Reduced edge instability and improved confinement discharges in the MST reversed-field pinch

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Abstract

Reduction of core-resonant magnetic fluctuations and improved confinement in the MST are reliably achieved through control of the poloidal electric field. However, the achieved confinement has been limited by a burst-like instability originating in the plasma edge. Now, improved control of the poloidal and toroidal electric fields allows multi-ms suppression of this instability, along with core fluctuation reduction, leading to (1) $T_e(0) \approx 840$ eV at 470 kA, (2) $\beta_{total} > 12\%$ at 200 kA, (3) an overall steepening of $T_e(r)$, (4) a *reduction* of T_e and n_e in the region $\rho \geq 0.9$, and (5) a reduced electron thermal diffusivity. Equally important is that the estimated energy confinement time at 200 kA significantly exceeds the "constant beta" scaling that has characterized the world RFP confinement database.

Outline

-- Improved energy confinement discharges in the MST

-- Edge burst-like instability occurring only during improved confinement

-- Suppression of these bursts

-- Profile measurements during burst suppression: increased gradients and (further) improved global confinement parameters

Improved confinement discharges and edge instability

-- Improved energy confinement can be driven by inductive increase of edge poloidal electric field (primary focus of this poster)

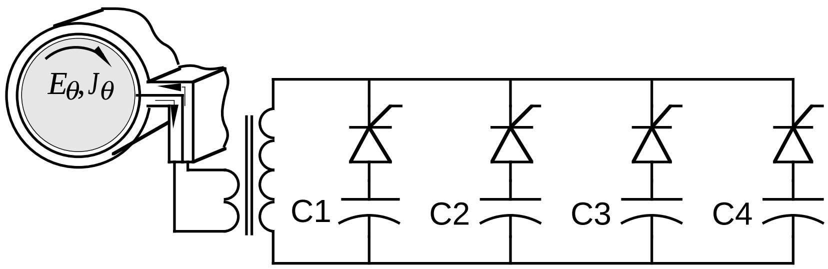
-- Can also occur spontaneously

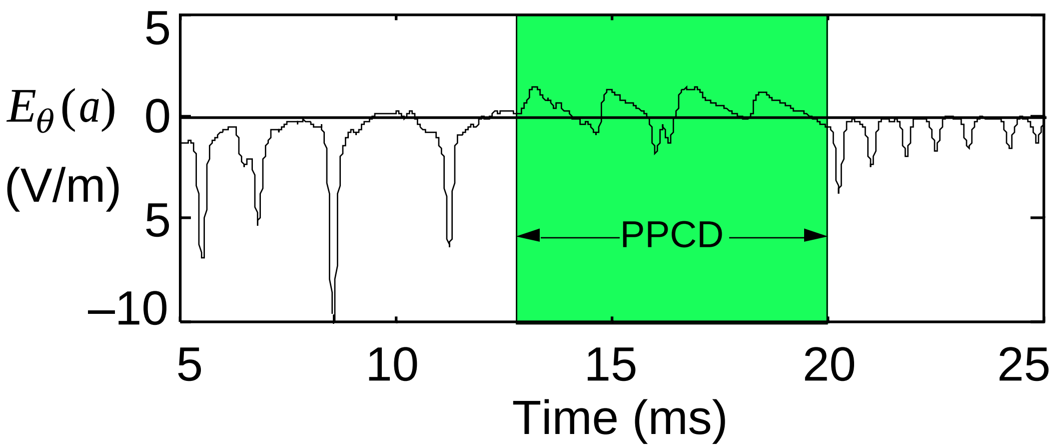
-- In both cases, a burst-like instability occurs in the edge, clamping or reducing the otherwise improved energy confinement

-- With burst suppression, confinement parameters improve

Driven improved confinement triggered by pulsed poloidal current drive (PPCD)

-- PPCD increases the edge poloidal electric field and current in a series of pulses (four shown here, but five are now in use)





-- Causes reduction of magnetic and electrostatic fluctuations everywhere (between bursts)

-- Hypotheses for why this occurs include (1) magnetic fluctuation reduction due to the change in the current profile and (2) electrostatic and magnetic fluctuation reduction due to strong $\mathbf{E} \times \mathbf{B}$ flow shear

Edge burst-like instability

-- Occurs with the same phenomenology during driven and spontaneous improved confinement

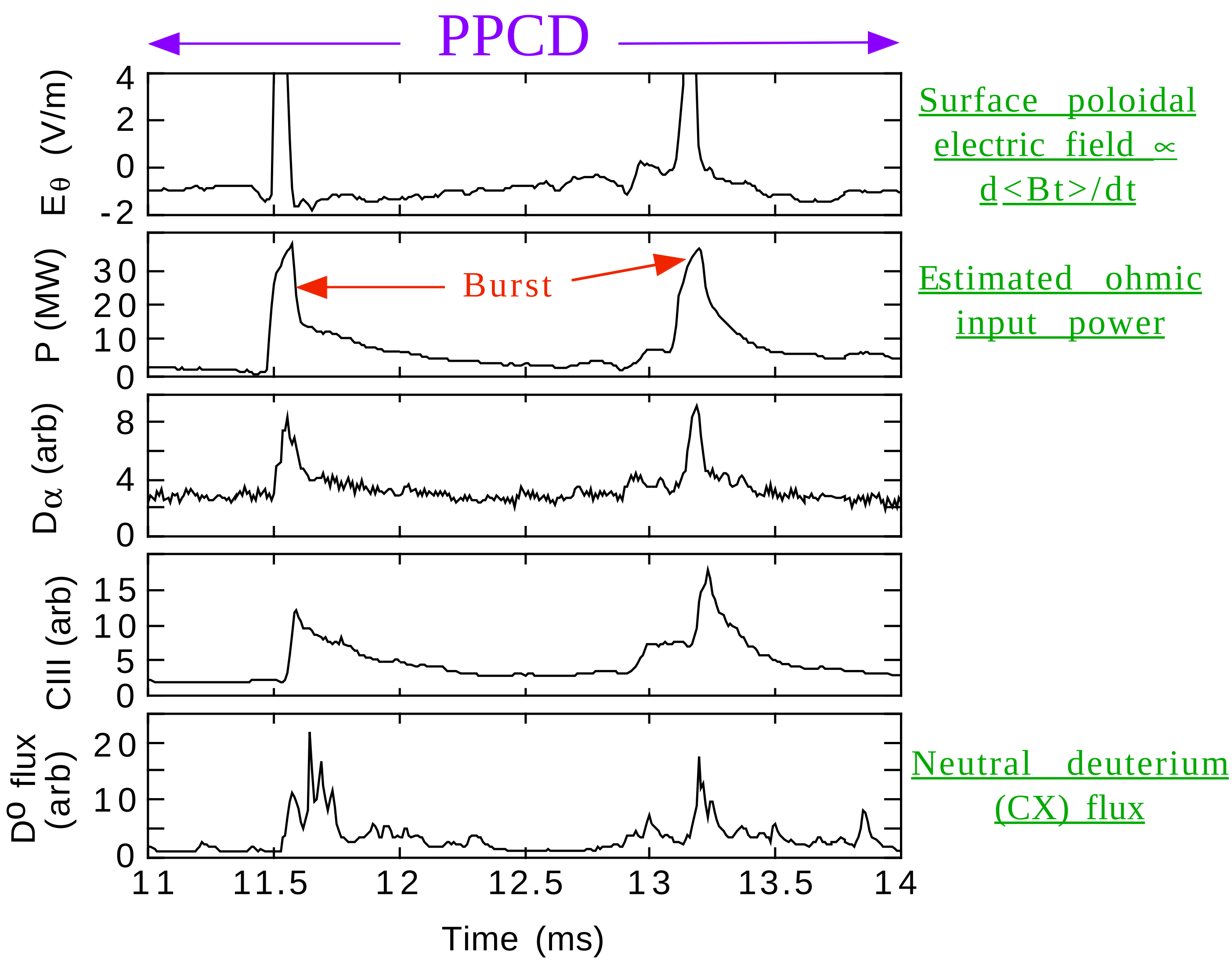
-- Causes short-lived increase of primarily edge fluctuations and degradation of global confinement

