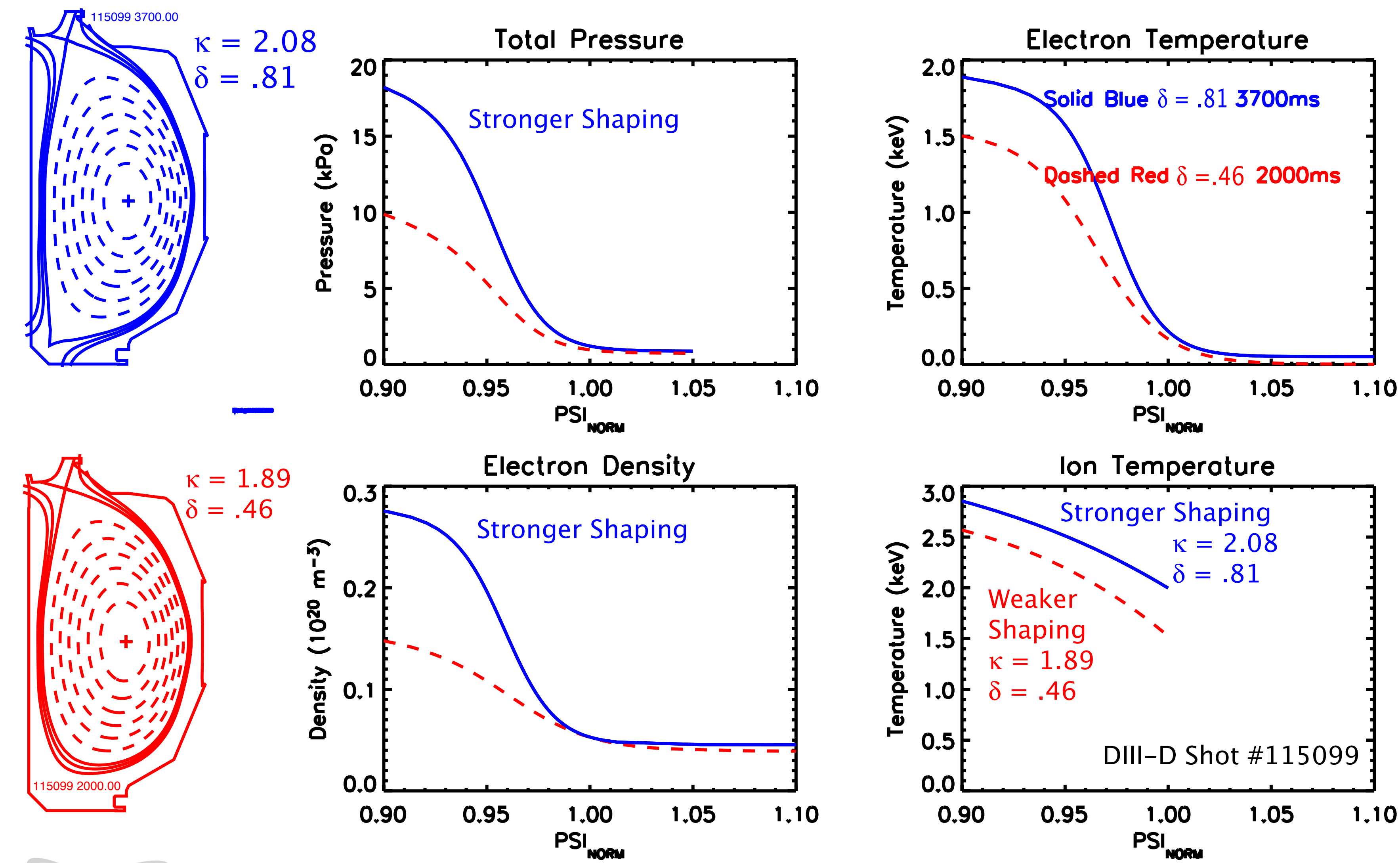
INCREASED SHAPING ALLOWS ACCESS TO HIGHER PEDESTAL DENSITY AND PRESSURE WITH NO ELMS



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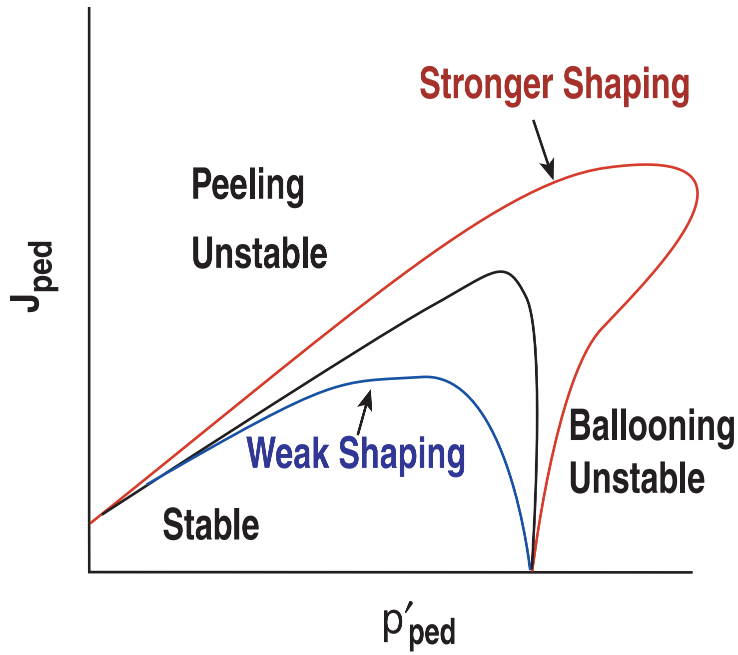
THEORY OF COUPLED PEELING/BALLOONING MODE SHOWS SHAPING EXTENDS THE STABILITY WINDOW TO HIGHER J_{PED} AND P'



-ELITE peeling/ballooning mode modeling shows that higher δ,κ allows operation at higher P'_{PED} and J_{PED} without ELM Instabilities

-Doubling of the pedestal density and pressure was achieved by increasing δ from 0.46 to 0.81 and κ from 1.89 to 2.08.

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STABILITY PROPERTIES OF THE QH MODE

During QH mode, upward Ip ramps induce ELMS while downward I_P ramps do not.

Modeling of the stability of coupled peeling/ballooning modes for a high δ QH mode discharge indicate marginal stability to current driven medium n modes.

- High resolution equilibrium reconstruction with a edge current density consistent with the edge bootstrap current completed using the CORSICA code.

Pedestal properties, I_P Ramp Experiments, and stability analysis indicate that QH mode lies at a current driven stability boundary to coupled peeling/ballooning modes.

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COUPLED PEELING/BALLOONING MODE STABILITY IS EVALUATED USING THE ELITE AND CORISCA CODES

The nonlinear growth of coupled peeling/ballooning modes is the leading candidate for the underlying MHD mechanism governing ELMs.

ELITE modeling requires an accurate, high-resolution equilibrium, presently evaluated in a multi-step process.

A 2D equilibrium is reconstructed from external magnetic data on a rectangular grid using the EFIT code, but this equilibrium does not resolve the sharply peaked edge bootstrap current.

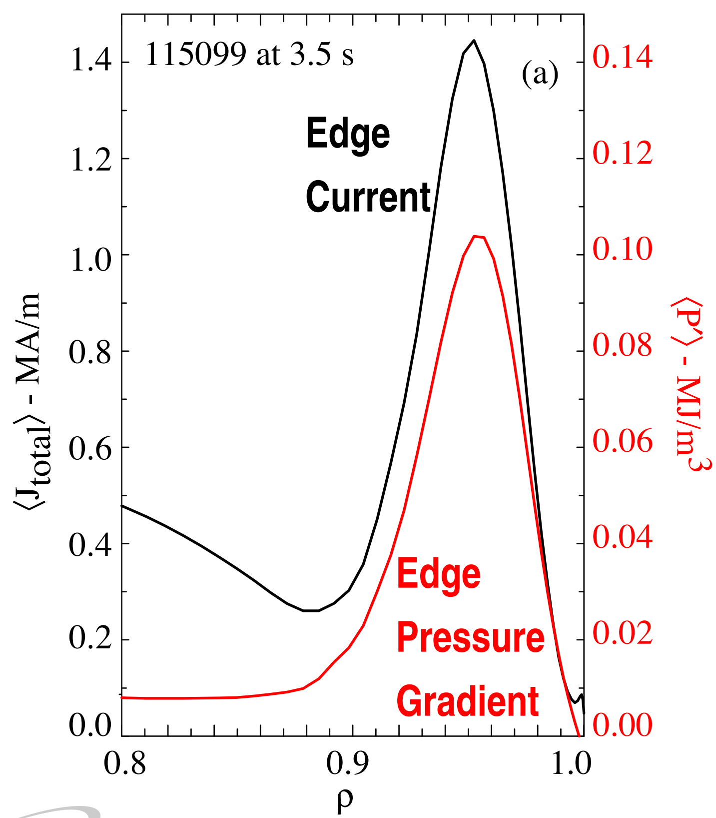
This equilibrium along with the measured kinetic data are imported into the time dependent MHD/transport modeling code, CORSICA

The neoclassical transport model, NCLASS is used within CORSICA to calculate the edge bootstrap current and a new equilibrium is constructed on a rectangular grid, consistent with the external magnetic data, and the edge bootstrap current.

