Multi-energy SXR characterization of actively stabilized resistive wall modes in NSTX

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APS-DPP 2008
November 17th – 21th, 2007
Dallas, Texas, USA

Abstract

A multi-energy soft X-ray (ME-SXR) array is used for the characterization of unstable and actively-stabilized resistive wall modes (RWM) in the NSTX spherical tokamak. Multi-energy brightness (line-integrated) and emissivity (spatially localized) SXR profiles indicate tentatively whether the RWM perturbation is introducing a density and/or temperature modulation. Fast electron temperature measurements are obtained from ratios of the SXR emissivity profiles by modeling the slope of the continuum radiation. The amplitude of the core electron temperature (T_e) modulations associated with the resonant-magnetic-perturbation (RMP) actively-stabilized resistive RWMs is of the order of 50-100 eV (~10%), and their time history is in good agreement with the slow evolution of the *n=1* magnetic perturbation measured by the poloidal and radial RWM coils. Together with the magnetics, the ME-SXR data suggests that in NSTX the mode is not entirely "*rigid*" and that acting with the stabilizing coils on its external structure may enhance the edge modulation as well as transfer some of the perturbation to the interior of the plasma. This multi-energy SXR treatment have also enabled the determination of significant temperature variations (>50% at *r/a*~0.5) associated to a β_N-collapse due to the saturation of RWMs.

RWM research in NSTX

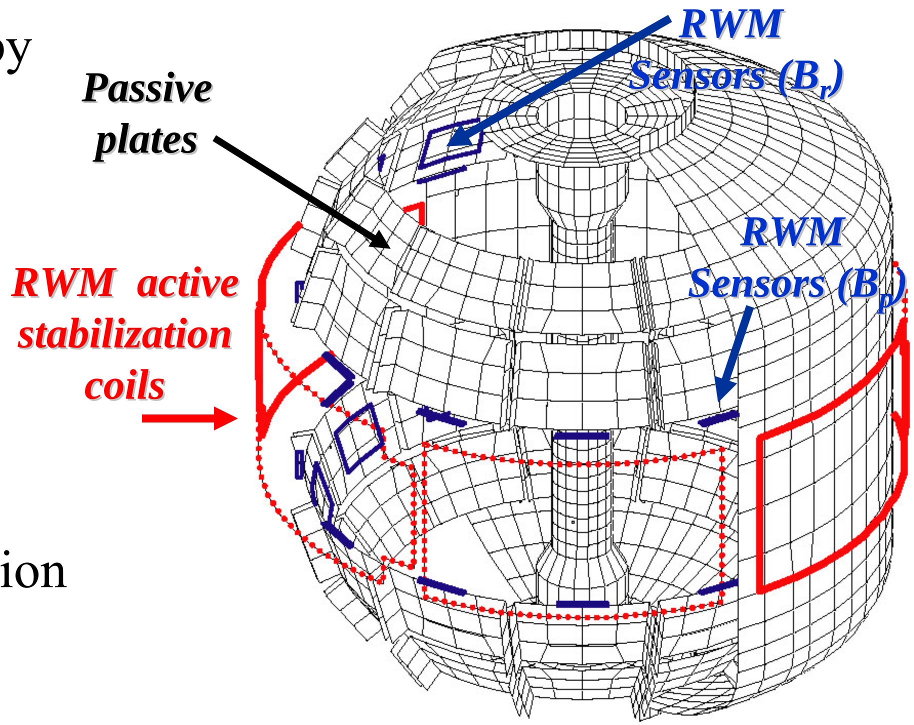
- RWM is an external kink modified by presence of resistive wall.

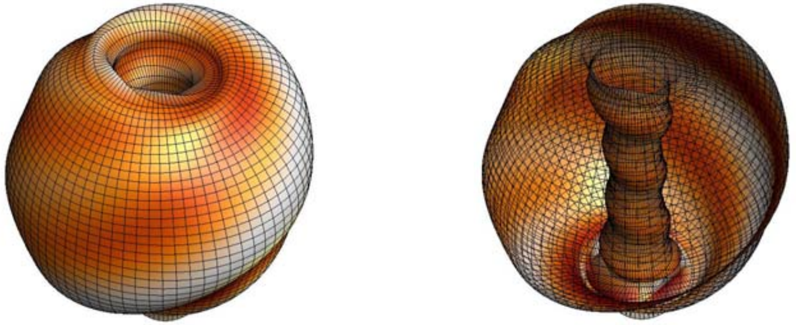
- RWM Characteristics:
  – slow growth: $\Gamma \sim 1/\tau_{wall}$
  – slow rotation: $f_{RWM} \sim 1/\tau_{wall}$
  – $\tau_{wall} \sim 10$ ms
  – stabilized by rotation & dissipation

- High toroidal rotation passively stabilizes RWM at high-*q*.

- RWM can affect both the outer and inner plasma.

- ***Long-pulse, high-β_N requires wall stabilization.***





(exterior view) (interior view)

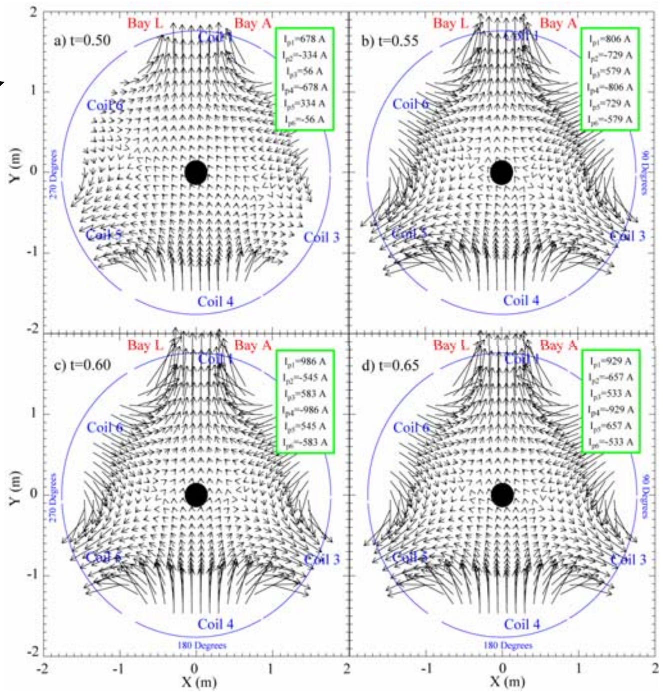
[1] S. A. Sabbagh, *et al.*, Nucl. Fusion, **46**, 635, (2006)

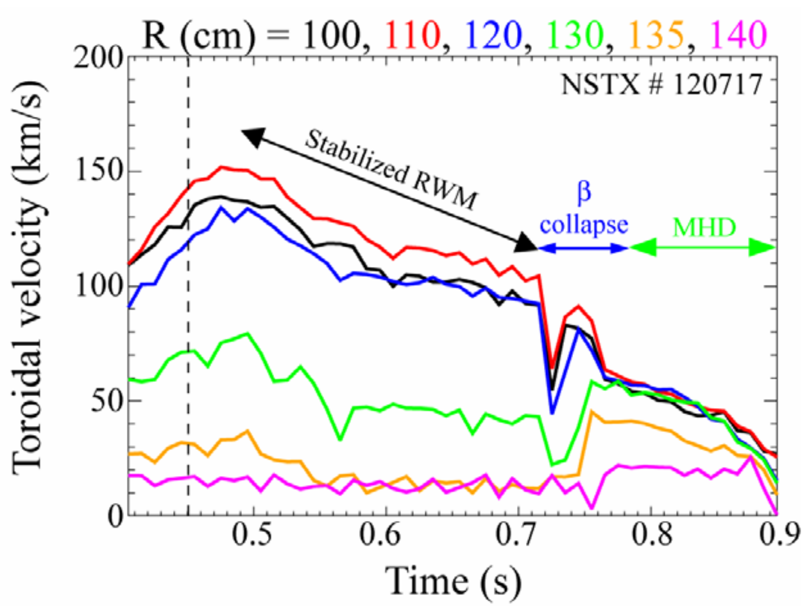
Recipe: n=3 magnetic braking + *n=1* active feedback

• RWM active stabilization has been successfully tested in the National Spherical Torus Experiment at the Princeton Plasma Physics Laboratory.

• Such experiment is made by applying both:
a) a non-resonant *n=3* magnetic braking [that reduces the toroidal rotation (ω_ϕ) significantly below a critical rotation ($\Omega_{\phi,c}$)],
b) together with a *n=1* active feedback stabilization field.

“Steady” n=3 magnetic braking

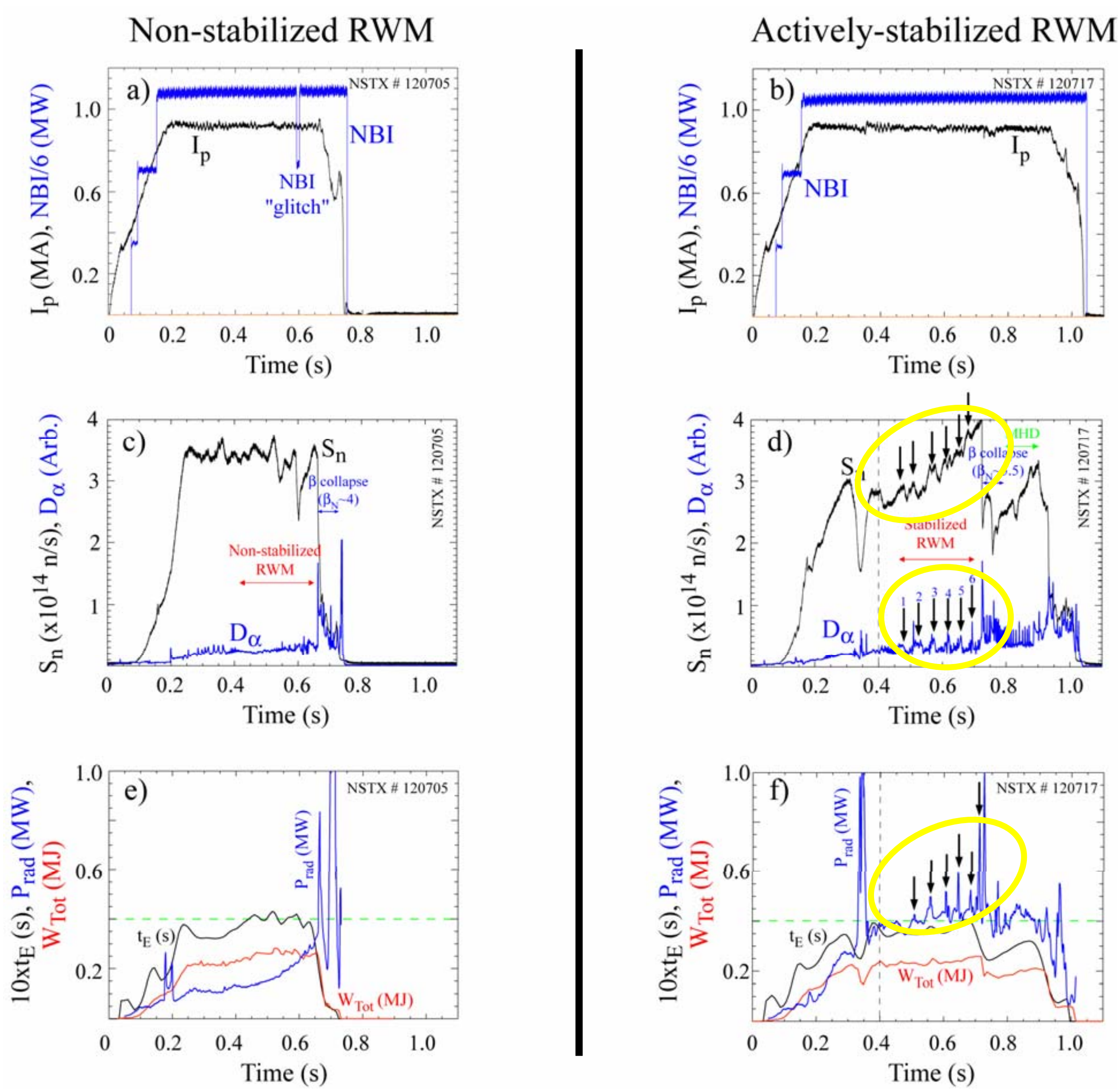




• This process successfully stabilized the RWM for up to seven energy confinement times (τ_E).

