Control of 3D equilibria with resonant magnetic perturbations and their effect in the MST RFP

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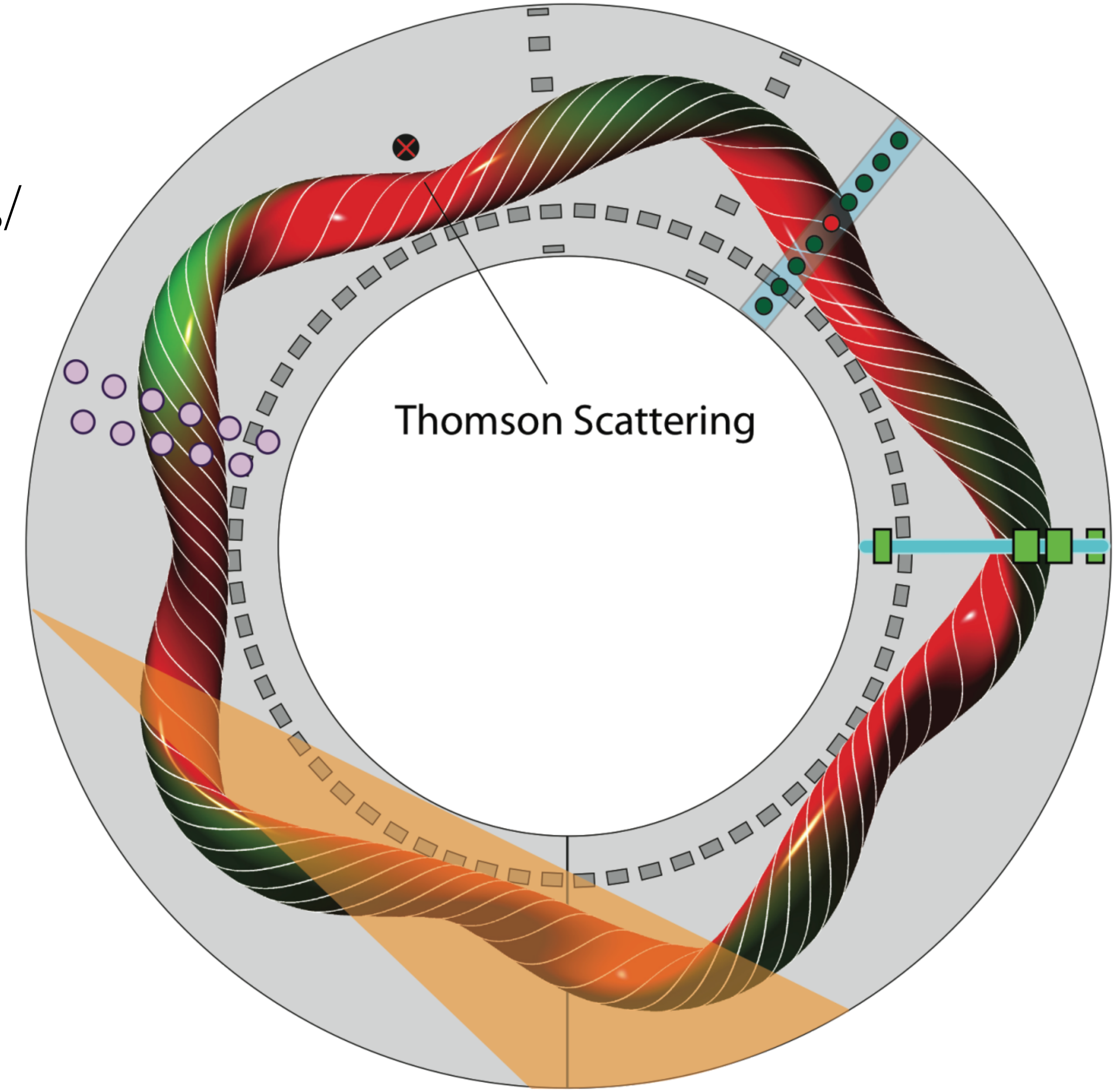
Motivation