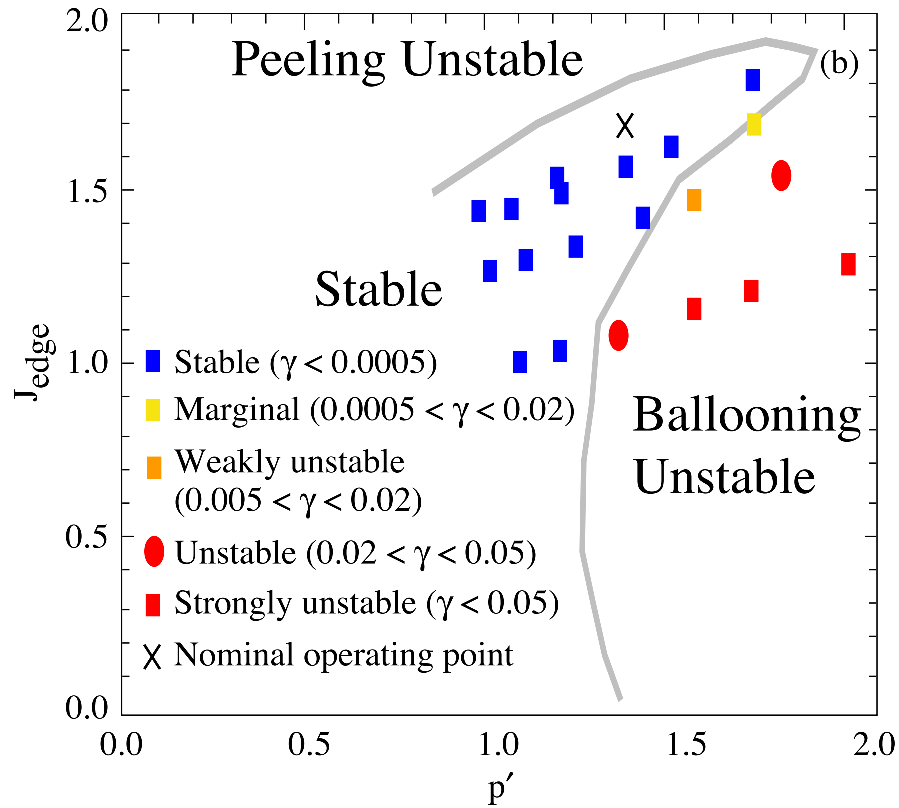
To achieve the high resolution needed by ELITE the final equilibrium is produced using a fixed-boundary, flux surface based inverse solver