[2] S. A. Sabbagh, *et al.*, Phys. Rev. Lett., **97**, (2006).
[3] A.C. Sontag, *et al.*, Nucl. Fusion, **47**, (2007).

Non-stabilized versus actively-stabilized RWM plasmas

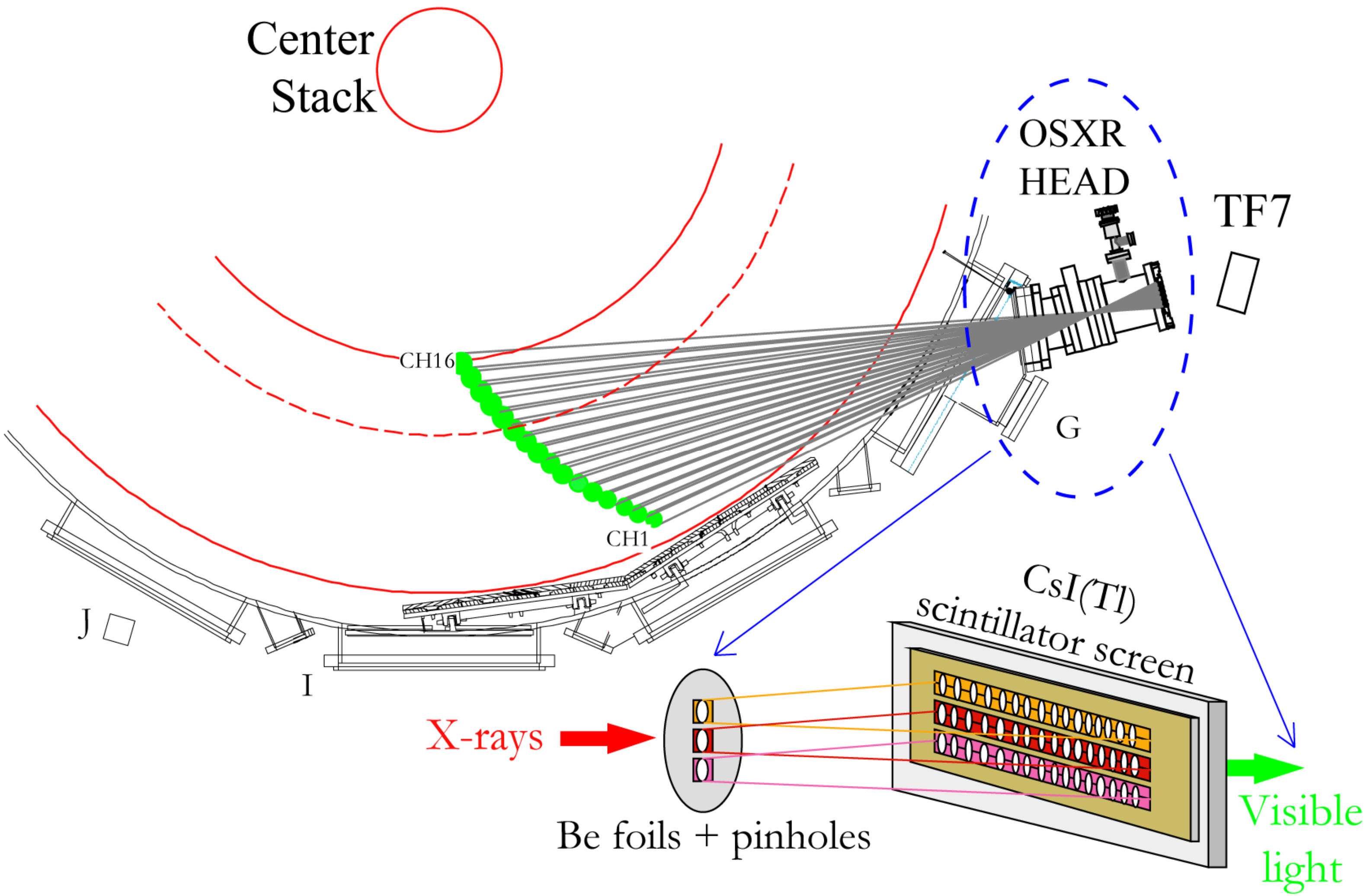


- The actively stabilized RWM have a non-resonant *n=3* magnetic braking and a *n=1* active feedback stabilization field.

- The arrows indicate perturbations in the neutron rate (S_n), D_α light and total radiated power that will be correlated with the **slow (~20 Hz) *n=1* component of the RWM.**

- These signals will also be correlated with **edge and core density and temperature fluctuations** of the same kind.

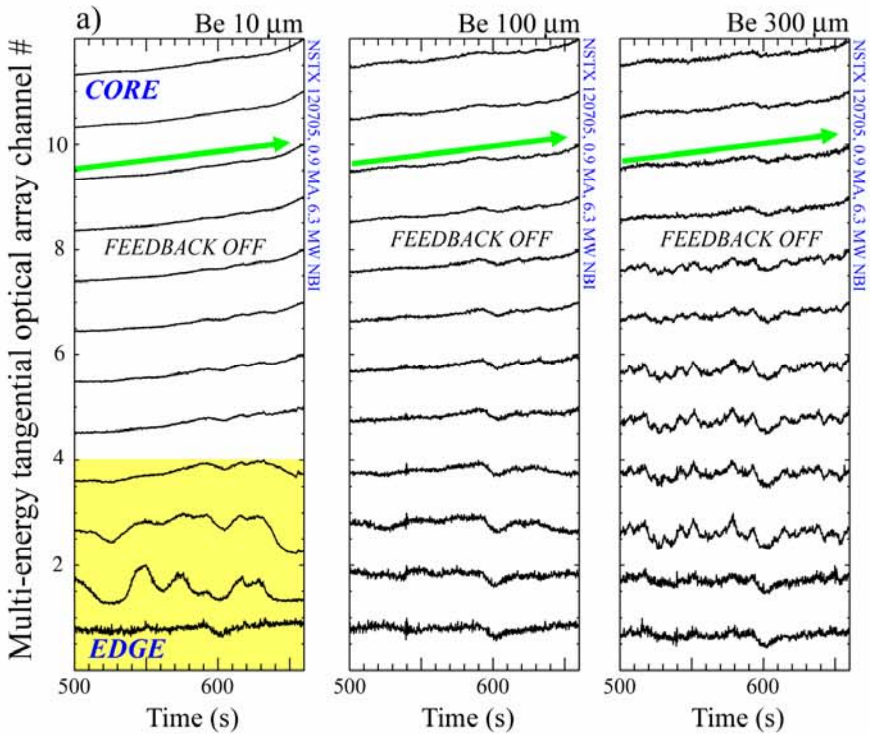
Main diagnostic: tangential multi-energy "optical" SXR array



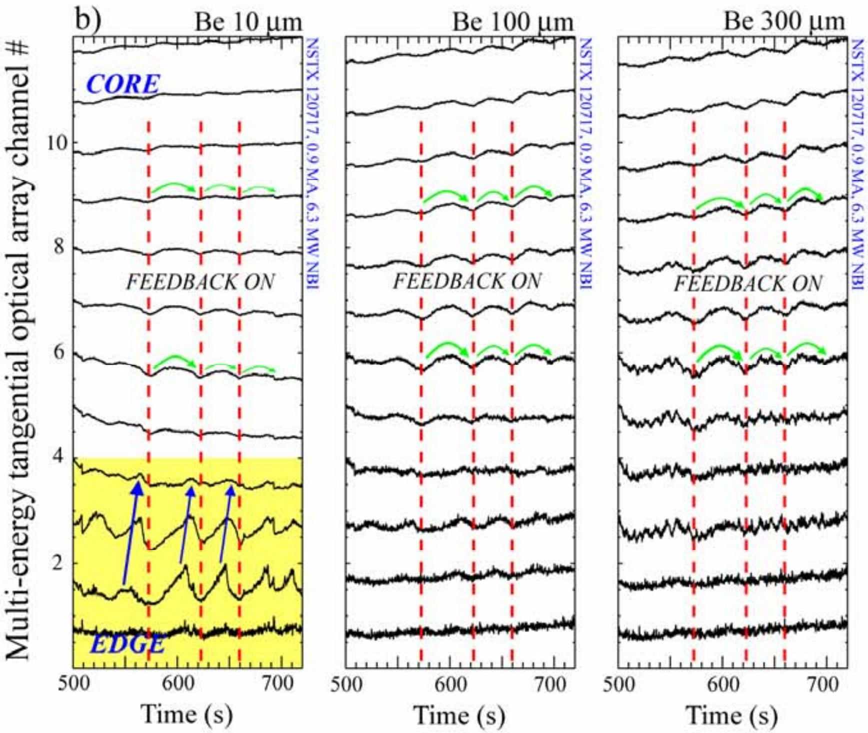
[4] L. Delgado-Aparicio, *et al*., Jour. Appl. Phys., **102**, 073304 (2007).
[5] L. Delgado-Aparicio, *et al*., Plas. Phys. Contr. Fus., **49**, 1245 (2007).