Like in Tokamaks and Stellarators, 3D structures/ equilibria are present in RFPs

Diagnosis of a 3D equilibrium requires orientation control



Outline

1. Introduction
   - RFP configuration
   - Axisymmetric to 3D equilibrium

2. The active feedback system to produce RMP

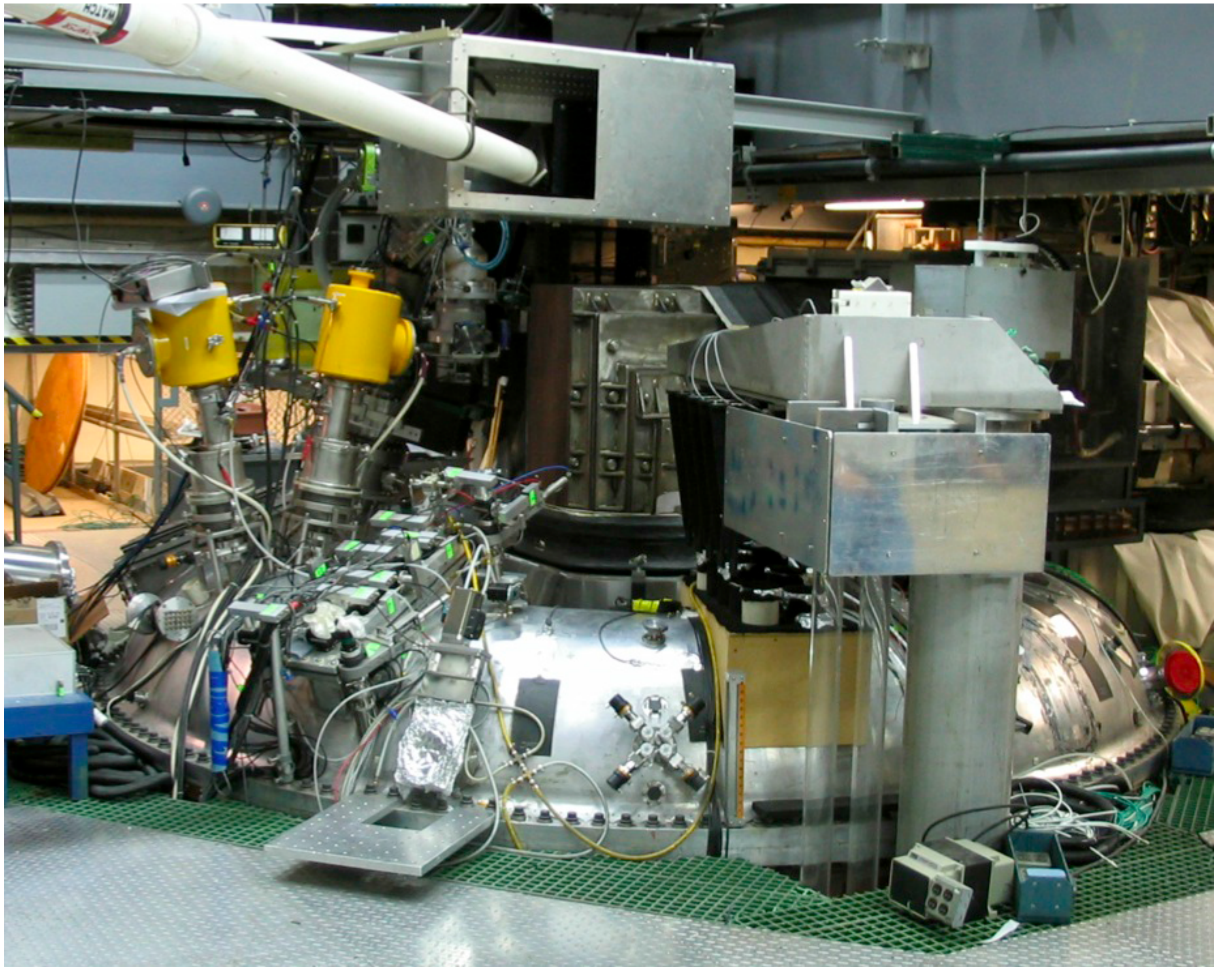
3. Orientation control with RMP

4. Orientation control to study thermal structures

5. Runaway electron suppression by RMP

6. Summary

Madison Symmetric Torus (MST)