ELITE STABILITY MODELING USING CORSICA EQUILIBRIA INDICATE THE HIGH δ QH MODE IS MARGINALLY STABLE

Edge Current and Pressure Profiles from CORSICA equilibrium for 115099



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

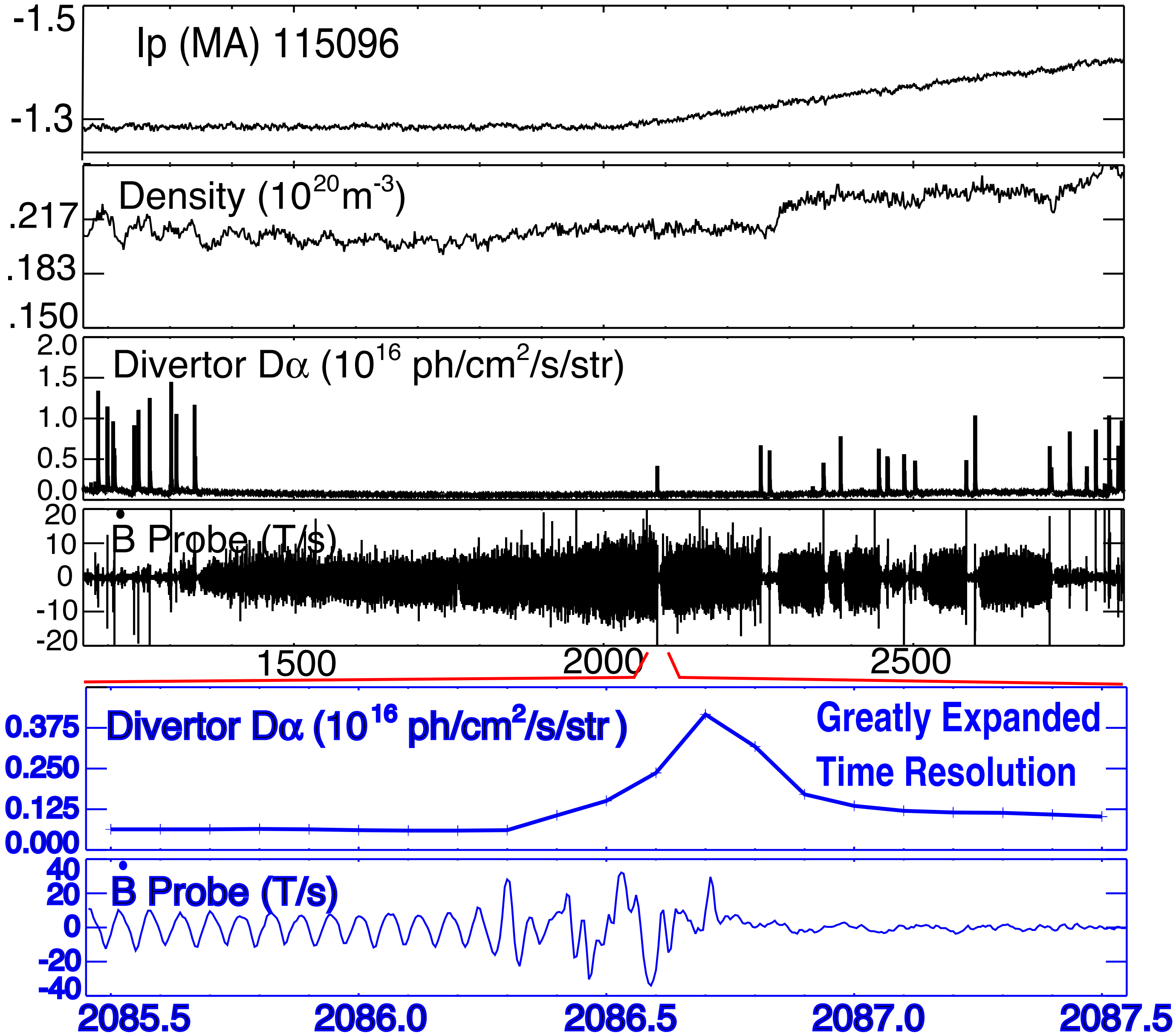


ELMS ARE INDUCED BY UPWARD CURRENT RAMP

Upward Ip Ramp at 0.15 MA/S in lower δ = 0.46 shape

Density Remains constant through first few ELMs after Ip ramp starts

During Ip ramp EHO is terminated abruptly by an ELM



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ELMS DO NOT RETURN DURING A DOWNWARD CURRENT RAMP

Ramp Rate -0.5 MA/S

Triangularity δ = 0.46

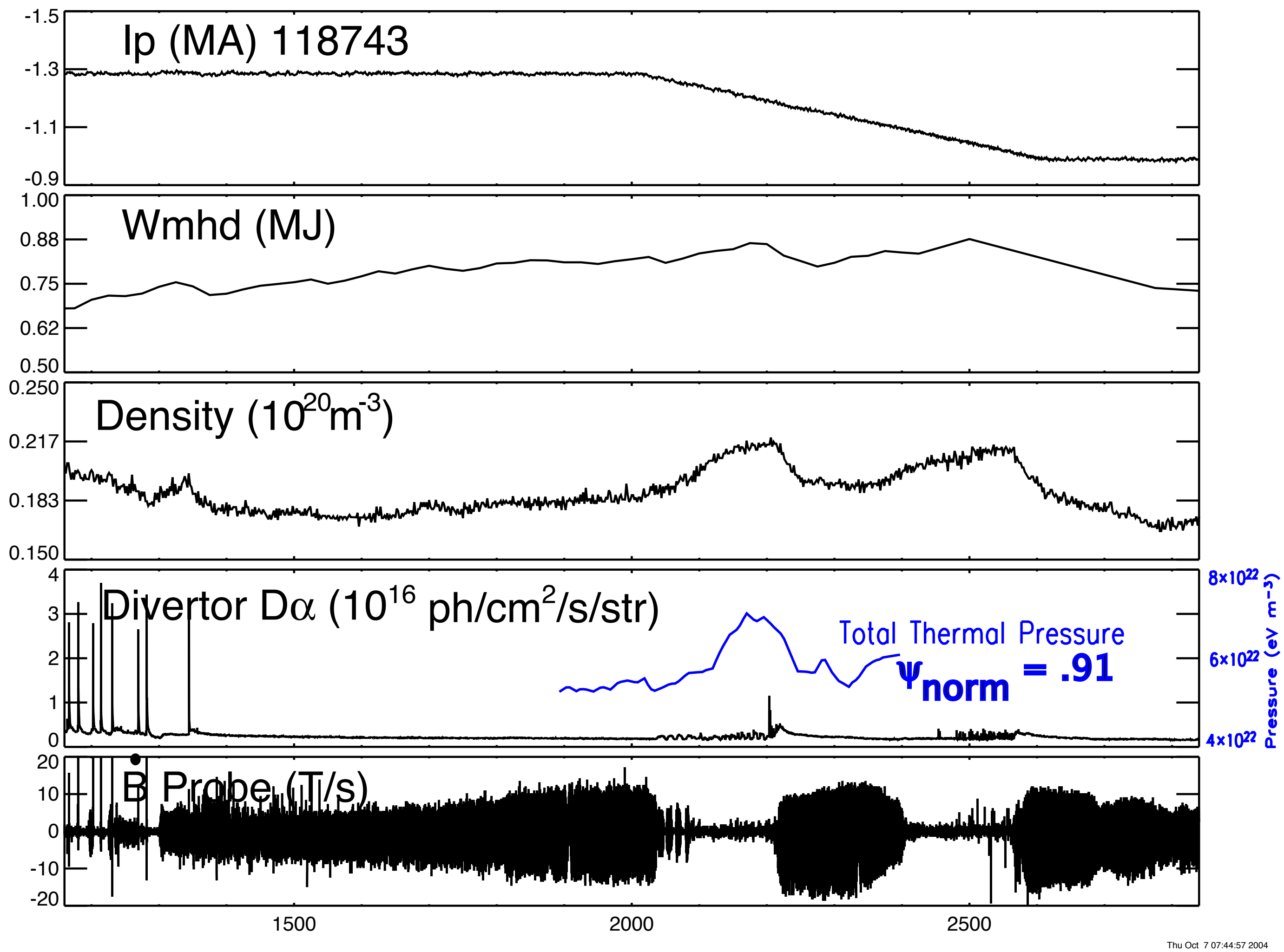
Stored Energy increases slightly when EHO is stabilized

Density Increases when EHO is stabilized

ELMs do not return during the ramp

Edge Pressure builds when EHO is stabilized

EHO is stabilzed then returns when edge pressure increases



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THE E_R WELL NEAR THE SEPARATRIX CAN BE VERY DEEP AND NARROW IN QH MODE

During high-powered QDB operation, E_R at the bottom of the well can be > -100 kV/m and the width of the well ~ 0.01 m

Rotational shear is also very high, both poloidal and toroidal.

A scan of the outer plasma edge across the CER viewing chords allows the well to be clearly defined.

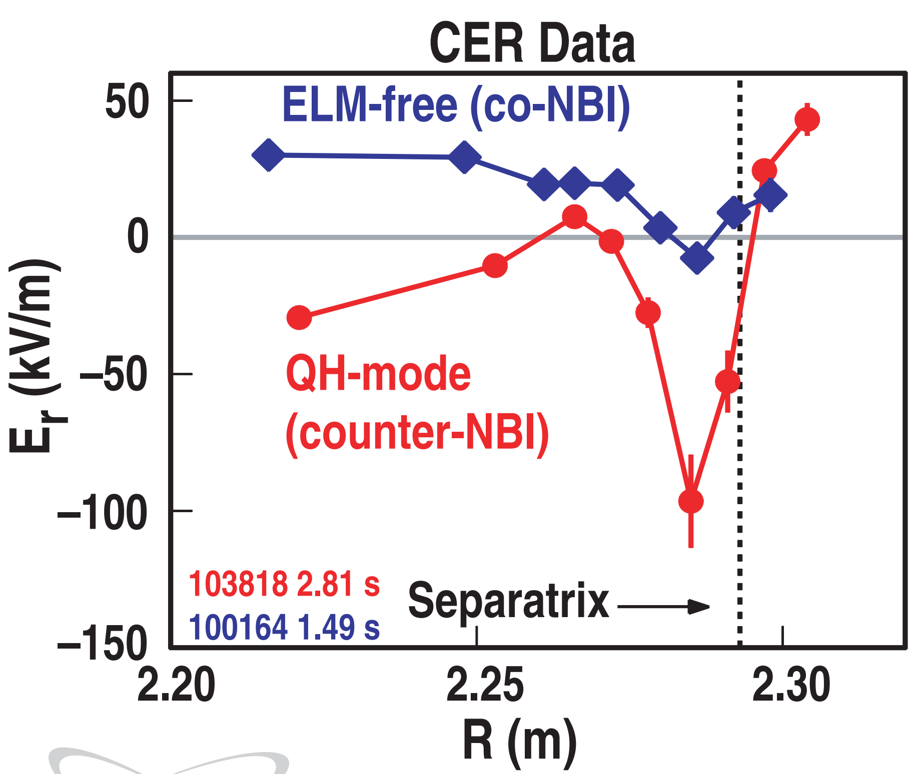
Prompt Beam Ion Loss due to counter injection has been shown not to play a dominate role in the E_R well or in the formation of QH mode.

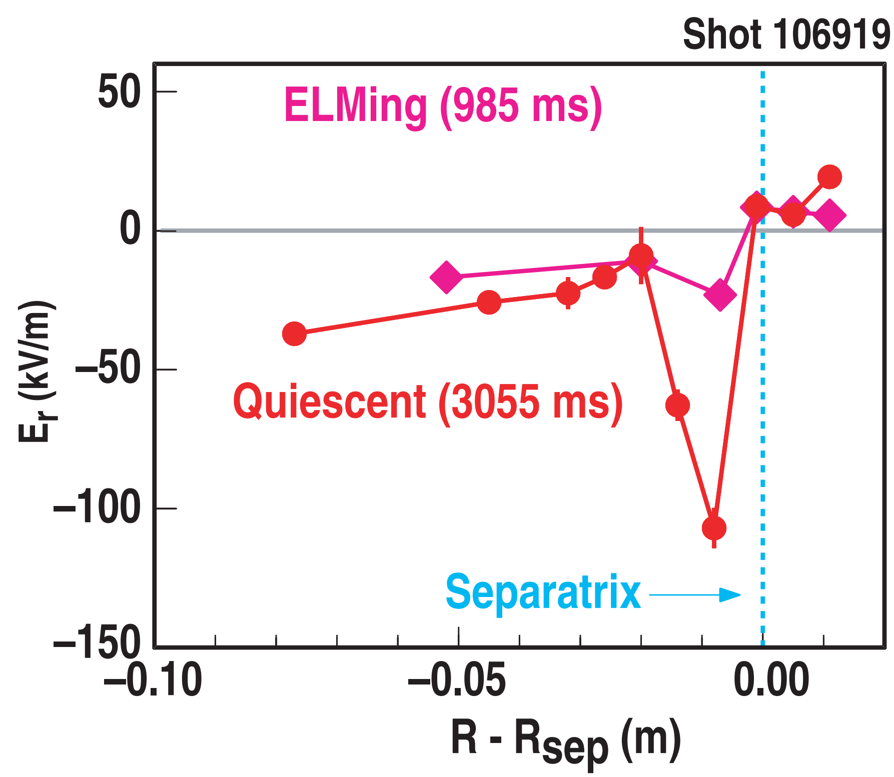
Fast ion loss associated with high-frequency magnetic bursts is observed in counter injected phases with no prompt beam ion loss and may contribute to the edge electric potential.