Detecting RWMs with the tangential ME-OSXR array

Control OFF (no active stabilization) NSTX # 120705



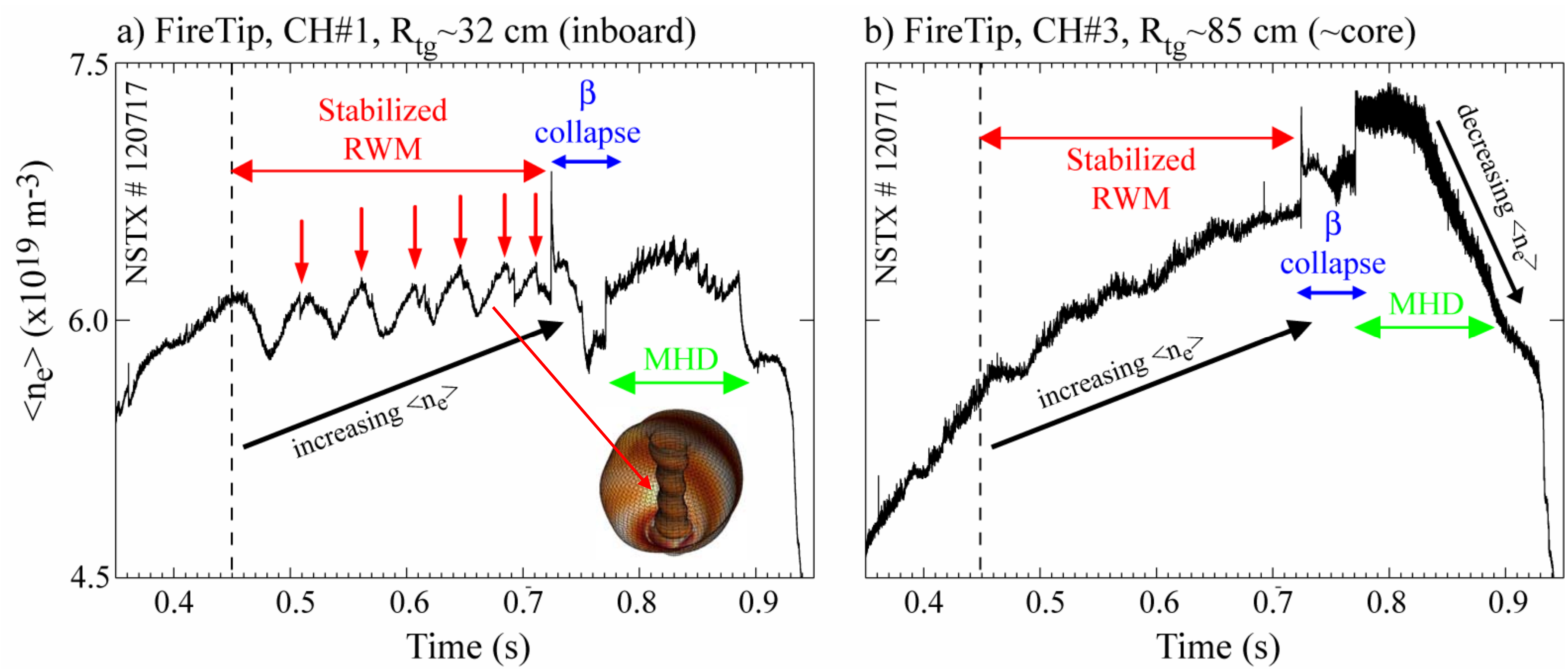
Control ON (active stabilization) NSTX # 120717



- RWM looks like a peripheral perturbation.
- Without stabilization the mode structure is peripheral and the plasma disrupts.

- With active stabilization, some mode perturbation appears to affect also the plasma core. **See neutron signals** (previous slide).
- Edge perturbation as well.

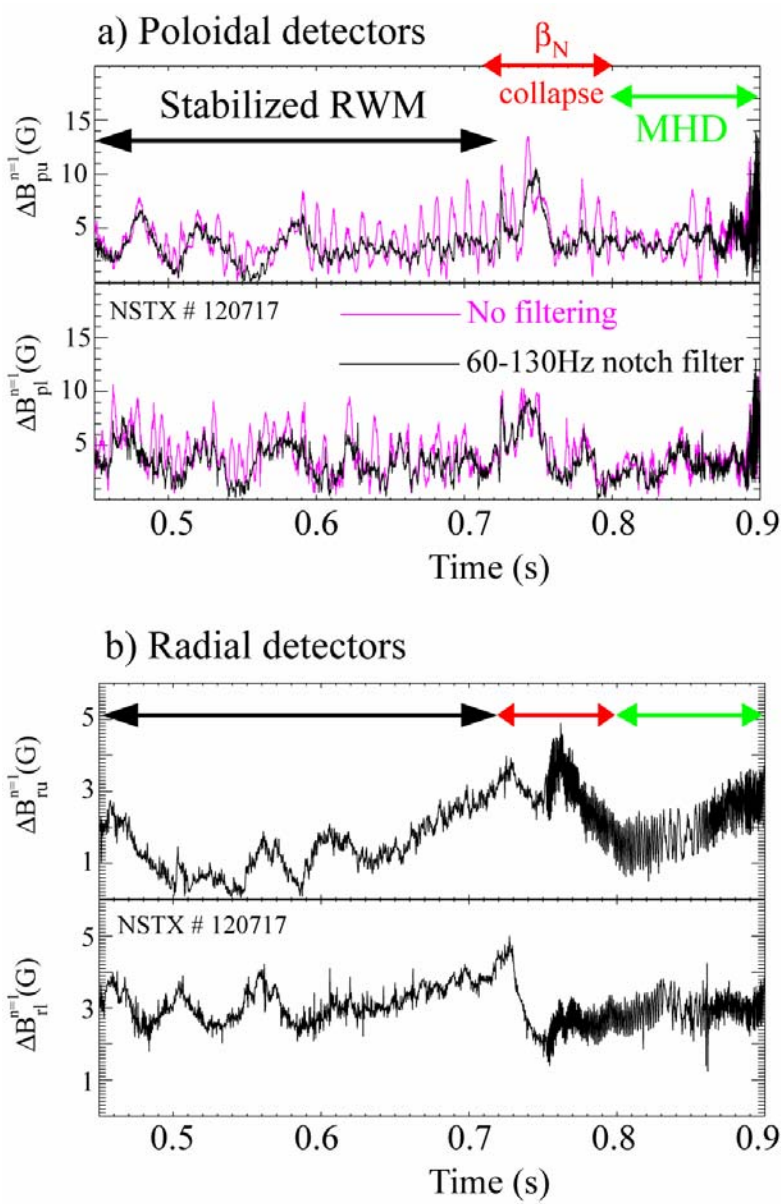
FIReTIP indicates $<n_e>_{edge}$ perturbation during RWM stabilization



• Since FIReTIP data are line integrated through beam path, the density oscillation associated to the stabilized RWM (**see red arrows**) appears to be dominant on inboard edge Ch1 [R_{tg}~32 cm] in comparison with core Ch3 [R_{tg}~85 cm].

• The radial location of the such density fluctuations seems to occur at the edge (as suggested also by the D_α measurements).

The slow (~20 Hz) *n=1* mode is measured by the RWM coils.

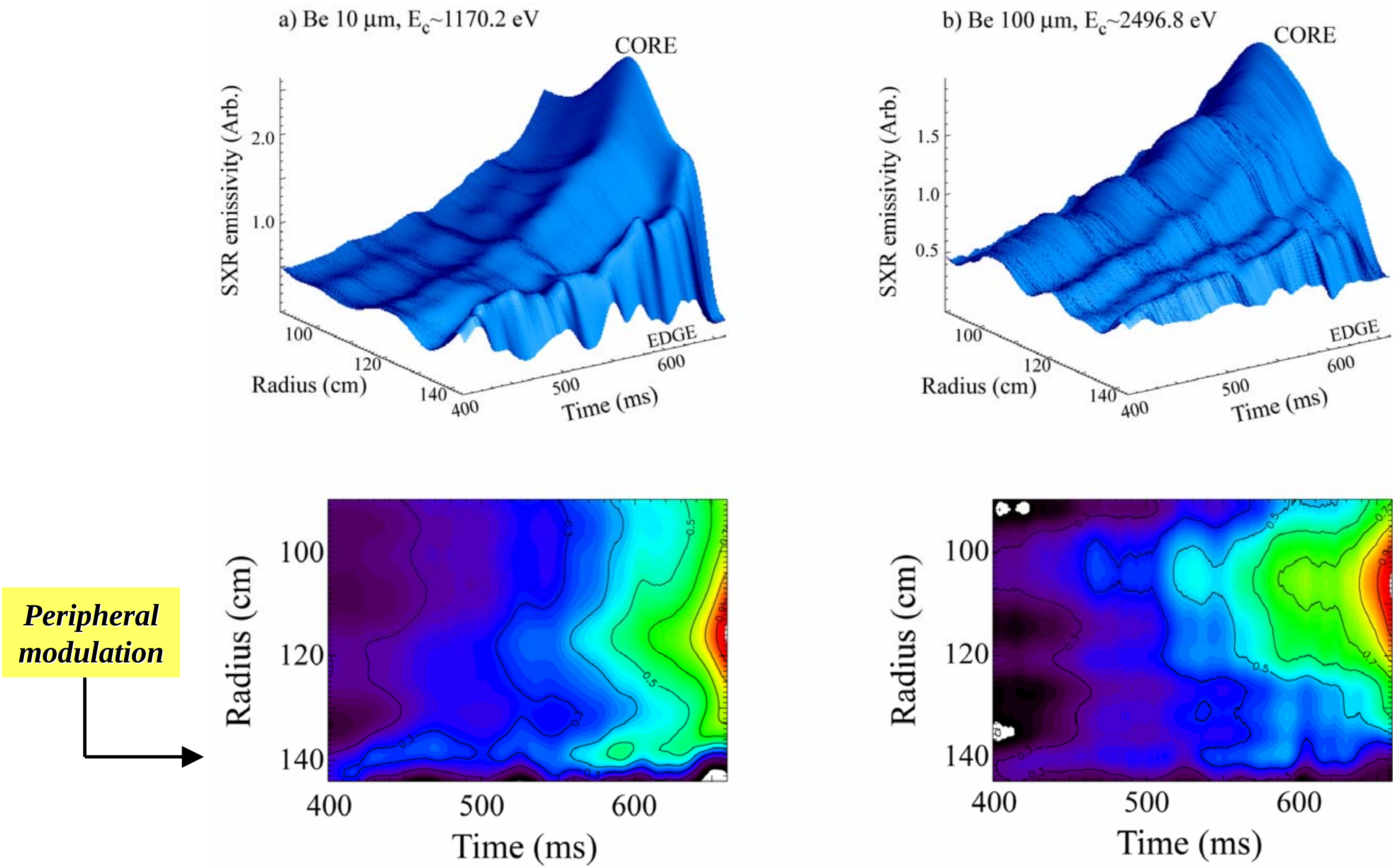


• This new plots have mode amplitudes that are slightly different than the ones reported in Sabbagh, PRL, 2006 [data showing what was stored in the operations files while running the mode identification algorithms].