-- Affects edge-resonant $m = 0$ magnetic fluctuations (modes)

-- Affects electrostatic fluctuations over broad frequency range

-- Cause of bursts unknown, but probably linked to observed edge pressure and/or current gradients

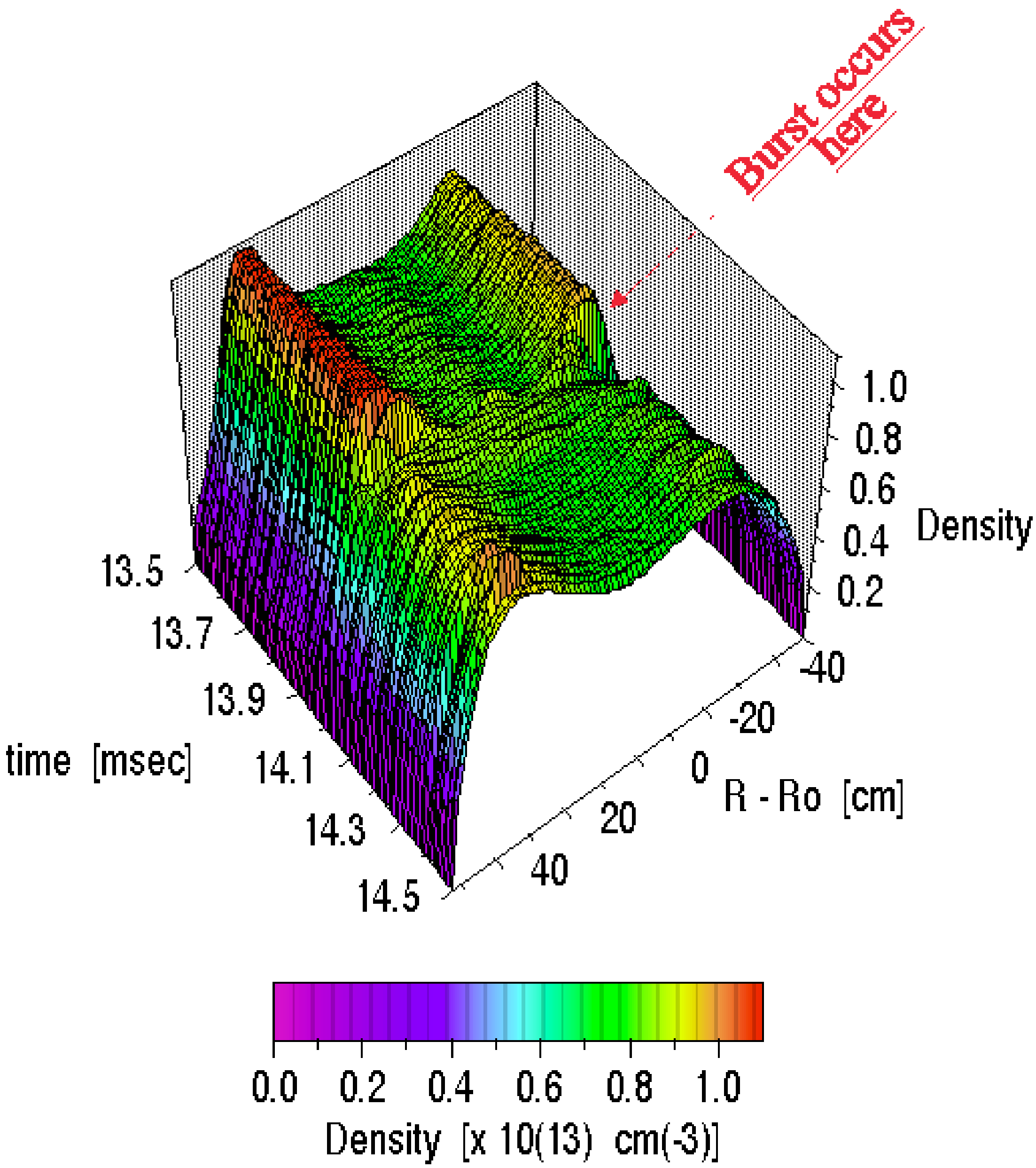
Each burst affects most MST plasma parameters, momentarily degrading periods of improved energy confinement