EDGE RADIAL ELECTRIC FIELD WELL IS DEEPER IN QUIESCENT PHASE

- CER data show much deeper E_r well in counter-injected quiescent H–mode than in co-injected ELM-free shot

- CER data show much deeper E_r well in quiescent phase than in ELMing phase of same discharge





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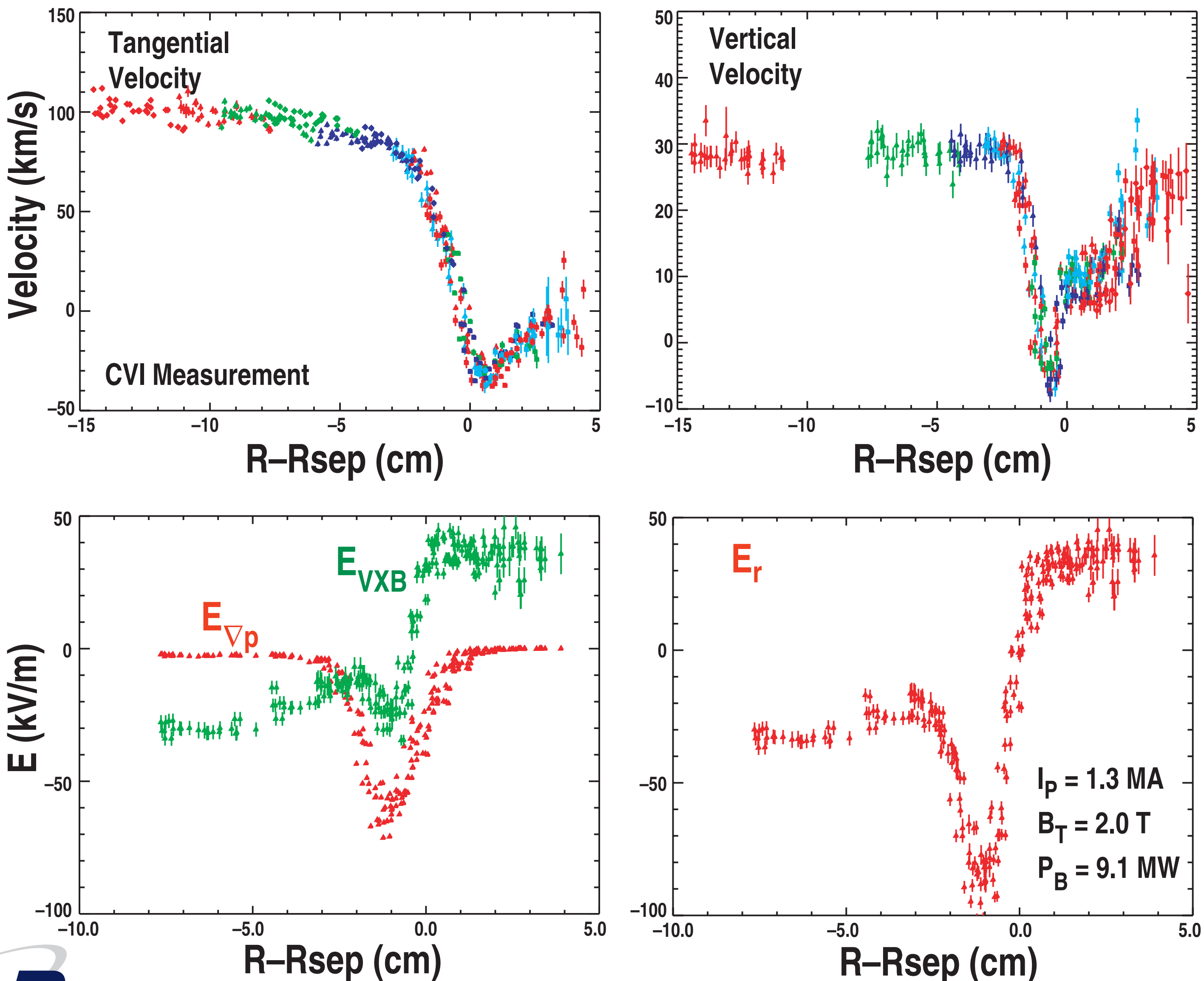
267–01/KHB/wj

EDGE SWEEP REVEALS FINE DETAILS OF EDGE ROTATION VELOCITY AND THE E_R WELL

- Data from shot 106999 from 3470 to 4100 ms



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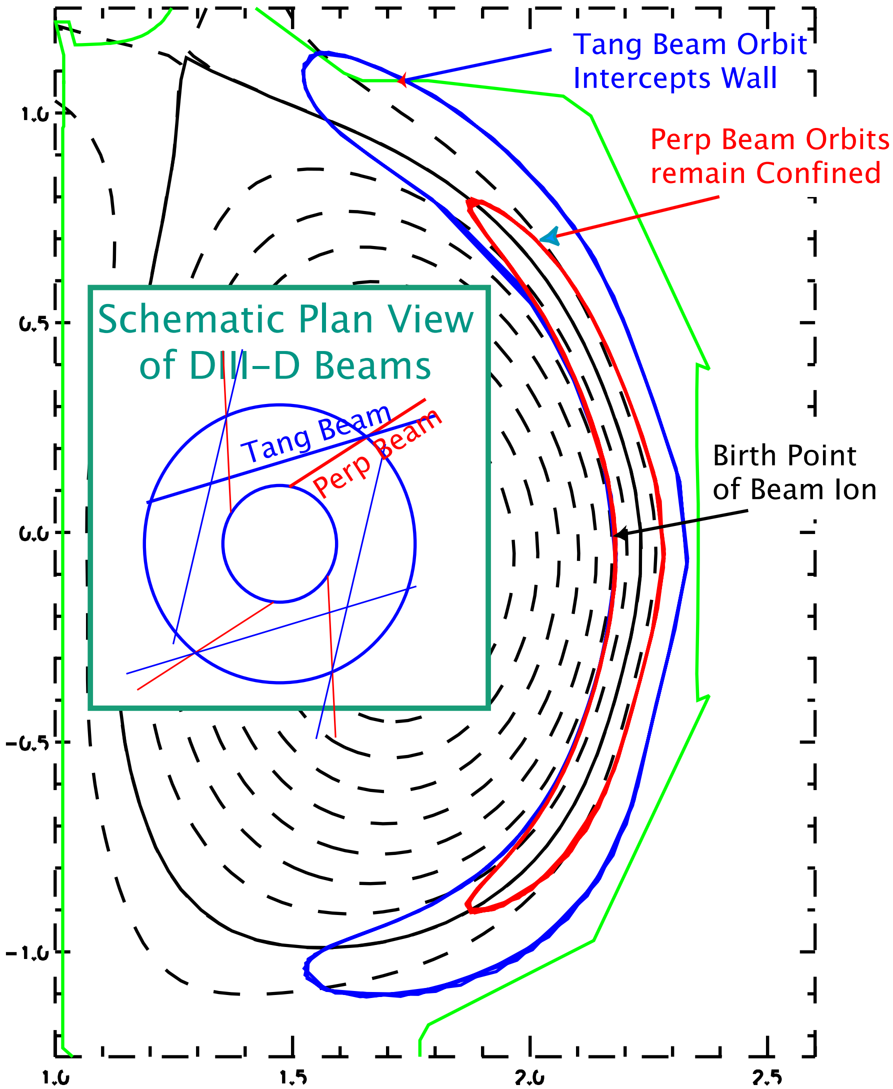
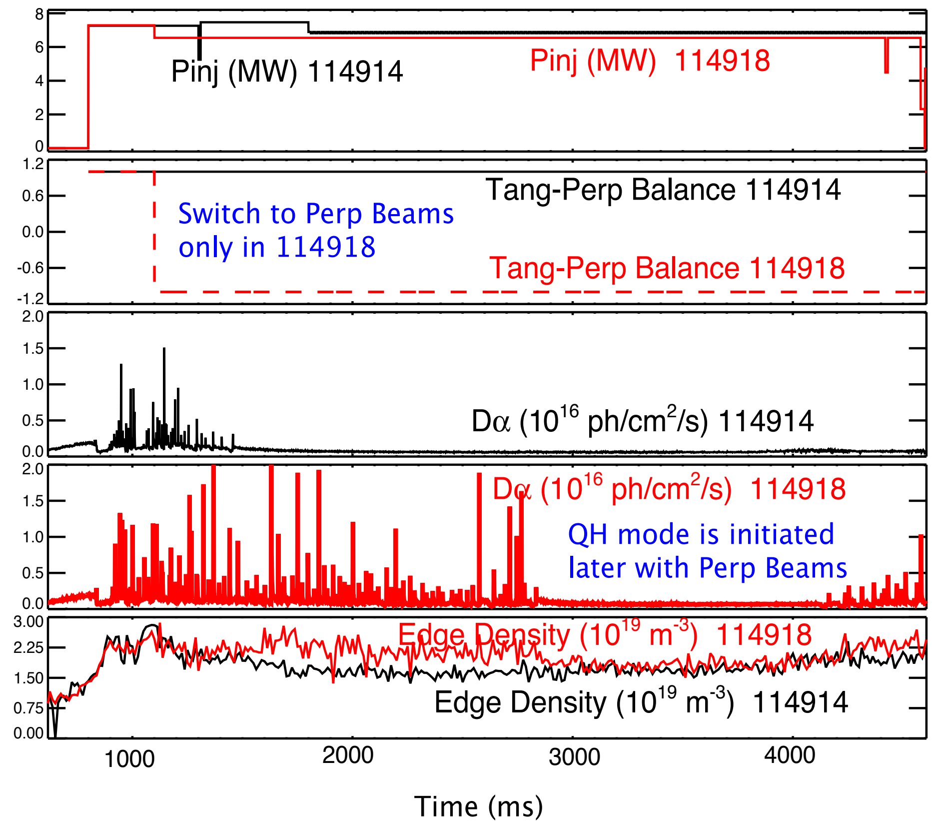
259-04/WPW/rs