•This new data has been revised using the present identification algorithm to the raw data [Levesque].

•A (60-130 Hz) notch filter has also been applied to the data from the poloidal detectors in order to **extract the same slow ~20 Hz *n=1* mode**.

SXR reconstruction shows indeed that the RWM is peripheral.



• Without stabilization the mode structure is peripheral and the plasma disrupts.

• The plasma core seem unaffected by the edge modulation.

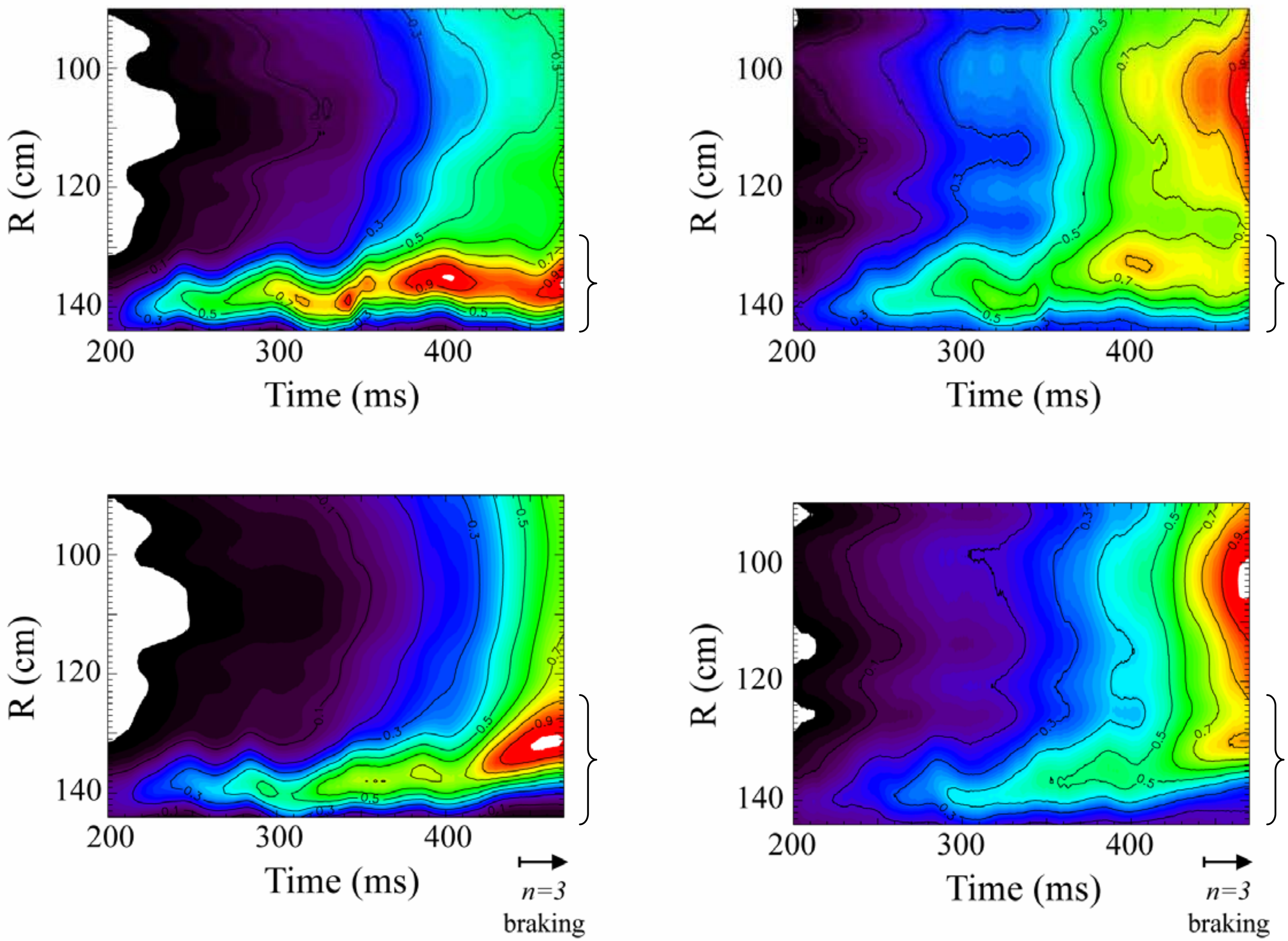
Other RWMs without stabilization also show a peripheral activity

Be 10 μm (low-energy)

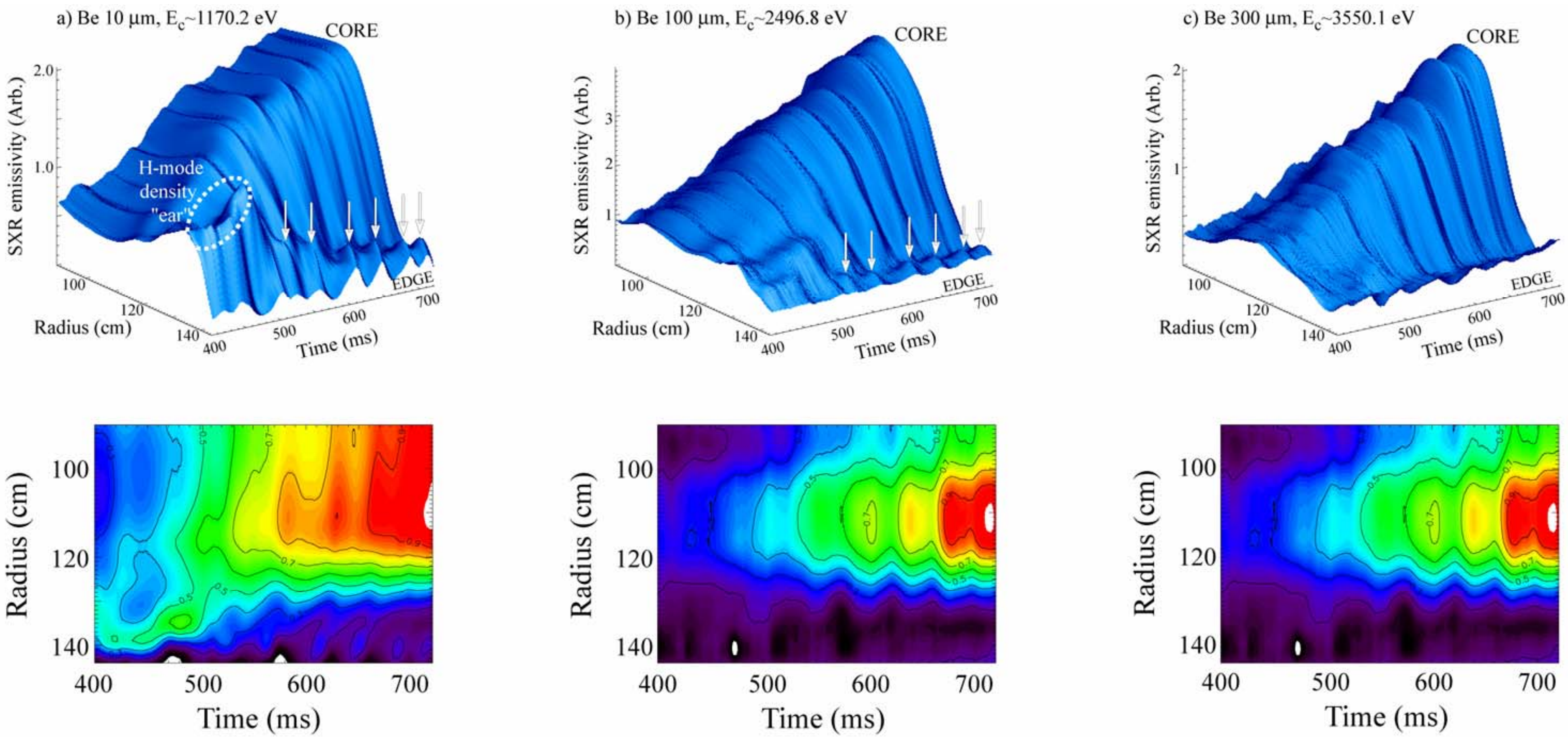
Be 100 μm (medium-energy)

120704 (neither braking nor stabilization)

120712 (n=3 braking @ t~450 ms)



Multi-energy SXR reconstructions of actively stabilized RWMs



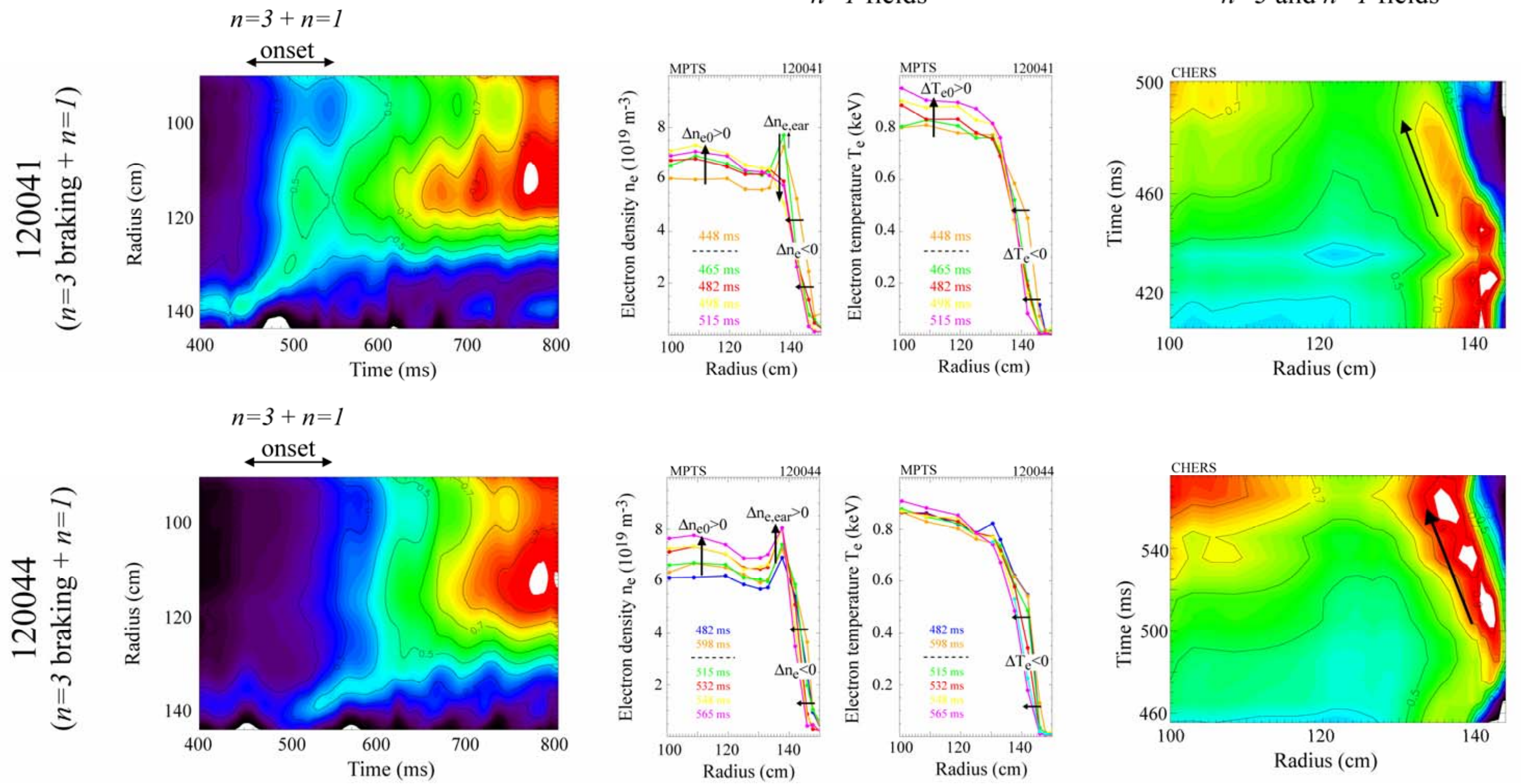
- *n=3* braking and *n=1* stabilizing fields modified kinetic profiles at early times.
- Are the RMPs taking out the H-mode density “ears”?
- Increased edge n_Z (C, metals) blobs (**see white arrows @ R~140 cm**) during stabilization.
- Good correlation with drops in $\boldsymbol{T_{e0}}$ (MPTS) and **neutron rates** (S_n).