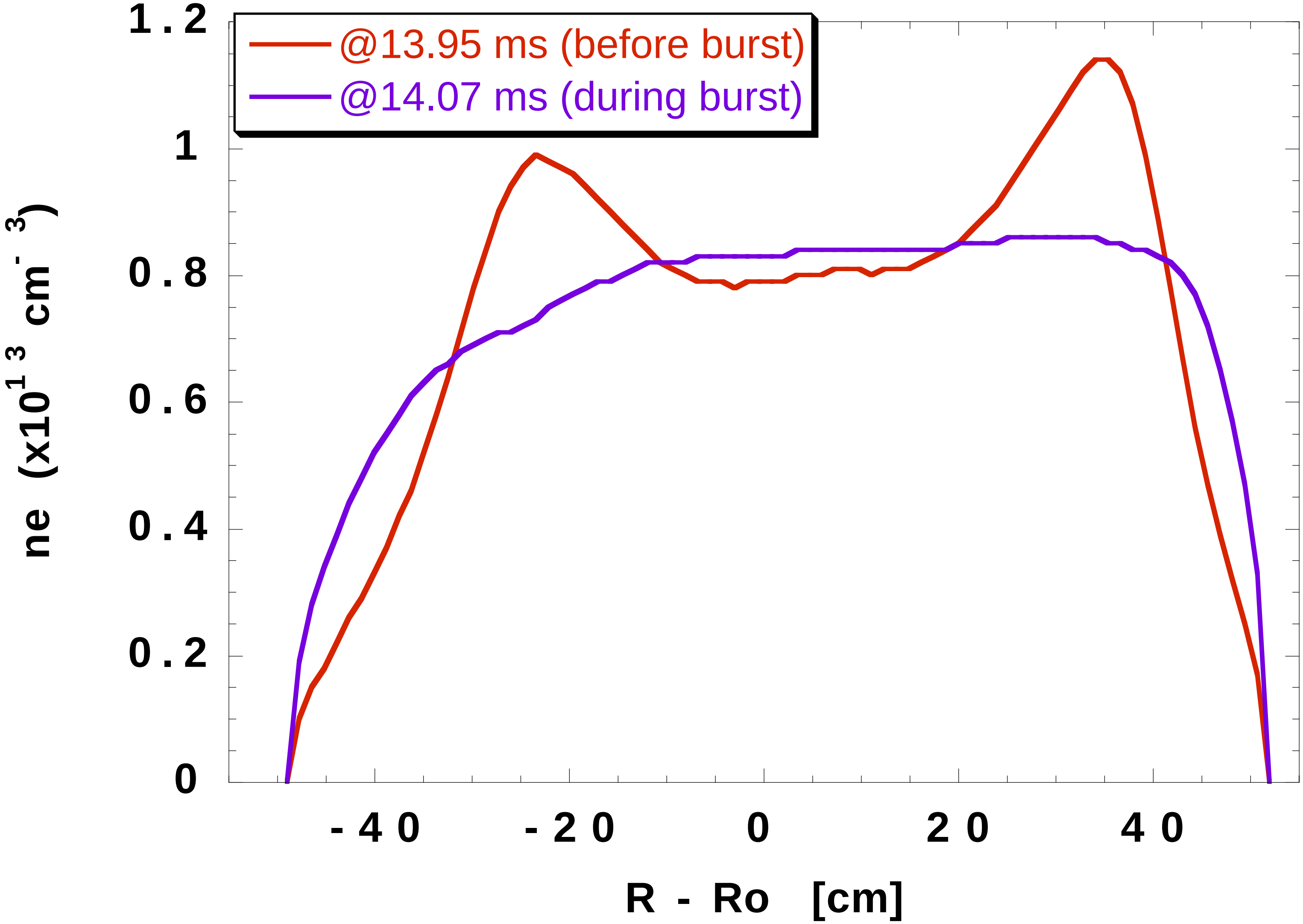
-- Each burst corresponds to generation of toroidal magnetic flux, like sawtooth crashes during standard confinement

-- Increase of ohmic power, radiation, neutral flux, etc. contributes to degraded energy confinement.

Each burst strongly affects the edge density profile (data from PPCD shown)



Each burst strongly affects the edge density profile (data extracted from previous profile time series)



Edge-originating bursts affect the core electron temperature, $T_e(0)$

-- Inferred from measurements of $T_e(0)$ during improved confinement with varying burst repetition rates

-- At ~ 450 kA, $\langle n_e \rangle \sim 10^{13}\ cm^{-3}$:

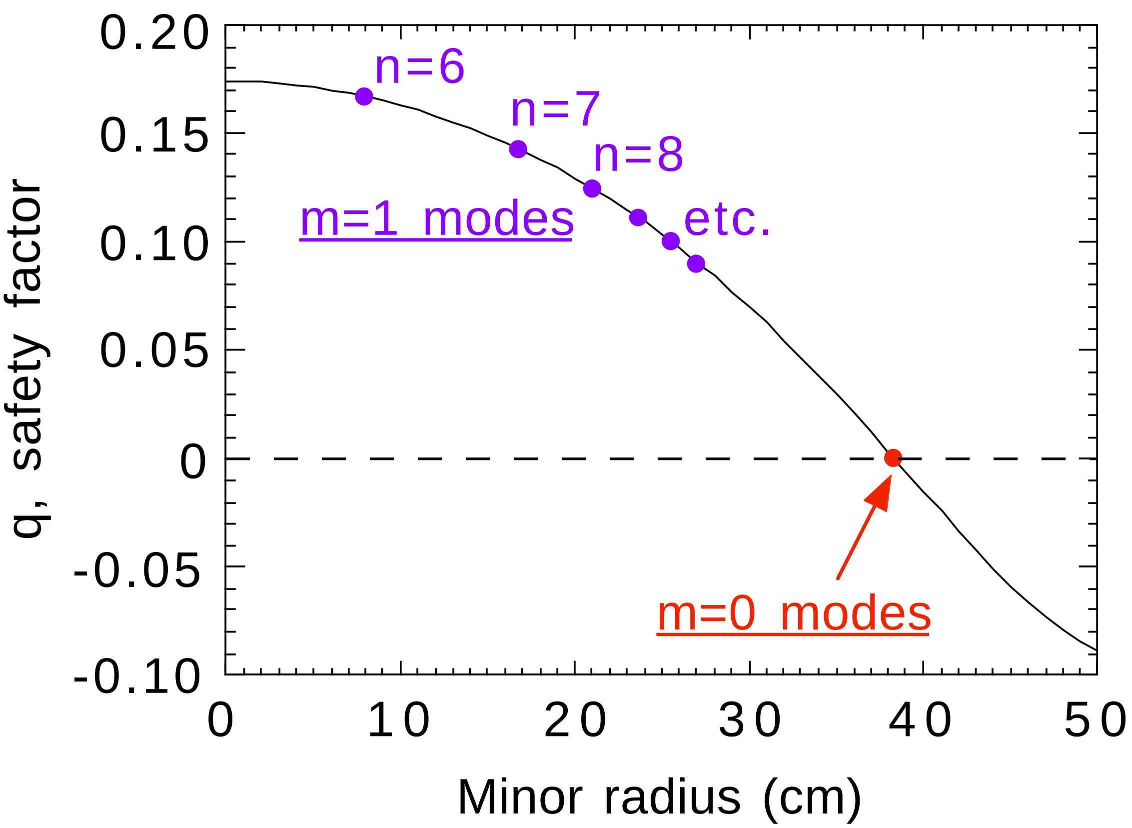
Confinement trigger	Burst spacing	$T_e(0)$ (eV)
spontaneous	~ 1 ms	480
PPCD	~ 3 ms	615
PPCD	≤ 10 ms	840*

*record for the MST

-- Each burst either decreases $T_e(0)$ or briefly halts its growth

The dominant magnetic fluctuations in the MST are m = 0 and m = 1 modes

-- Shown below is a q profile typical of improved confinement discharges:

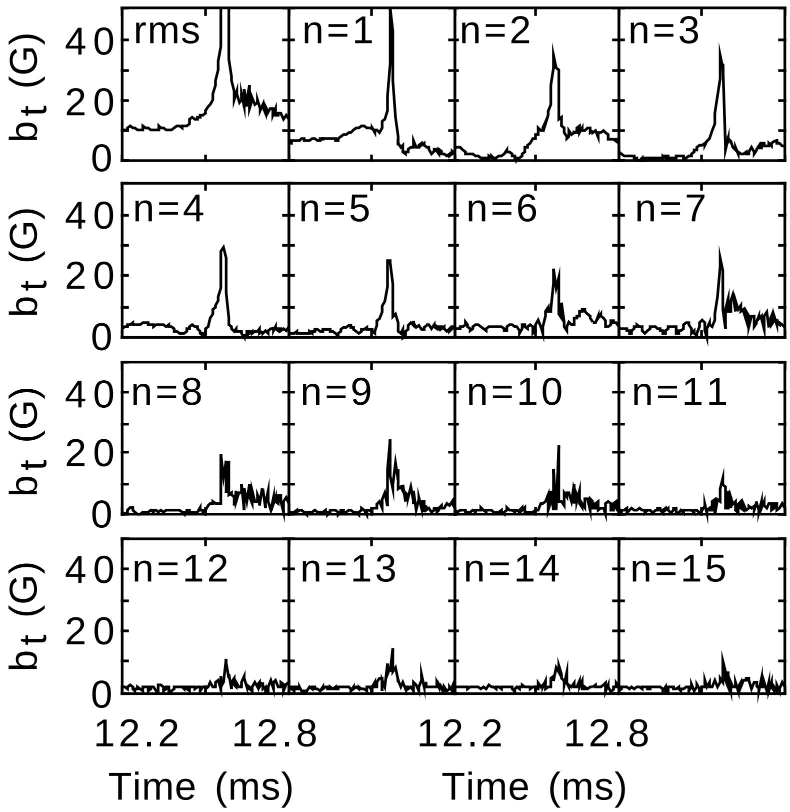


-- Fluctuations with n ≤ 5 correspond only to m = 0 modes

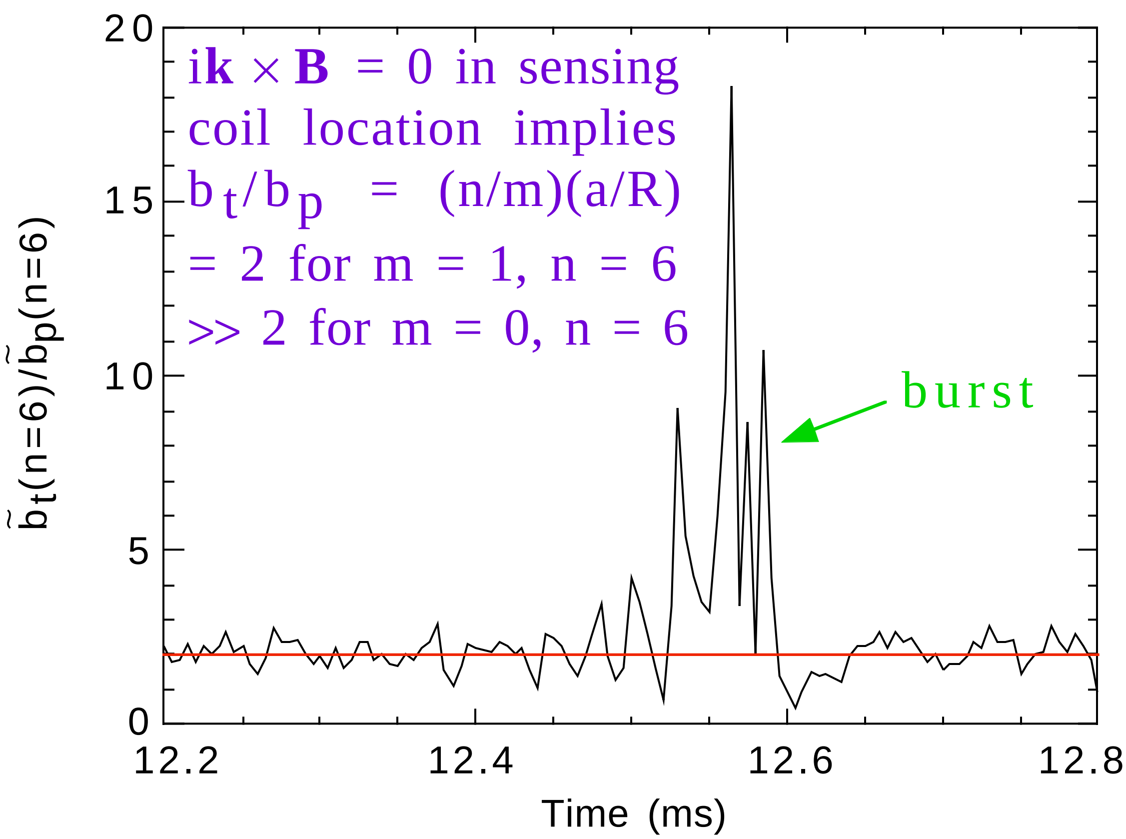
-- Fluctuations with n > 5 include both m = 0 and m = 1 modes

-- All these fluctuations can be measured with sensing coils at the plasma boundary