RFP configuration

$R = 1.5$ m

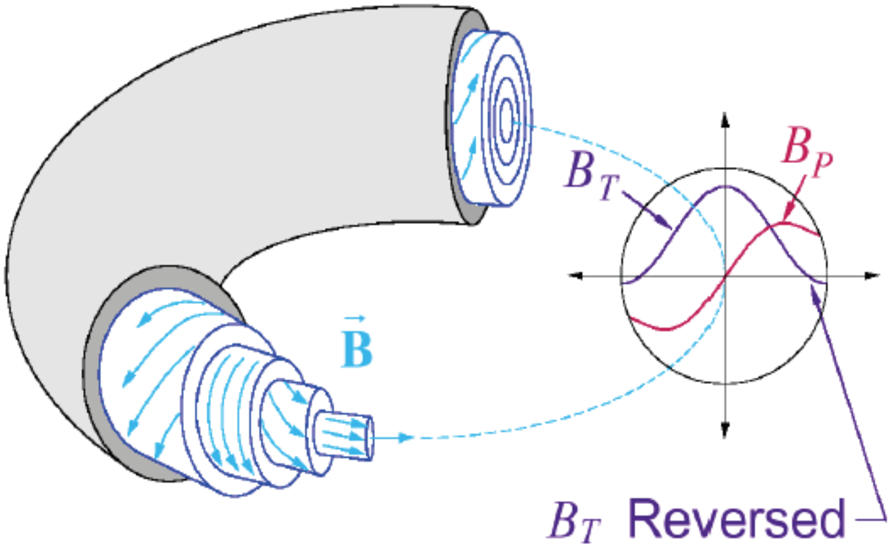
$a = 0.5$ m

$I_p \leq 0.6$ MA

$n_e \sim 10^{19}$ m^{-3}

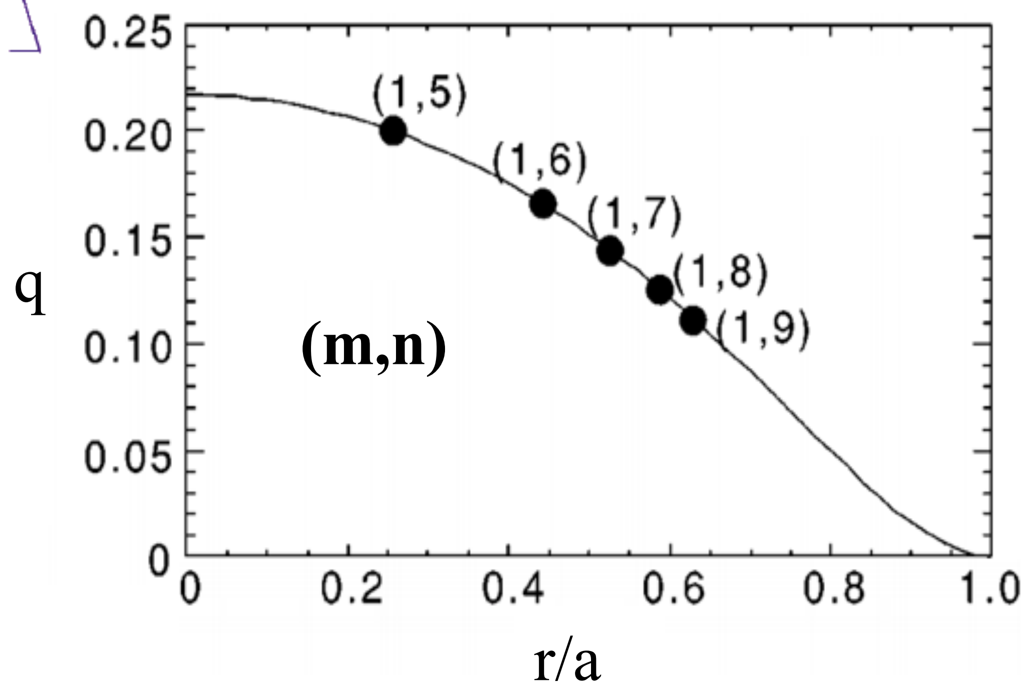
T_e, $T_i < 2$keV

Reversed Field Pinch



- Ideally ignition by ohmic heating (no need for auxiliary heating)
- ***q*** profile is monotonically decreasing

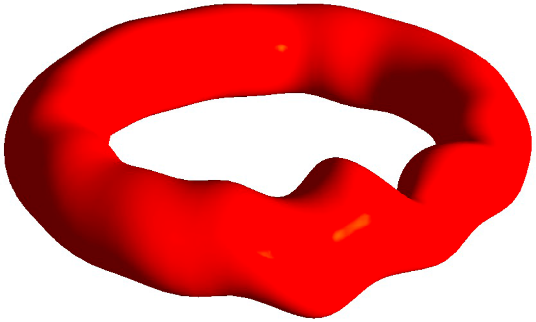
- ***q*** on axis depends on the aspect ratio of the device
- Presence of many m=1 resonant tearing modes