Modification of the kinetic profiles triggered by the $n=3+n=1$

Low-energy SXR emissivity (Be 10 μm)

Kinetic profiles before and after applying $n=3$ and $n=1$ fields

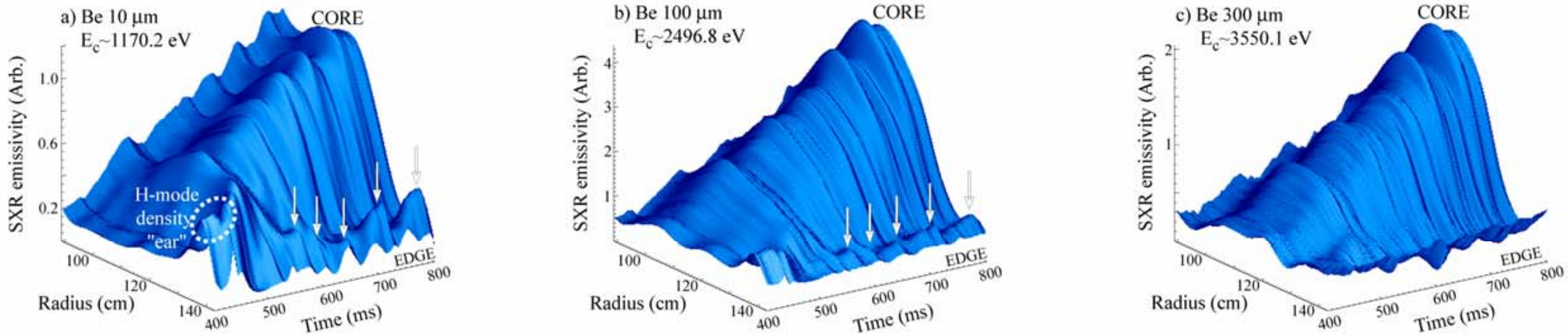
Normalized carbon density profiles before and after applying $n=3$ and $n=1$ fields



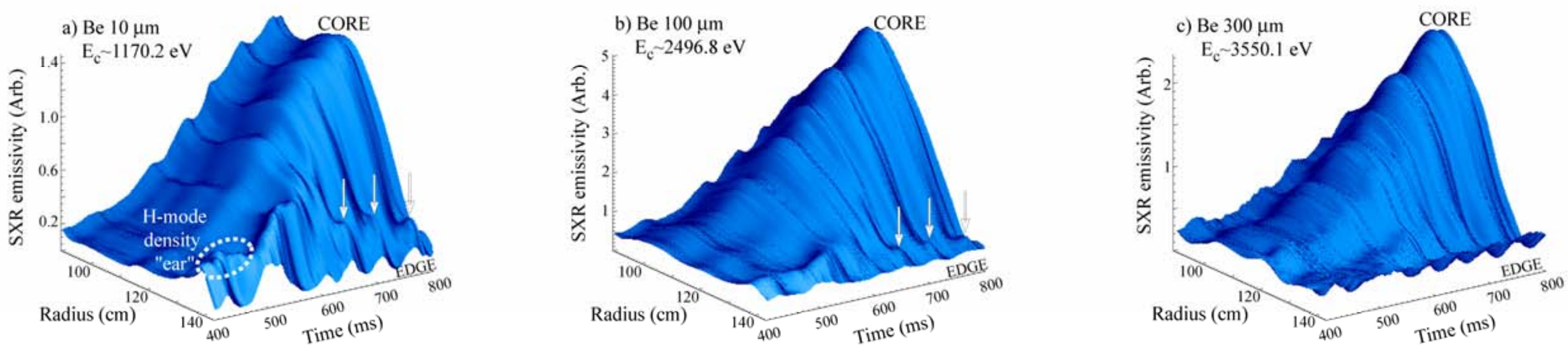
- Is the edge transport changing as a result of the use of the RMPs?
- Are the RMPs facilitating the transport of impurities through the H-mode barrier?

Edge & core modulations are also present in other stabilized RWMs

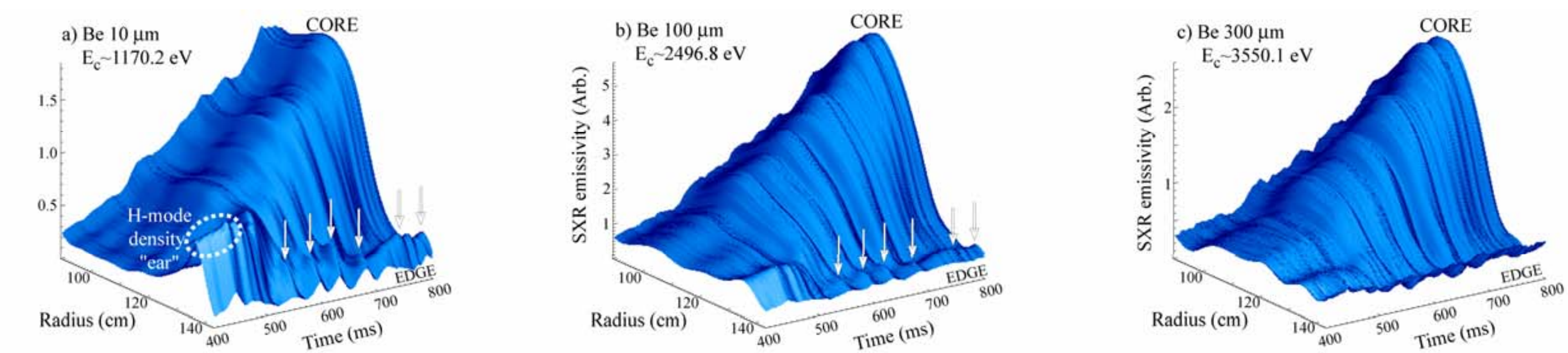
120041
(n=3 braking +n=1)



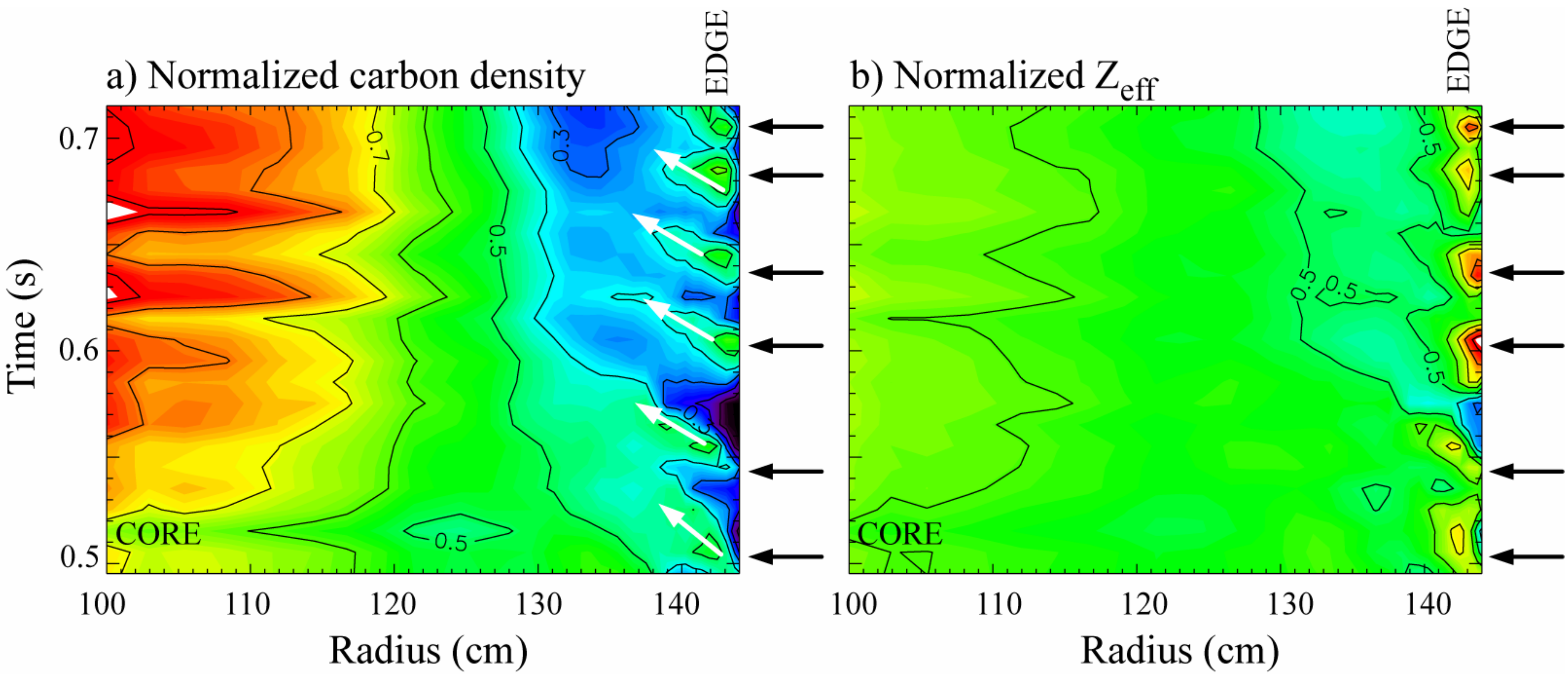
120044
(n=3 braking +n=1)