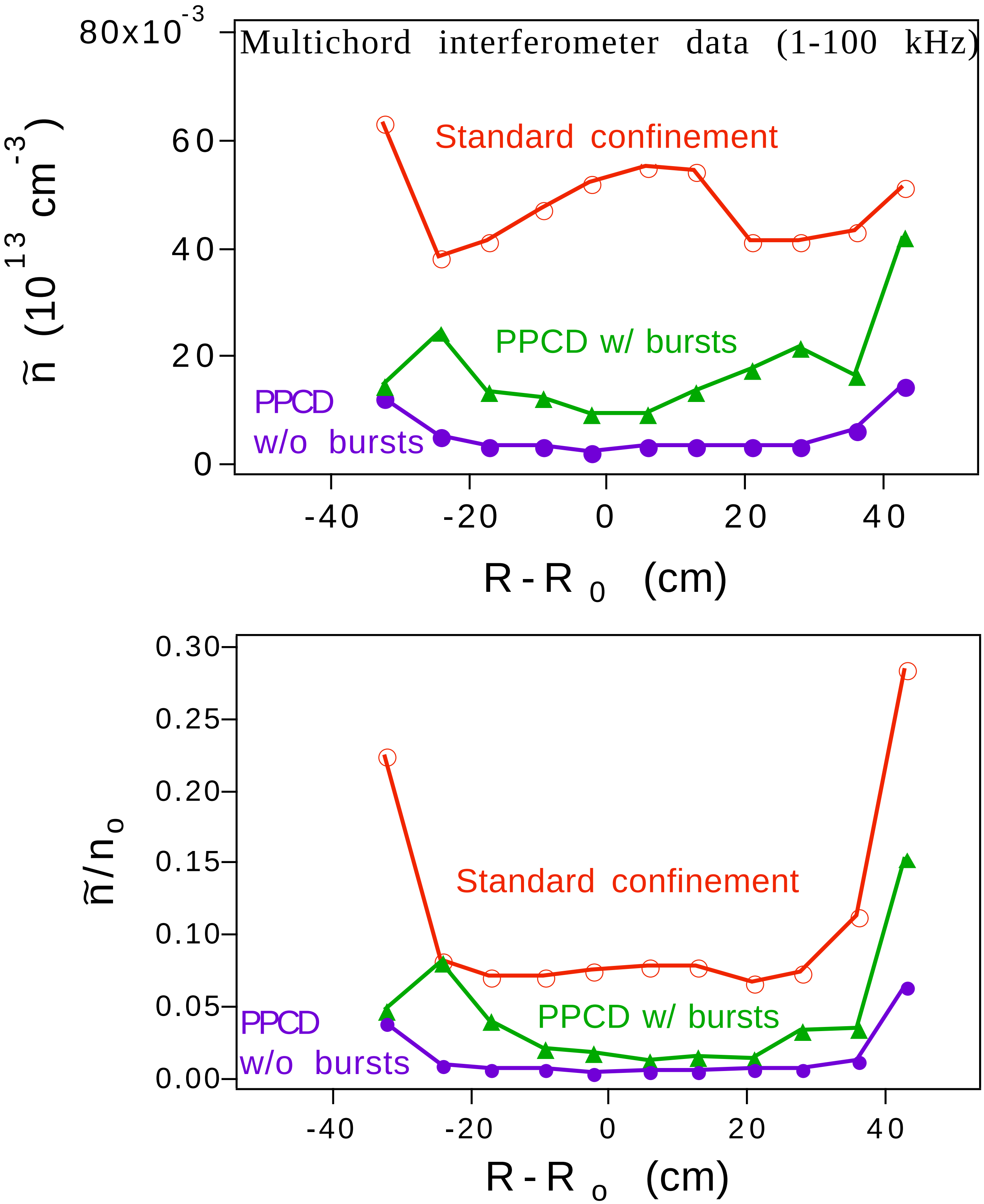
Each burst corresponds to an increase in primarily m = 0 magnetic fluctuations



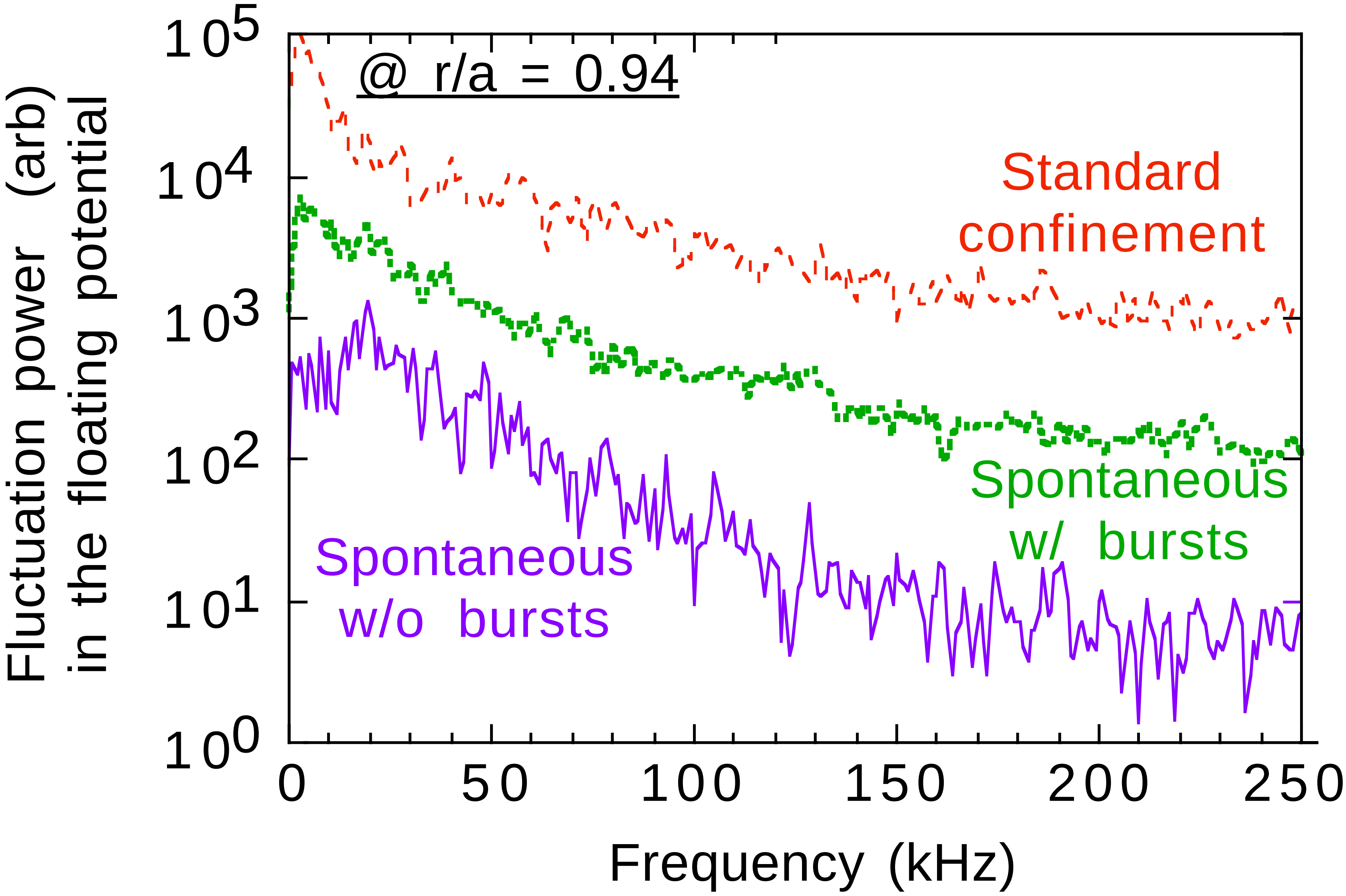
Toroidal mode spectrum during PPCD with a burst at ~ 12.55 ms



Bursts increase density fluctuations primarily in the edge



Bursts increase edge potential fluctuations over a broad range of frequencies (standard and spontaneous-improved confinement data shown)



Interim conclusions

-- Bursts correspond to a degradation of energy confinement

-- Increase in edge magnetic and electrostatic fluctuations likely to contribute to this transport, but relevant transport measurements have yet to be made

-- Edge origin indicated by the bursts' appearance in the m = 0 magnetic fluctuations and their effect on the density profile and density fluctuations