PROMPT BEAM ION LOSS IS NOT A DOMINANT DRIVER OF THE EDGE E_R OR QH MODE



QH Mode is Initiated and Sustained In Perp Beam Only Discharge



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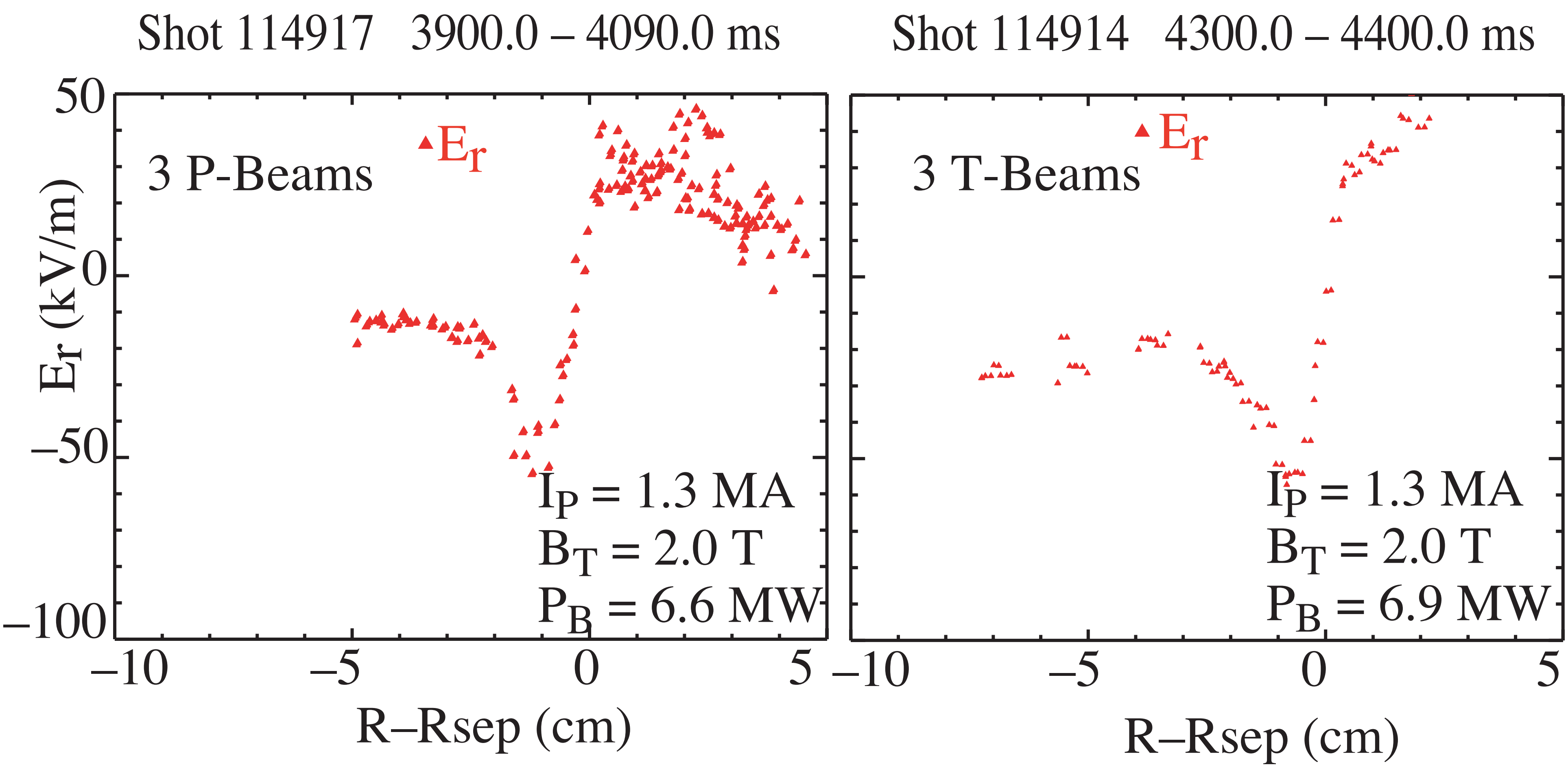
E_R WELL IS VERY SIMILAR IN TANG AND PERP BEAM QH DISCHARGES