120047
(n=3 braking +n=1)

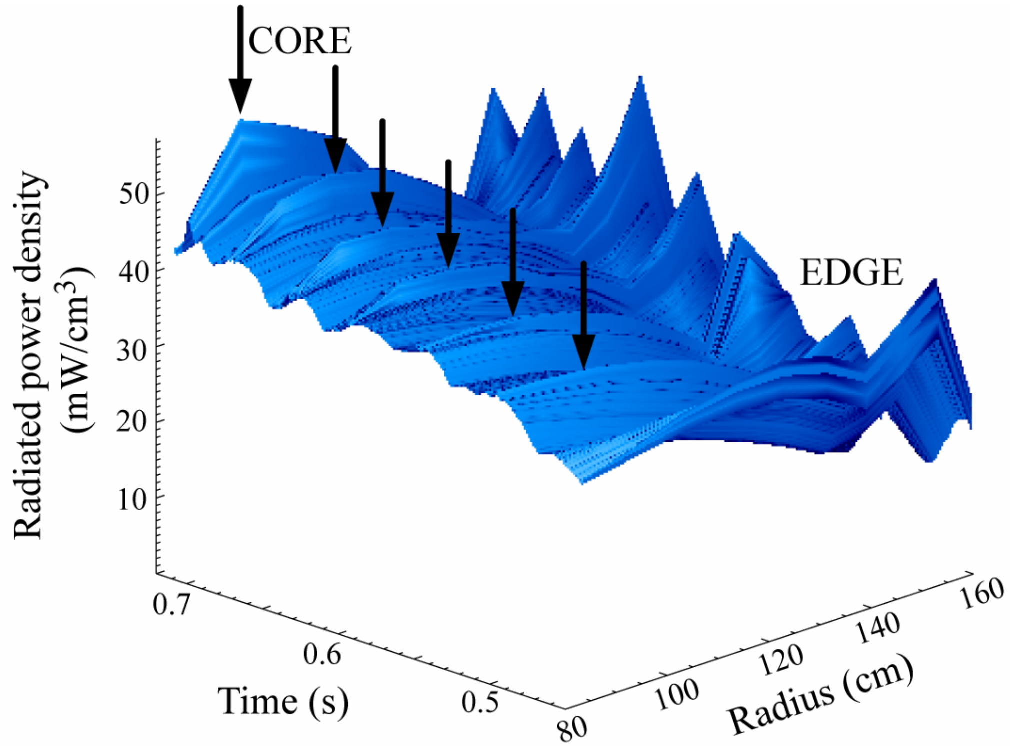


CHERS indicates edge & core n_Z perturbation during stabilization



- The edge and core carbon density have the same slow ~20 Hz mode ($n=1$) activity.
- n_C at edge and core are out of phase, suggesting possibly edge and core islands.
- Ion temperature seem to be unaffected by the RWM stabilization.

Bolometer indicates $<n_e \cdot n_Z>$ perturbation (inboard ≈ outboard)



• The $n_e \cdot n_Z$ modulation (**see black arrows**) is also observed using the radiated power density measurements.

• There is a comparable radiated power modulated at the inboard edge (CS: not shown here).

• The edge and core perturbations are out of phase.

Fast electron temperature measurements

Fast $T_e(R,t)$ measurement from SXR continuum radiation

→ Consider **plasma continuum radiation**, (i.e. Bresstrahlung and recombination radiation)
$\gamma(T_e,Z)$: enhancement over Bresstrahlung due to free-bound recombination,

$$\frac{dP_x}{dh\nu} \sim \frac{1}{\sqrt{T_e(\mathrm{keV})}}\gamma(T_e,Z)Z_{eff}n_e^2\exp\left(-\frac{h\nu}{T_e}\right)$$

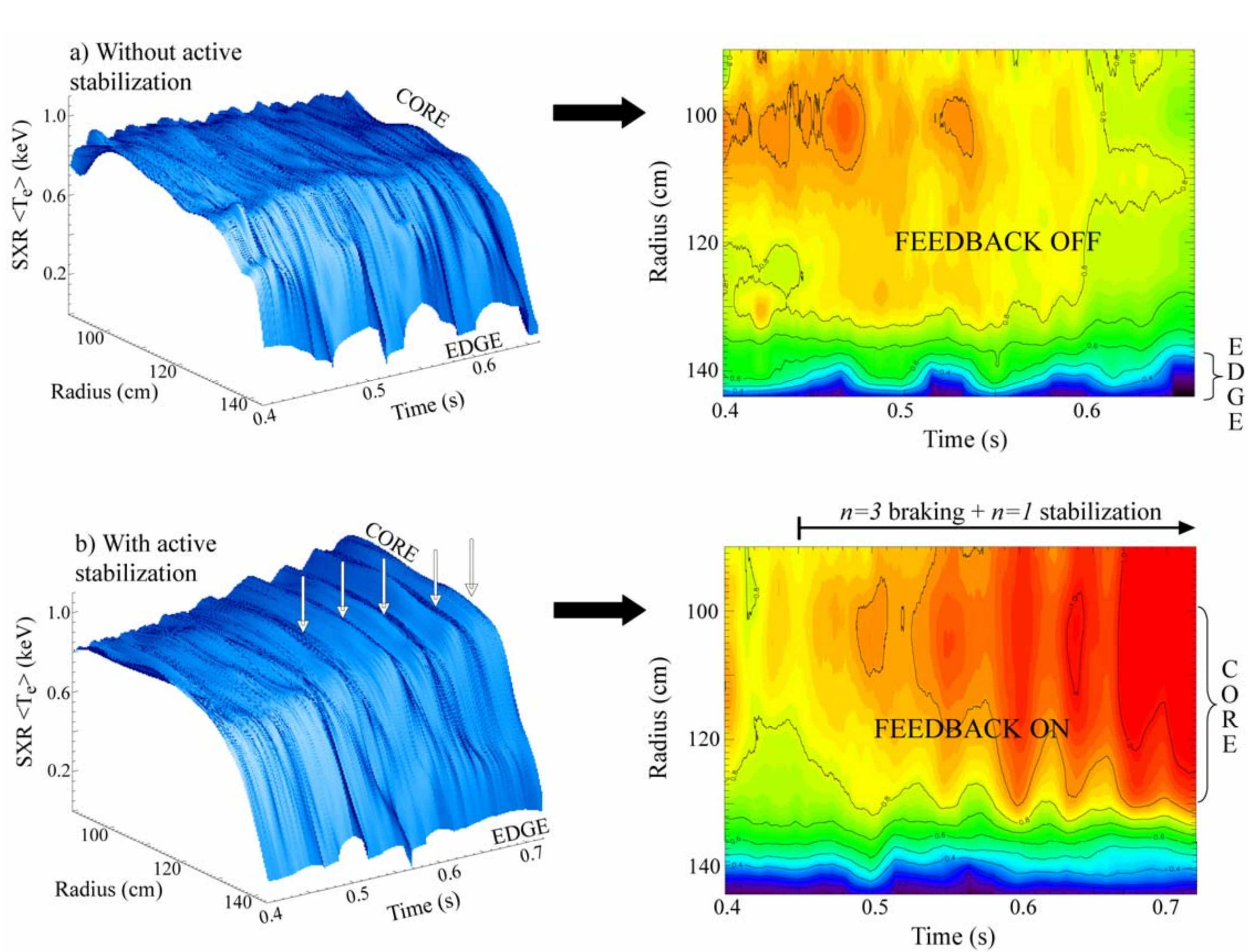
→ The SXR power absorbed by **two** detectors is,

$$\boxed{\mathrm{Ratio} \equiv R = \frac{P_1}{P_2} = \exp\left(\frac{-\Delta E_c}{T_e}\right)}$$

→ With feedback on the original SXR emissivities we can determine $n_e \cdot n_Z$

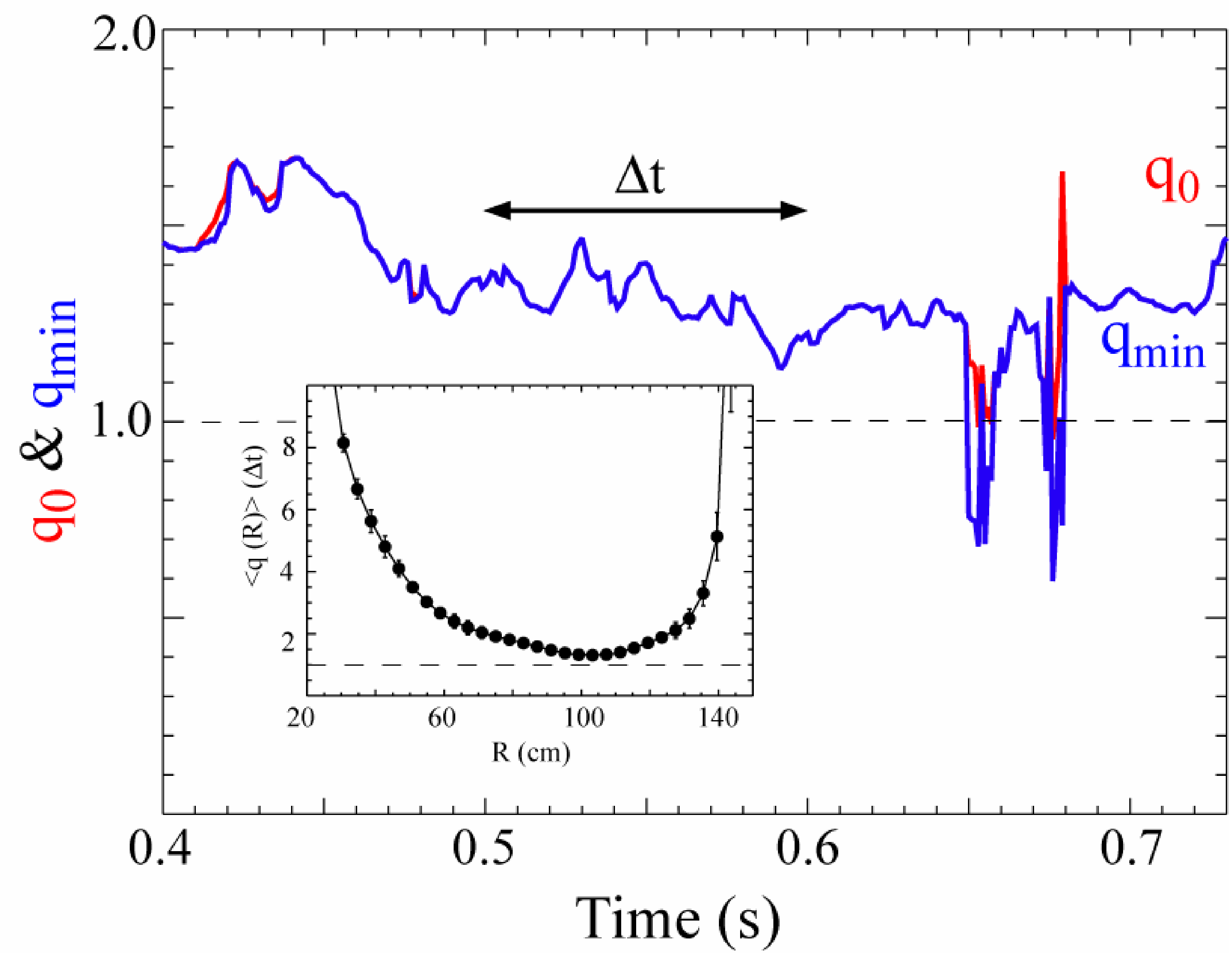
→ Basic assumptions: a) **Maxwellian distribution** of electrons with a characteristic T_e.
b) **Spectrum** dominated by **continuum radiation**.
c) Sample the same **plasma volume**.
d) ***Abel inversion is only a first order approx. in the case of the toroidally non-axisymmetric emmisivity of helical perturbations.***