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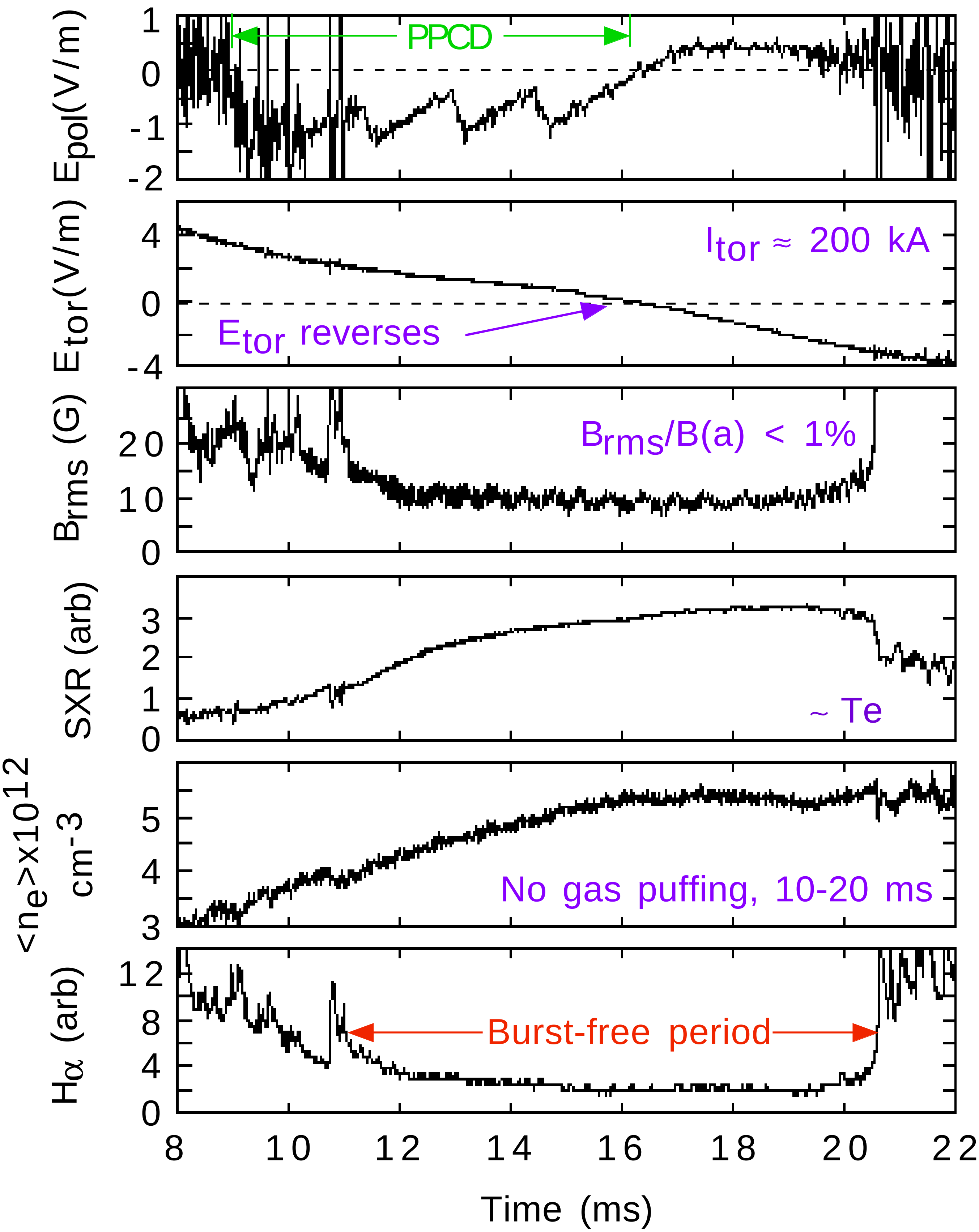
-- Next we discuss the suppression of these bursts and confinement parameter improvements

Suppression of bursts for up to 10 ms now possible in 150-500 kA PPCD discharges



Suppression of bursts

-- Formerly, bursts could only be suppressed for ≤ 3 ms

-- Suppression for ≤ 10 ms due primarily to better/longer sustainment of edge parallel electric field, $E_{parallel} = \mathbf{E} \bullet \mathbf{B} / B$

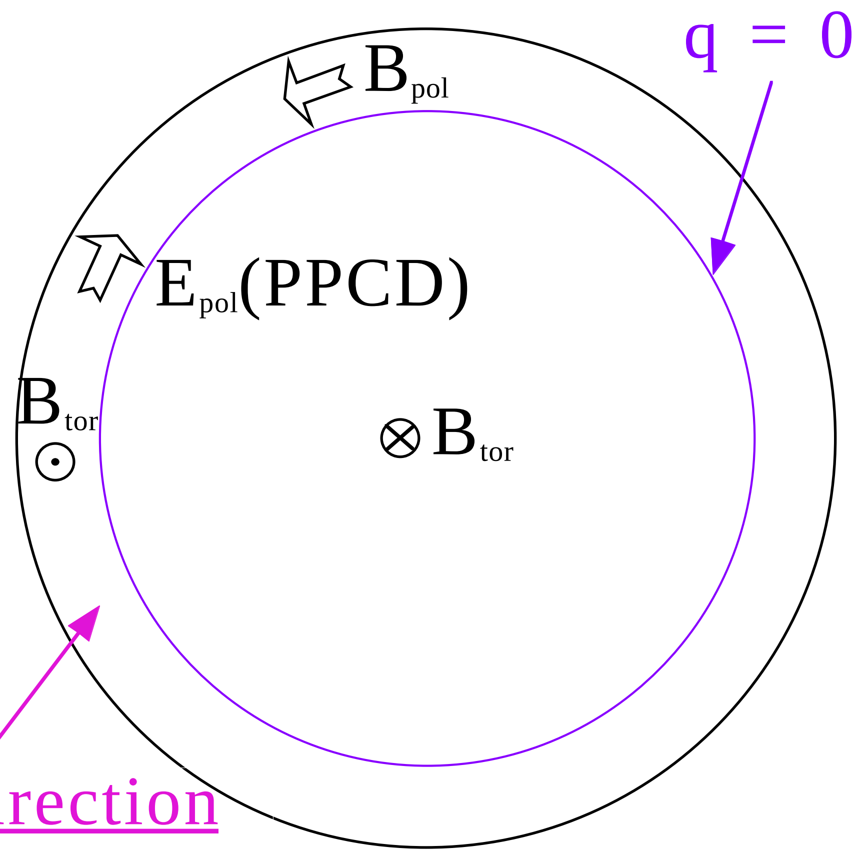
-- E_{pol} simply not allowed to decay to zero between PPCD stages

-- E_{tor} reversed (see next page) following PPCD

-- Requires good wall conditions, and a $\langle n_e \rangle$ limit applies: bursts are irrepressible above a certain $\langle n_e \rangle$

Reversing E_{tor} following PPCD sustains toroidal component of $E_{parallel}$ in the edge