Different ways to operate MST to decrease the stochasticity

Standard RFP

Overlapping of many tearing modes produces stochasticity and consequently poor confinement



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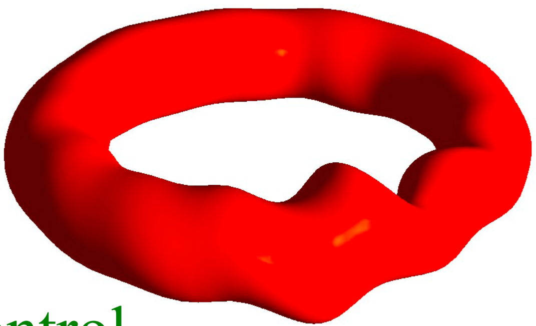
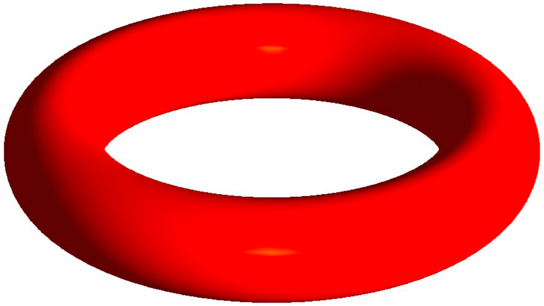


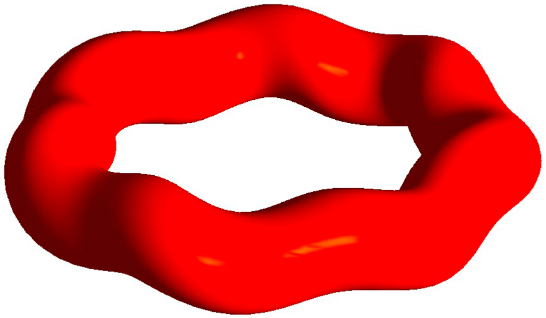
Current Profile Control



Pulsed Poloidal Current Drive (PPCD)