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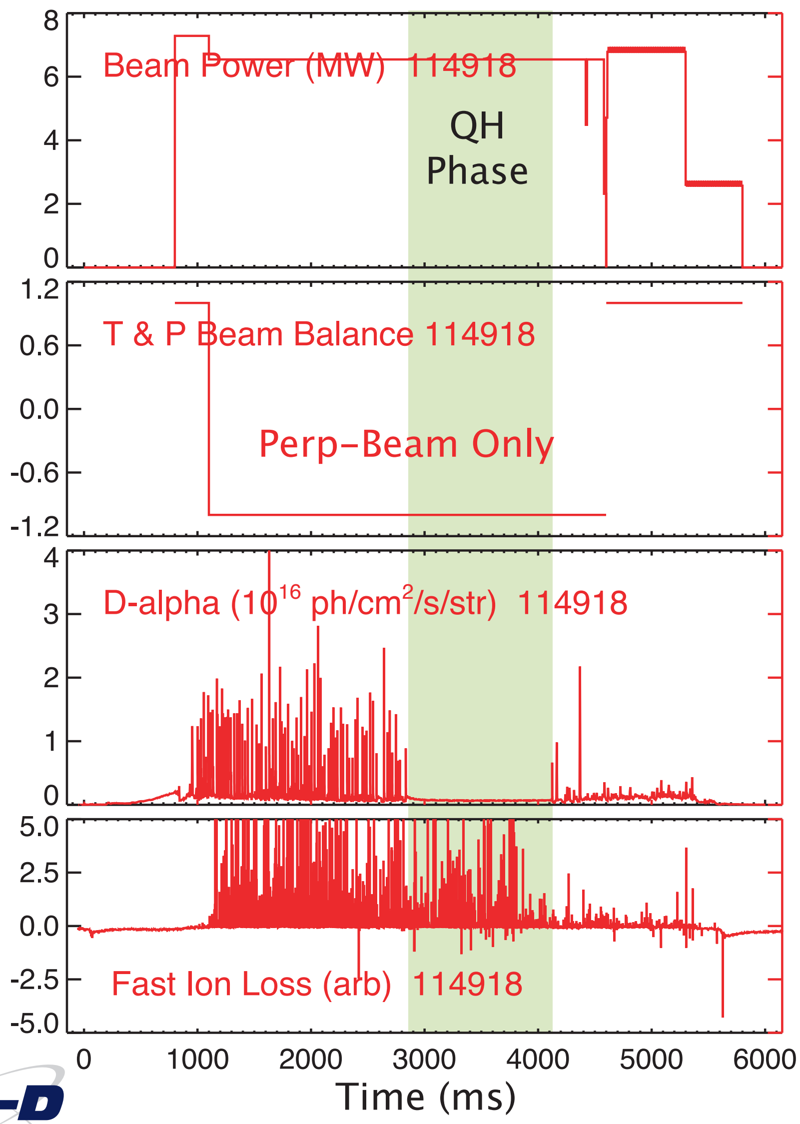
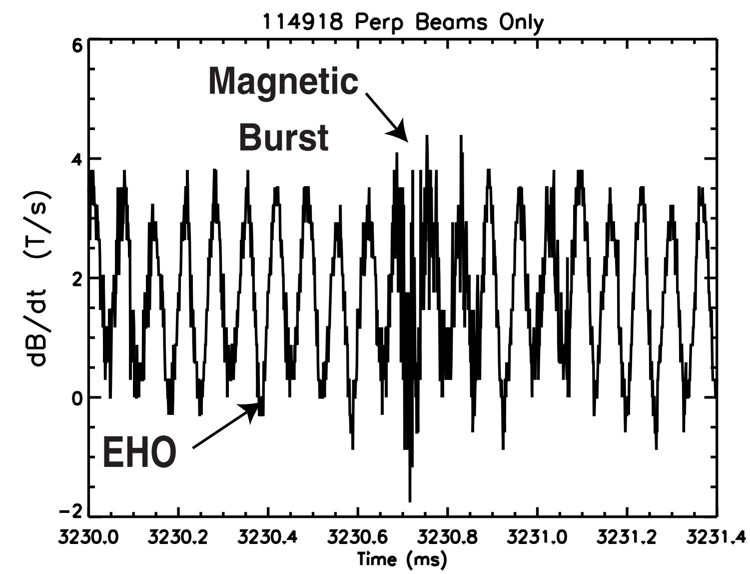
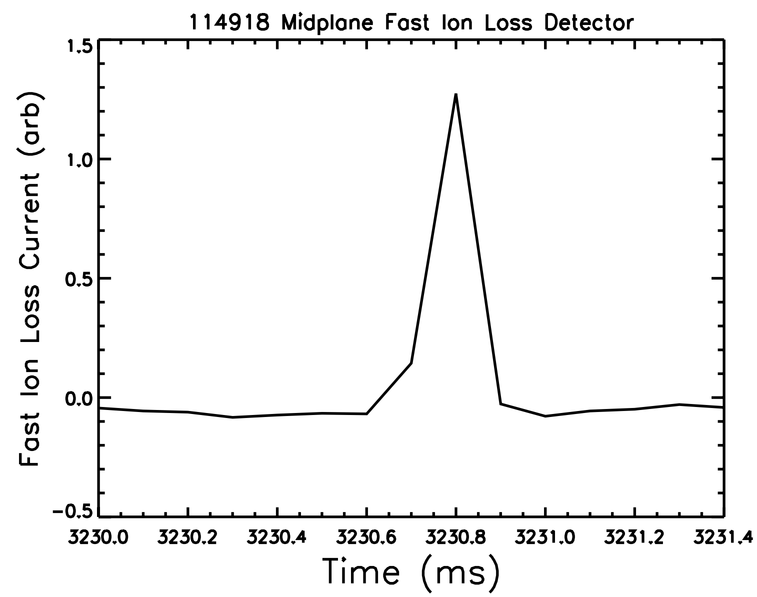
FAST ION LOSS ASSOCIATED WITH HIGH FREQUENCY MAGNETIC FLUCTUATIONS OBSERVED IN PERP BEAM COUNTER INJECTION







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DENSITY, IMPURITY, AND CURRENT DENSITY PROFILE CONTROLLED DURING HIGH-PERFORMANCE QDB DISCHARGES

Density peaking and associated impurity accumulation controlled using central ECH.

Safety Factor, q_0 and q_{MIN}, controlled with combination of ECCD and NBI.

Simultaneous application of ECH, ECCD, and NBI allowed near stationary operation of QDB at q_0 and $q_{MIN} > 3/2$ with reduced central impurity density at $\beta_N = 2.5$ for 2.0 s.

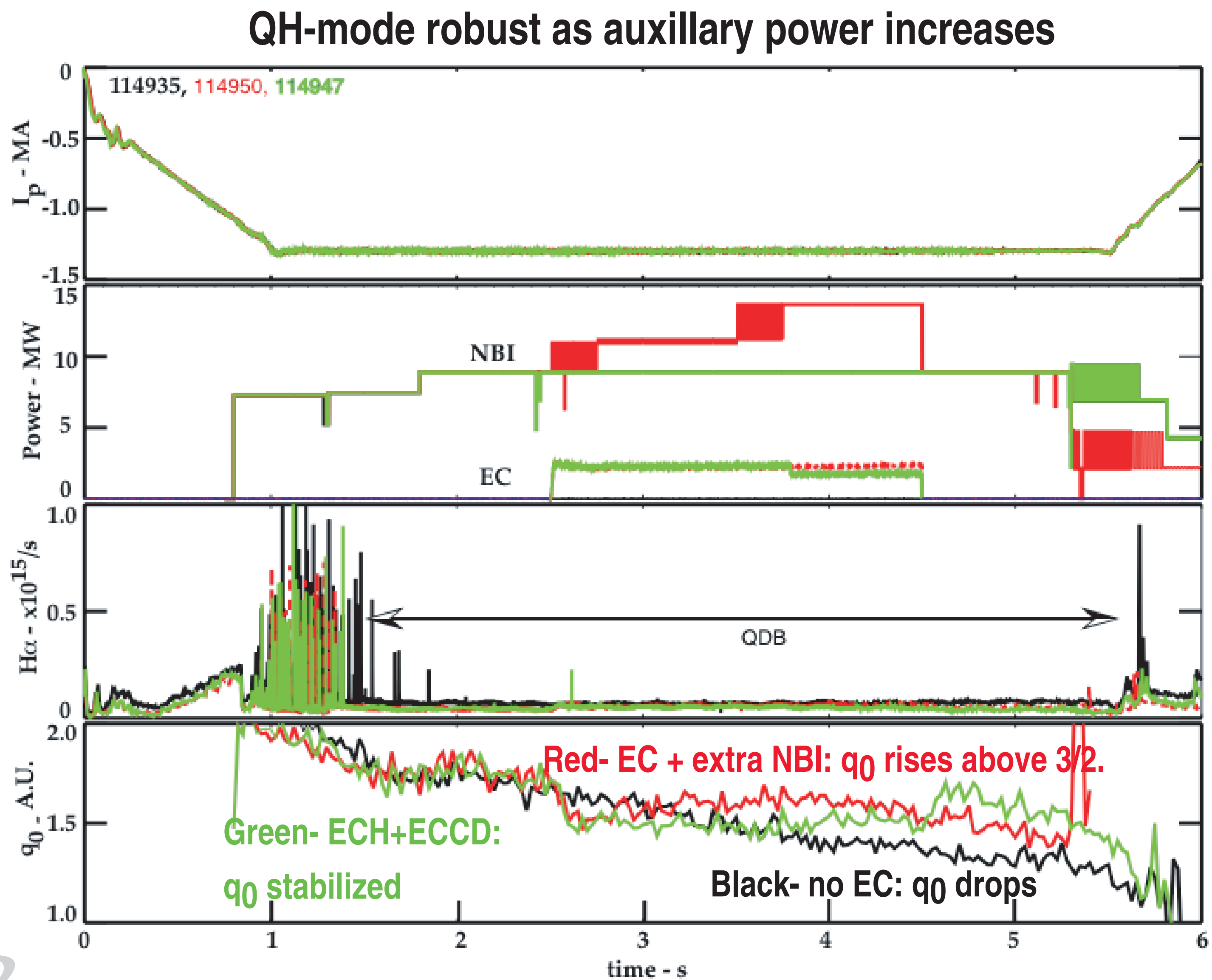
Recent ITPA database shows QDB performance competitive with other high performance operating modes

ELECTRON CYCLOTRON HEATING AND CURRENT DRIVE KEEPS q_0 STATIONARY

Black-NBI Only

Green-EC+NBI

Red-EC+More NBI



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WITH ECH+ECCD+NBI CONTROL OF DENSITY PEAKING IMPURITY ACCUMULATION AND q_0 AT HIGH PERFORMANCE