⊙ normal E_{tor}
⊗ reversed E_{tor}



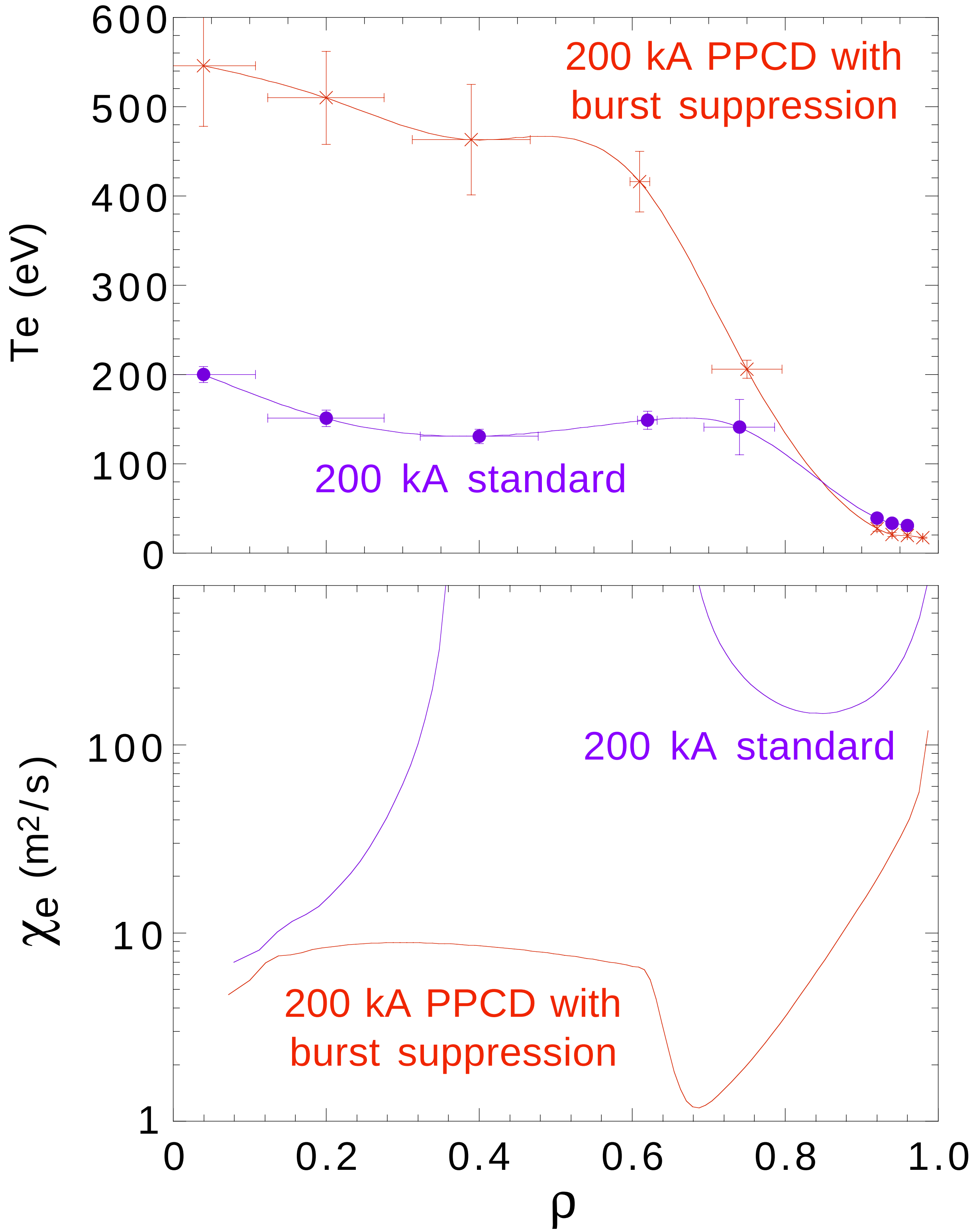
Edge parallel direction is up and into the paper

-- Normally, by definition, E_{tor} is parallel (to **B**) on axis and antiparallel in the edge

-- Reversed E_{tor} (opposite the direction of B_{tor} in the edge) adds to $E_{parallel}$

-- E_{pol} increase (PPCD) and E_{tor} reversal are transient, but their combination has led to significantly improved confinement parameters, discussed next...

With PPCD and burst suppression, T_e and ∇T_e increase, except in the extreme edge, and χ_e decreases (but see next page)



T_e and χ_e notes and caveats

-- Measured similar T_e profile shapes in hotter 400 kA discharges

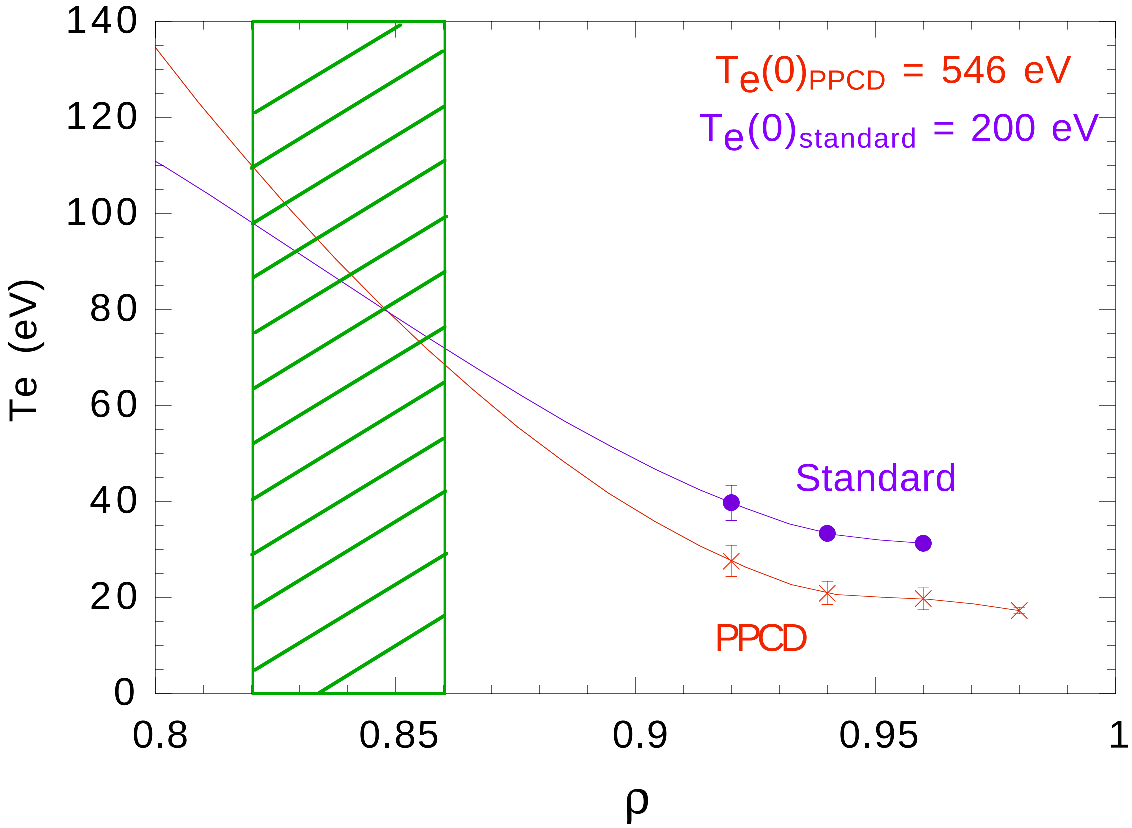
-- Inner (5) T_e datapoints from single-time-point, single-spatial-point TS system, averaging many discharges for each point