Chapman B E 2002, Phys of Plasmas ***9*** *(5) 2061*

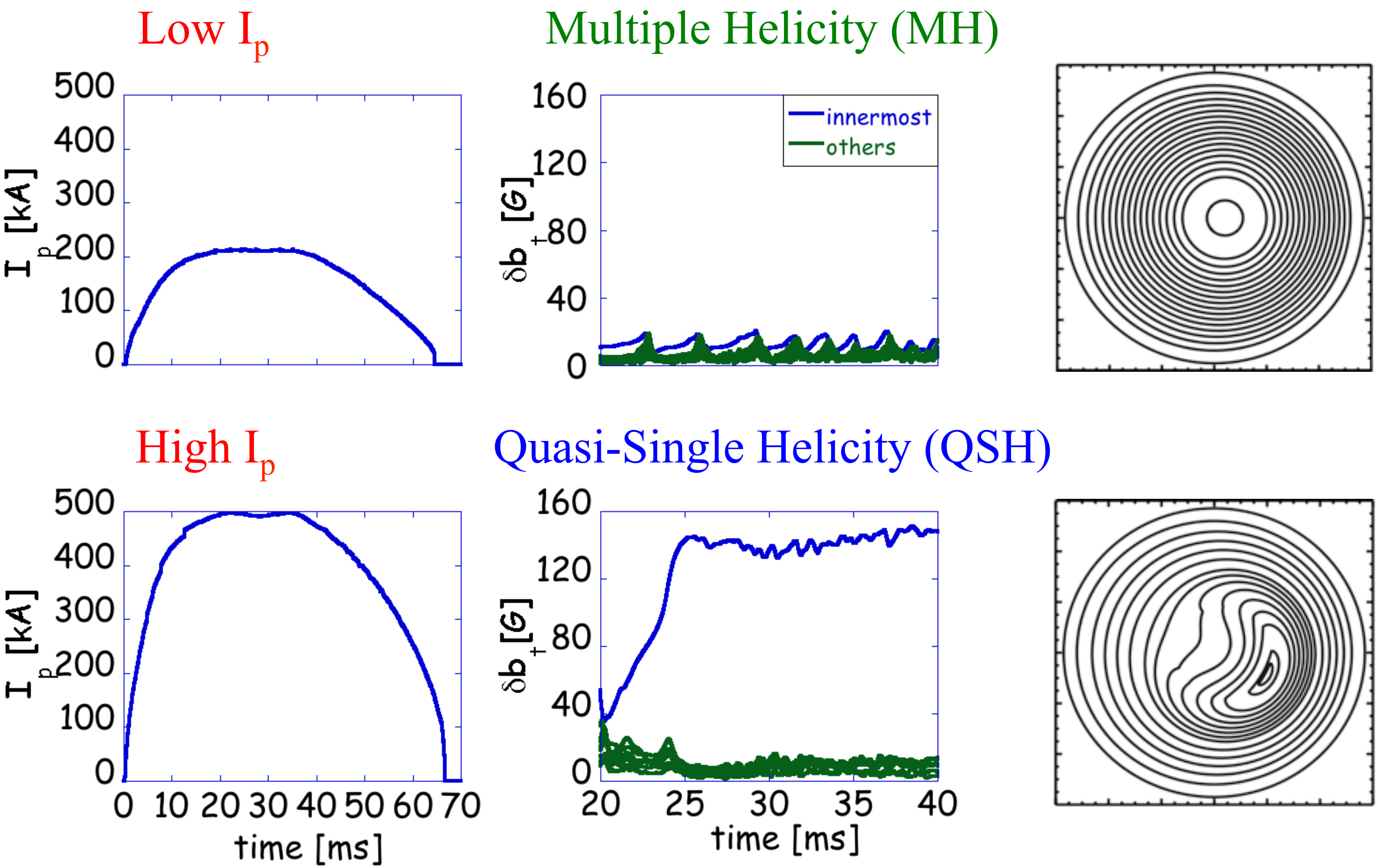
Self-organization



High plasma current

Lorenzini R 2009, Nature Physics ***5*** *570*

High current plasmas stimulate transition from axisymmetric to 3D equilibrium



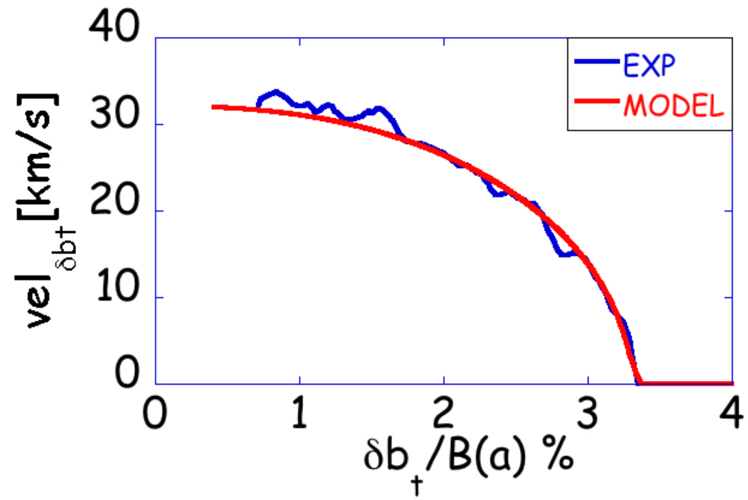
Tearing mode deceleration and eventual semi-random locking

- Tearing mode, $\mathbf{b}_{mode}$(m,n) induces eddy currents in conducting shell(s) surrounding the plasma

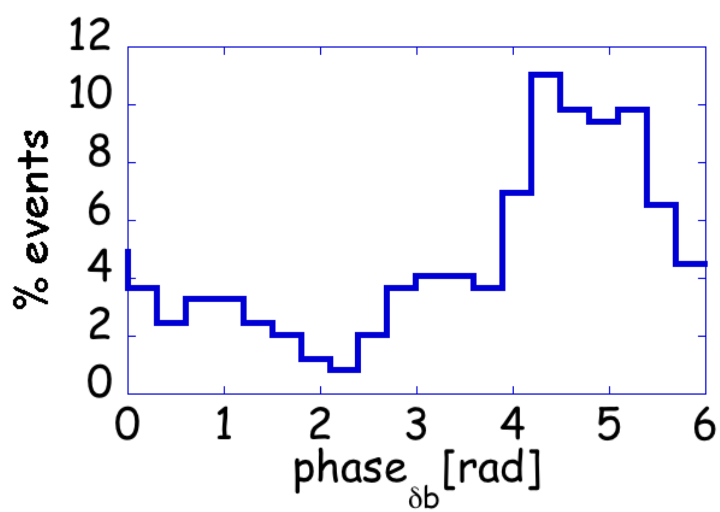
- Eddy currents cause current sheet, $\mathbf{j}_{sheet}$(m,n) near r_s, with a phase lag with respect to $\mathbf{b}_{mode}$(m,n)