Comparing non-stabilized vs. stabilized RWM before β_N collapse



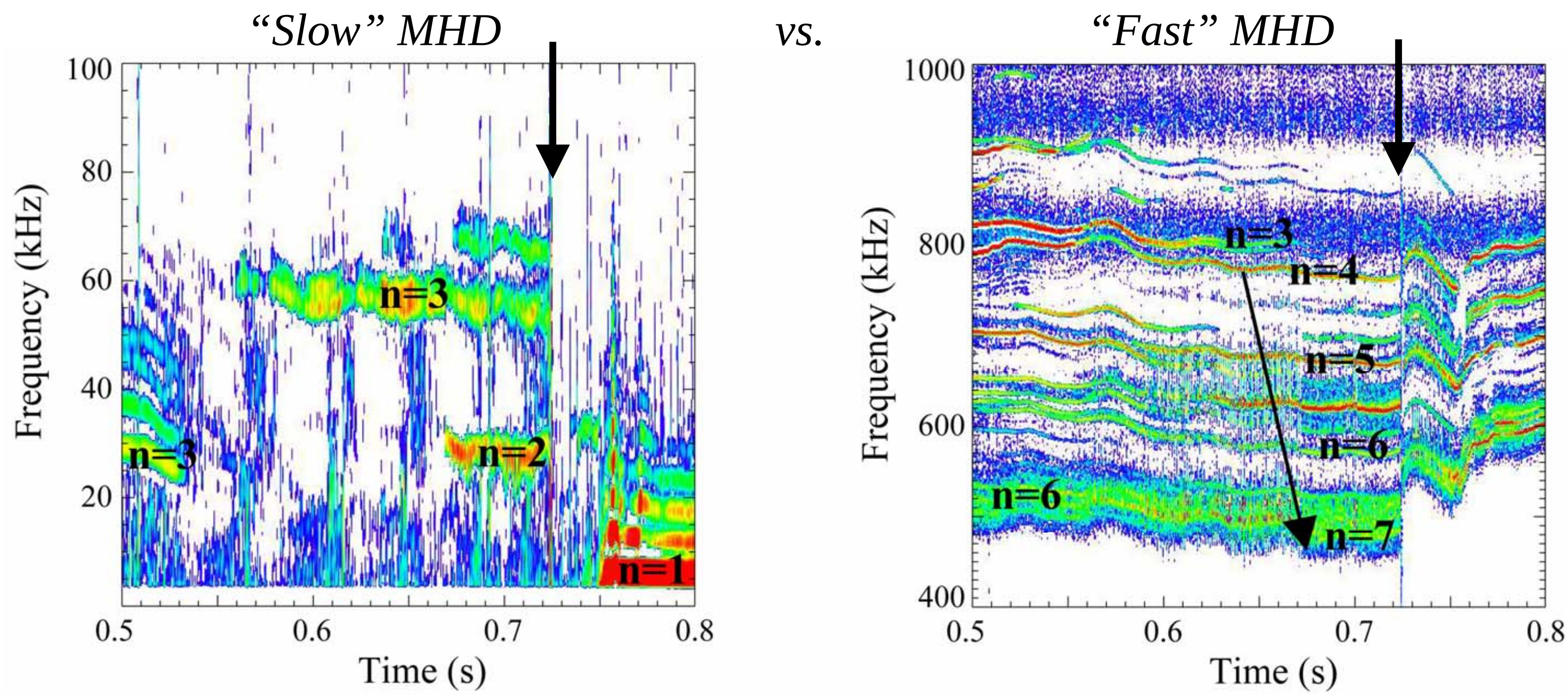
The non-stabilized RWM shows a peripheral T_e modulation while the actively stabilized RWM carries a core T_e perturbation with the same frequency as the slow $n=1$ mode (~20 Hz).

Monotonic q-profile >1 suggest no internal MHD activity



β_N collapse during RWM stabilization

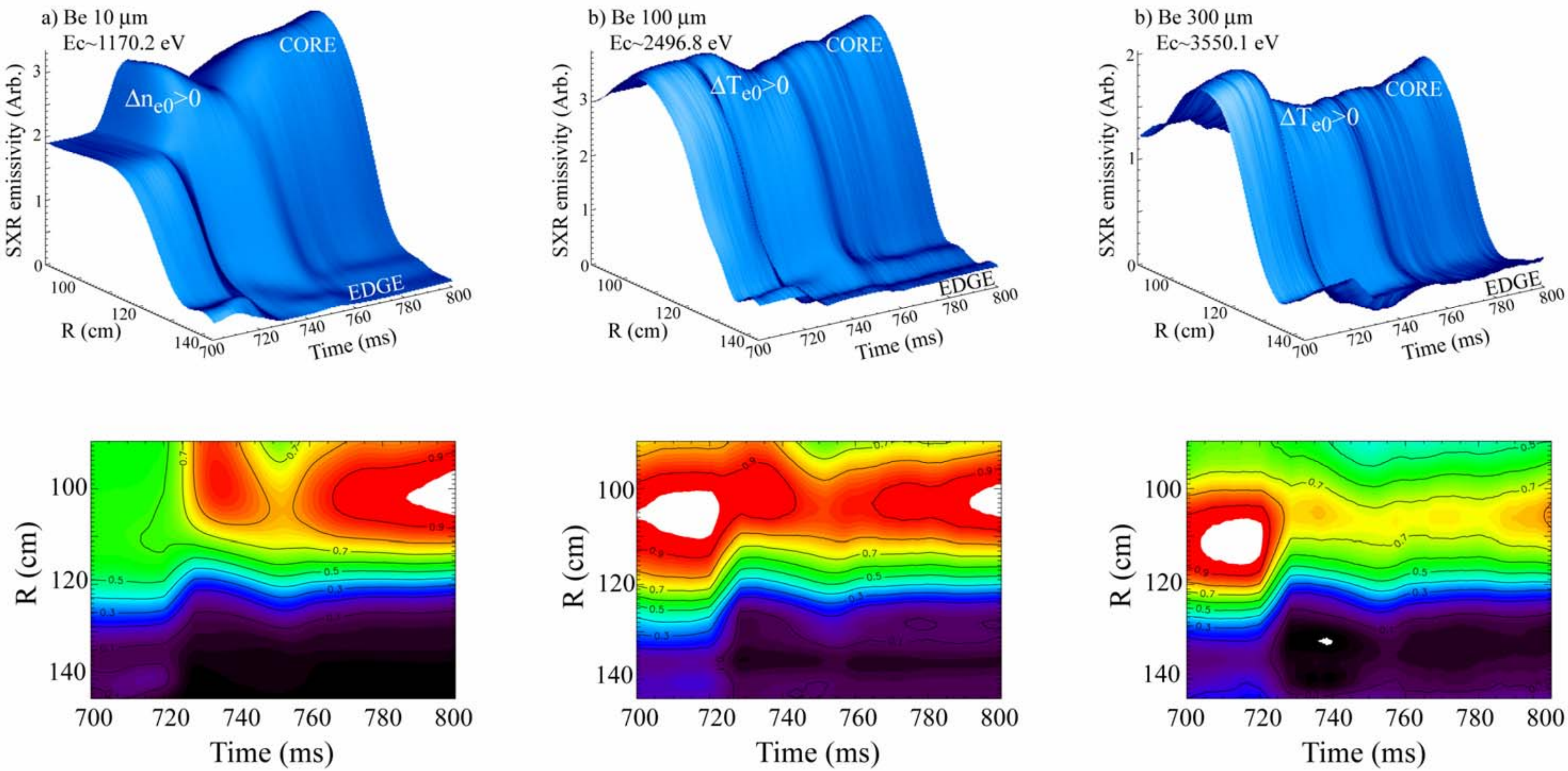
After several confinement times the plasma disrupts (β_N collapse)



- During stabilization there is a *n*=3 mode that later, coupled with a *n*=2, eventually disrupts the plasma (see low frequency MIRNOV signals).