-- Horizontal error bars reflect TS spatial resolution and are probably lower bounds

-- Edge points from Langmuir probe

-- χ_e based on assumed $Z_{eff}(r) = 2.0$; we believe that χ_e drops, but absolute magnitude and structure of $\chi_e(r)$ cannot be trusted

Langmuir probe reveals that the edge T_e (and n_e, not shown) decrease during PPCD



-- Edge density profiles have similar shape

-- Profile shape not really known for $\rho <$ 0.9 (curves are spline fits to TS datapoints)

-- Green hashes indicate region where strong $E \times B$ flow shear has been measured in PPCD (weak in standard case); no flow shear data exists for $\rho < 0.82$

-- Reduction of T_e and n_e may indicate that transport is locally reduced in the hashed region (and perhaps beyond)

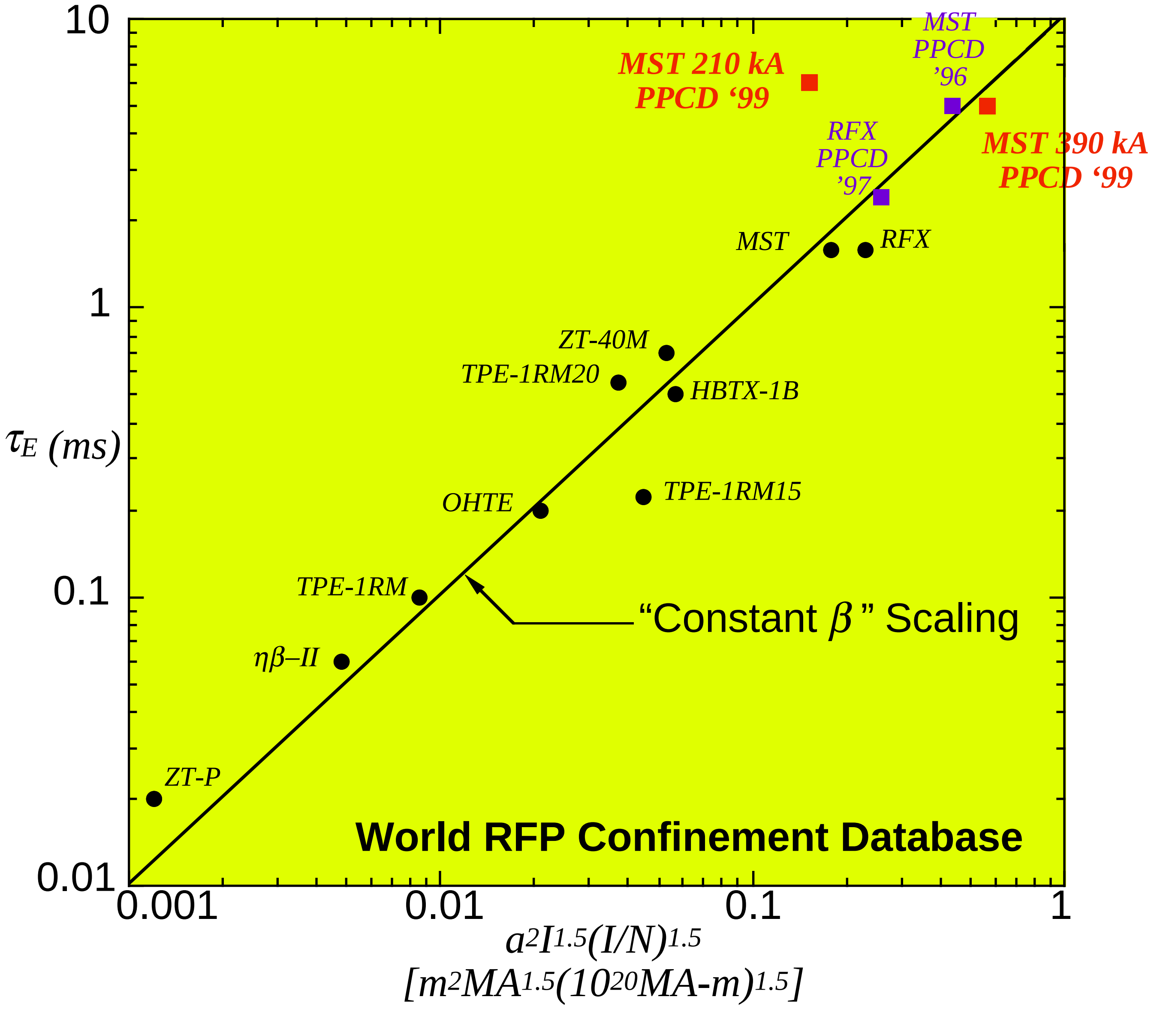
Comparison of standard and PPCD improved confinement parameters

I_p(kA)	$\langle n_e \rangle \times 10^{13}$ cm^{-3}	$T_e(0)$	W(kJ)	β_{tot}(%)
210	0.8	200	1.9	6.3
210	0.7	546	4.7	12.6
430	1.0	400	4.4	3.3
390	1.0	770	8.9	8.0
470	1.2	840	?	?

-- 430 kA/390 kA T_e and n_e profiles similar in shape to 210 kA/210 kA profiles; no T_e profile data for 470 kA case

-- Assumed $T_i(r) = (1/4)T_e(r)$ and $T_i(r) = (1/2)T_e(r)$

Assuming Zeff(r) = 2, estimated energy confinement time of 200 kA PPCD exceeds "constant β" scaling



-- Were Zeff(r) = 11, 210 kA PPCD '99 would fall on the scaling line --> unlikely

-- PPCD '96 case had $T_e(0)$ = 615 eV at 440 kA, while 390 kA PPCD '99 has $T_e(0)$ = 770 eV: uncertainty lies in Pohmic and Ti(r)

Summary/discussion

-- A burst-like instability occurs in the edge of improved energy confinement discharges

-- Energy confinement is degraded by each burst

-- Magnetic and electrostatic fluctuations increase in the edge, but their relative contributions to transport have not been determined

-- Burst suppression now possible, leading to improvements in confinement parameters

-- Temperature and temperature gradients increase; electron thermal diffusivity decreases

-- Edge temperature and density decrease (outside region of strong $E \times B$ flow shear)

-- Core energy transport is believed to drop during improved confinement

-- Perhaps edge energy transport drops as well?

-- Measurements outstanding: (1) Zeff (and Pohmic), (2) E_r profile with new HIBP, and (3) better resolved temperature and density profiles with new TS system