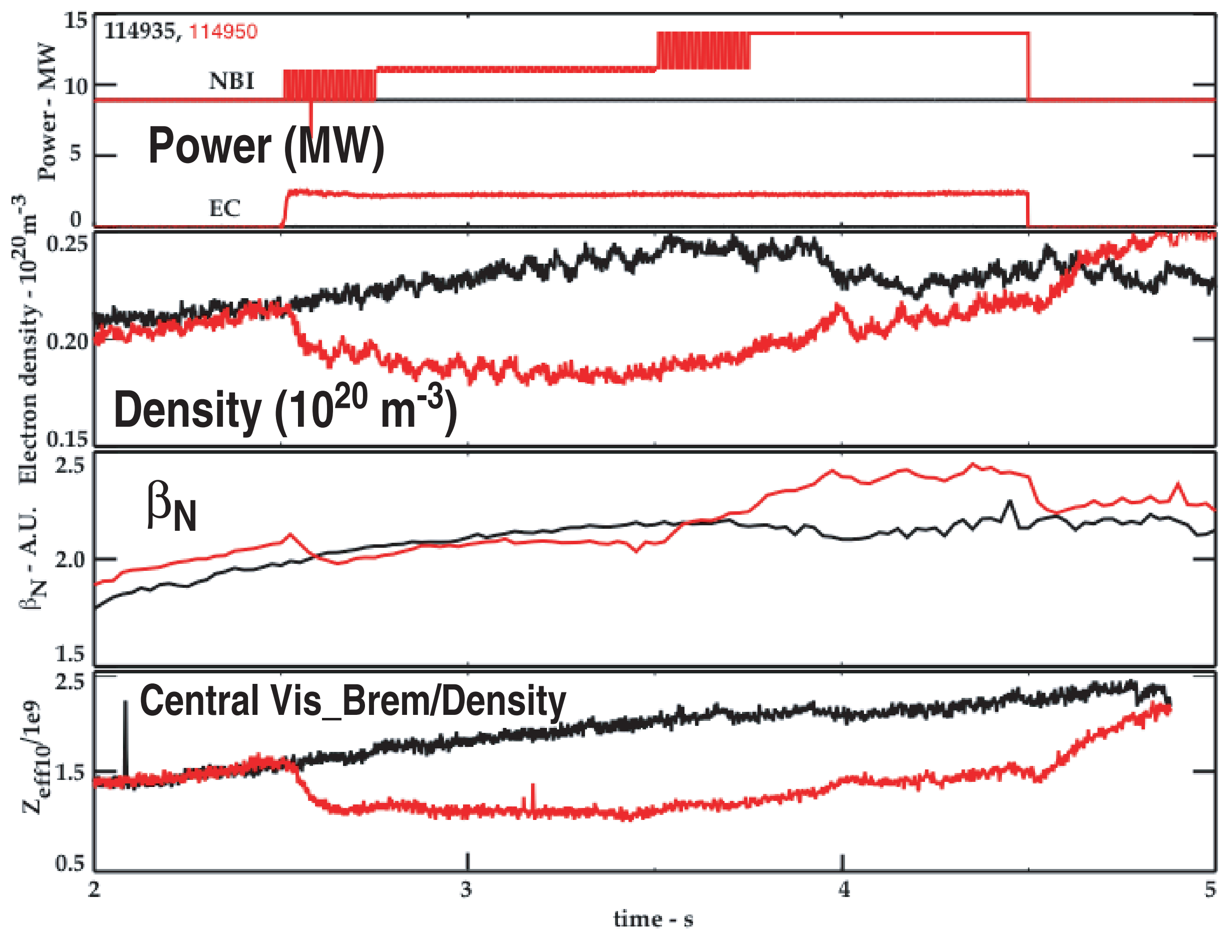
BLACK-EC + NBI

RED-EC + ADDITIONAL NBI

EC INDUCED LOSS OF DENSITY RECOVERED USING ADDITIONAL NBI

ADDITIONAL NBI RESULTS IN INCREASED β

EC iNDUCED IMPURITY CONTROL CONTINUES AT HIGHER NBI



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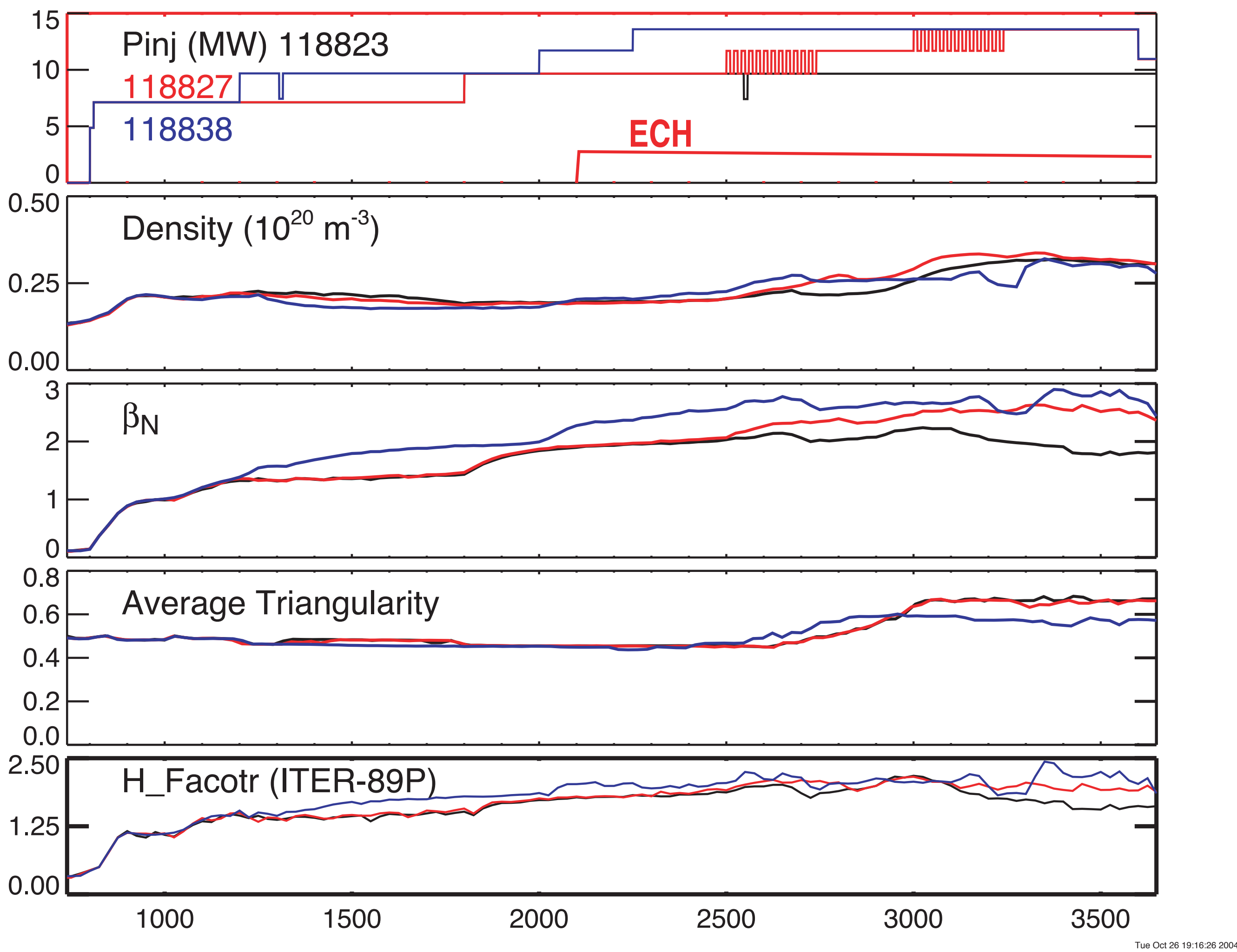
QDB: CONTROL TOOLS ENABLE HIGHER DENSITY AND β OPERATION
NBI, ECH, PELLETS, ERROR FIELD CORRECTION, SHAPE