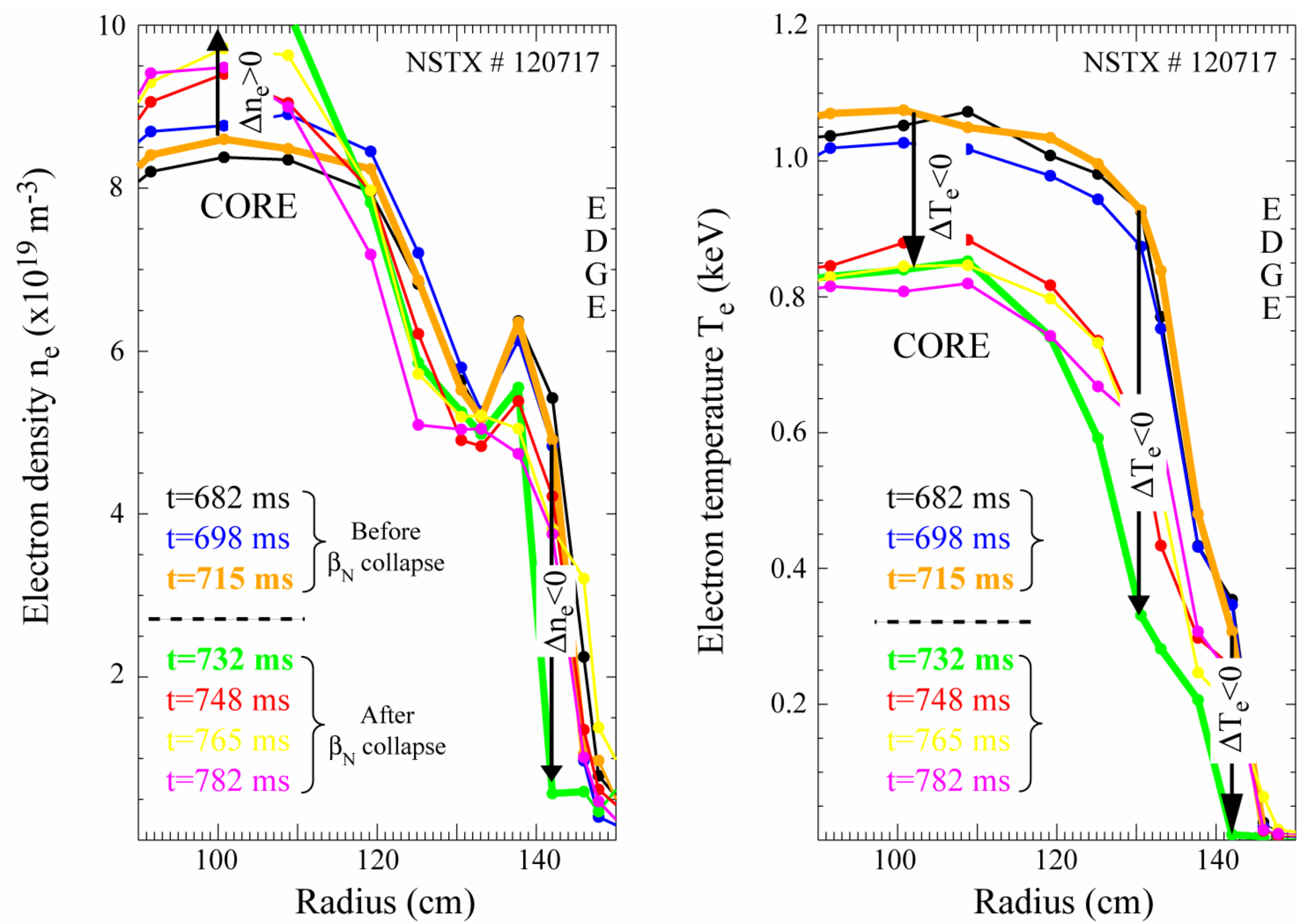
- The NBI-driven compressional and global Alfvén eigen-modes are "not affected" by the disruption (slight change in frequency – see high frequency MIRNOV signals).

SXR reconstructions during β_N collapse and plasma recovery

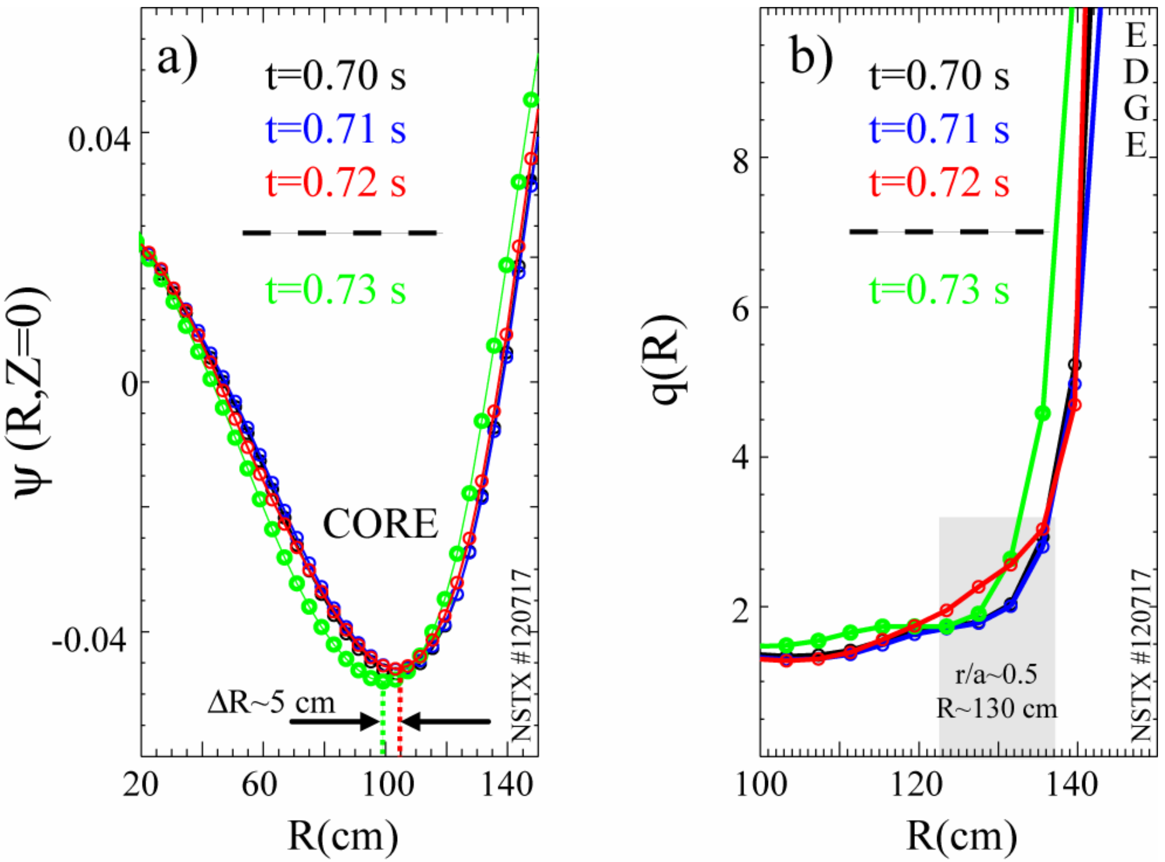


- Both the medium- and high-energy arrays observe the peripheral and core T_e crash.
- The low-energy array detects a raise in $n_{e,0}$ after the crash (in agreement with MPTS).
- Possible displacement of plasma center after β collapse.

Increasing n_{e0} and decreasing $T_e(R)$ after the β-collapse

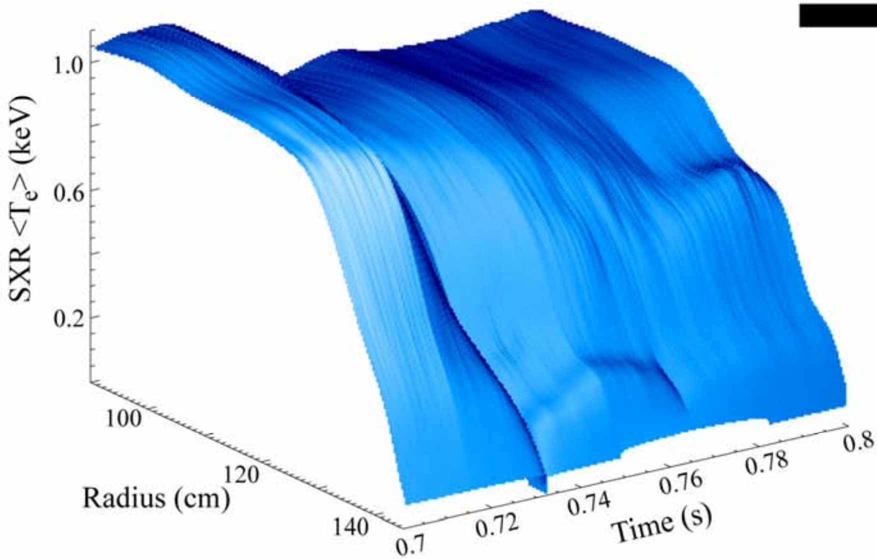


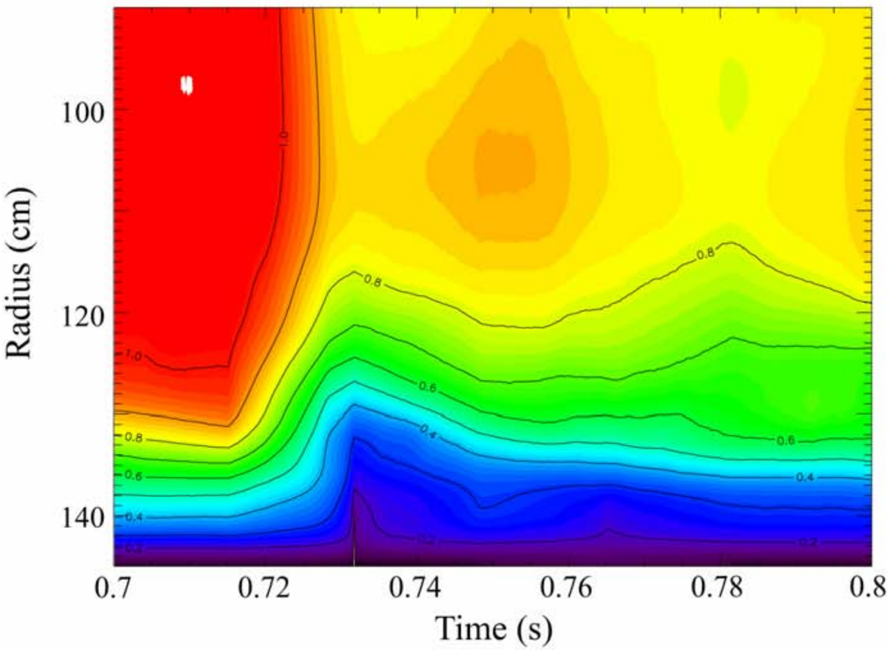
Strong change in the magnetic shear before β-collapse



• These plots suggest that there is a strong modification of the magnetic shear (hollow current profile) at mid-radius before the β_N collapse, after which the plasma center has been displaced radially inwards (ΔR~5 cm, as suggested also by the ME-SXR emissivities).

Fast T_e (R,t) estimate for β_N collapse (NSTX # 120717)





- The SXR T_e profiles are flat from R=100→130 cm (r/a=0→0.5) before the disruption and become slightly peaked after it (as also suggested by the MPTS signals).

- $\Delta T_{e,core}$~200 eV , $\Delta T_{e,mid\text{-}radius}$~600 eV and $\Delta T_{e,edge}$~300 eV as also measured by the MPTS,

- This is a zero-th order approximation since the RWM and the β_N collapse event are not axysimmetric perturbations (very 1st assumption for the validity of the Abel inversion).

Summary

• The temperature and density profiles at the gradient region are changed due to the presence of the resonant magnetic perturbations (RMPs).

• The non-stabilized RWM shows a peripheral T_e modulation while the actively stabilized RWM carries a core T_e perturbation with the same frequency as the slow $n=1$ mode (~20 Hz).

• The ME-SXR data suggests that the RWM may not be entirely “rigid” and that acting with the stabilizing coils on its external structure may transfer some of the perturbation to the interior of the plasma.

Statement and future plans

• Compared to magnetic measurements, the ME-SXR technique has advantages for low-f MHD detection, such as spatial localization and insensitivity to stray magnetic fields.

• Characterization of the RWM internal structure w/o stabilization.

• Measure the helical structure of the RWMs (kink vs. island models).

Prints

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