NBI Ramp
β_N 2.2 -> 2.6

ECH Pressure Profile Control
β_N -> 2.8

Error Field Correction
β_N -> 2.9



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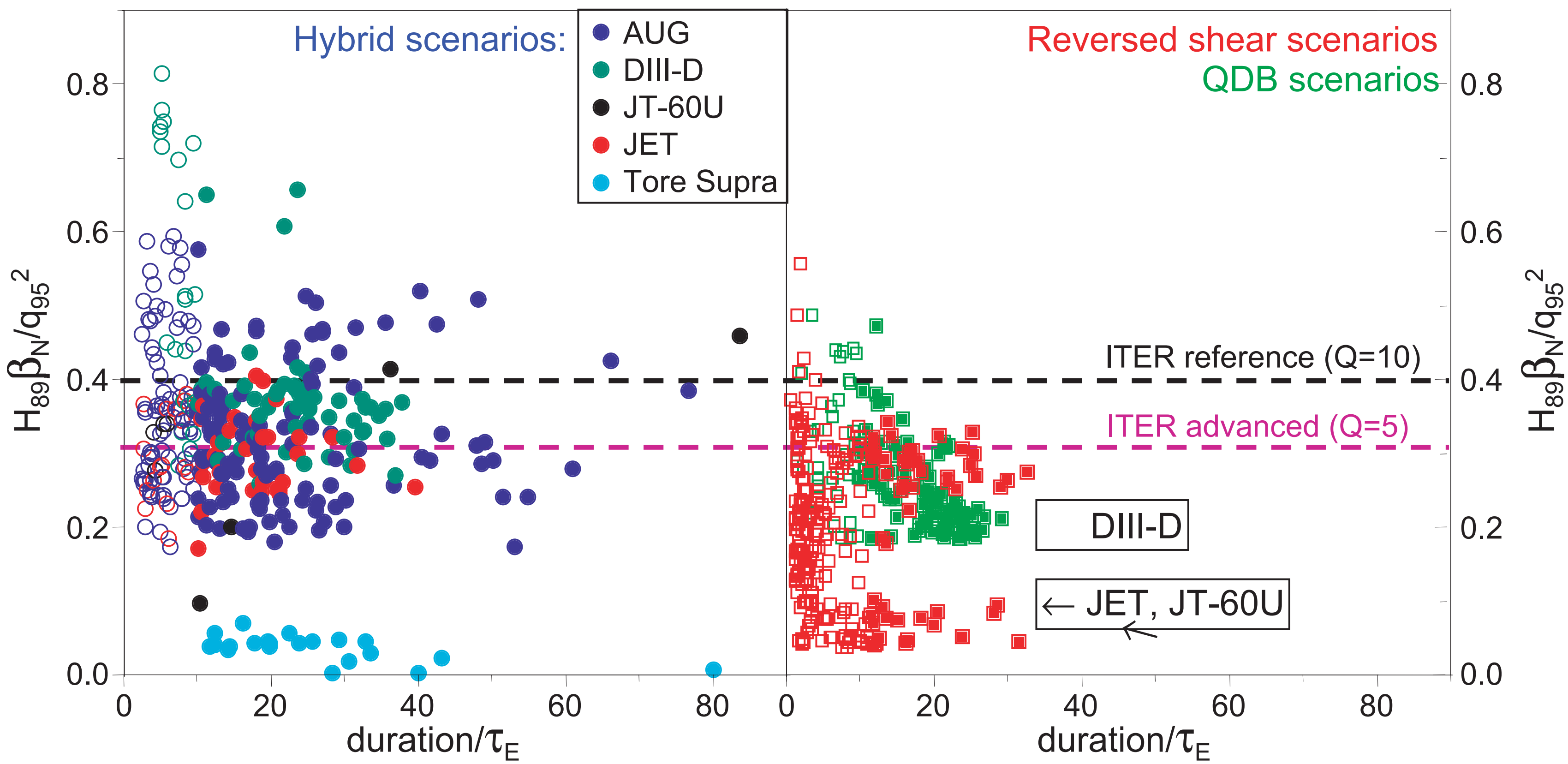
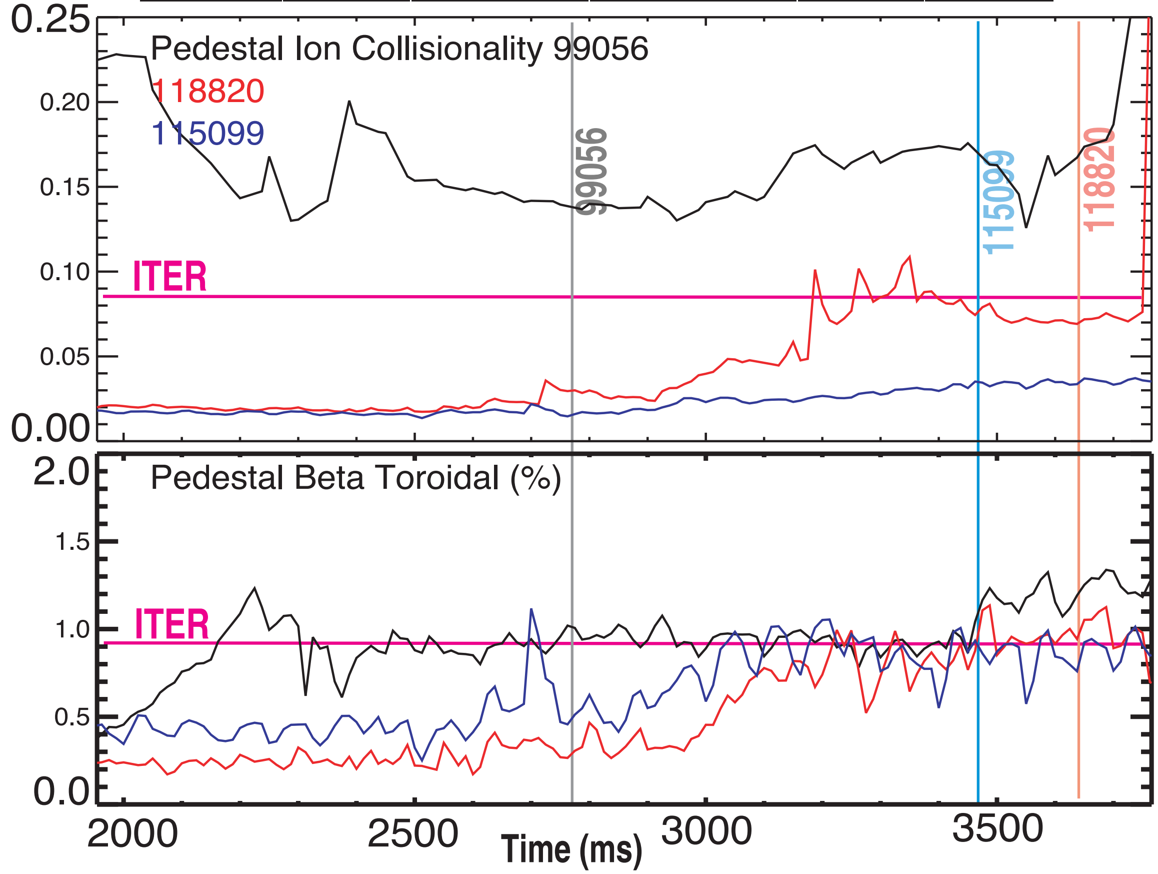
ITPA ADVANCED TOKAMAK DATABASE SHOWS THAT ELM-FREE QDB MEETS THE ITER PERFORMANCE GOALS



Taken from A.C.C. Sipps et al., paper P3-36, these proceedings

PEDESTAL β_T AND ION COLLISIONALITY LEVELS COMPARABLE TO ITER ACHIEVED IN QH-MODES

SHOT	ν_i^*	β_{TPED}(%)	$H_{ITER-89P}$	Z_{EFF}	ν_e^*
115099	0.03	0.82	1.8	2.6	0.2
118820	0.07	0.97	1.9	2.0	0.2
99056	0.14	0.94	1.8	2.4	0.3
ITER	0.08	0.91	1.8	1.7	0.1



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Tue Oct 26 11:38:29 2004

CONCLUSIONS

Quiescent H mode is an ELM-Free, high confinement mode with an H-mode edge transport barrier and pressure pedestal.

Edge profile analysis, current ramp experiments, and ELITE stability modeling indicate that the QH mode pedestal is marginally stable to current-driven, low to medium n coupled peeling/ballooning modes.

A deep and narrow radial electric field well, strong rotational velocity shear and E x B shear are measured in the pedestal region.

Prompt fast ion loss to the wall due to counter injection is not essential in the formation of QH mode and does not play a major role in the E_R well.

ECH, ECCD, and NBI have been used to control the density and current profile and mitigate impurity accumulation. Using these control tools combined with plasma shaping resulted in achieving $\beta_N = 2.5$ at near stationary conditions.

ITER relevant values of pedestal beta and ion collisionality have been simultaneously achieved in QH mode discharges at high δ.

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