- Local $\mathbf{j}_{sheet}$ x $\mathbf{b}_{mode}$ braking torque results which always oppose the mode rotation

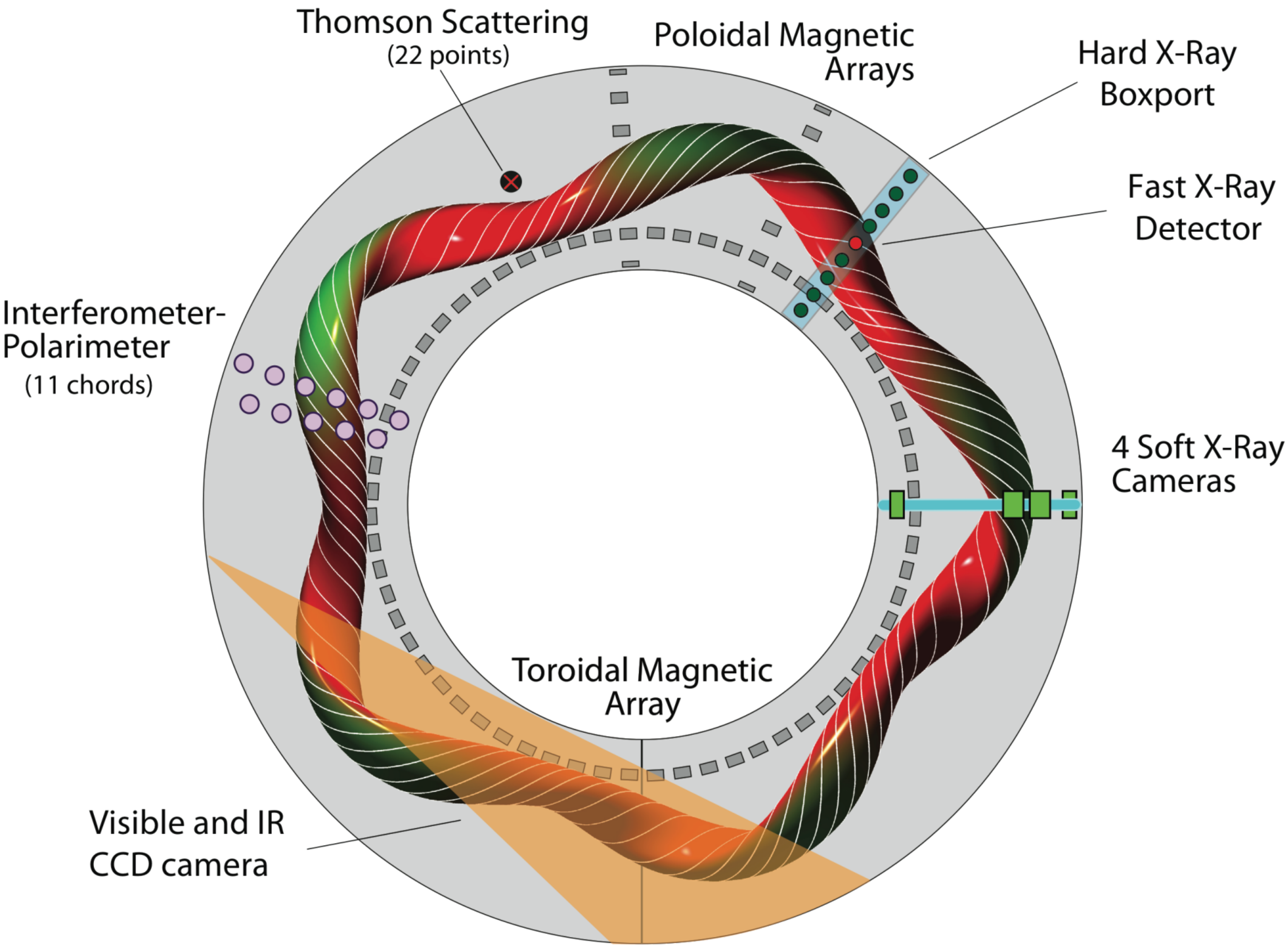
- A small finite resonant error field can lock a slow rotating mode to the wall



*BE Chapman et al 2004, Phys. of Plasmas **11** (5) 2156*



Not all the helix orientations are favorable for the diagnostics



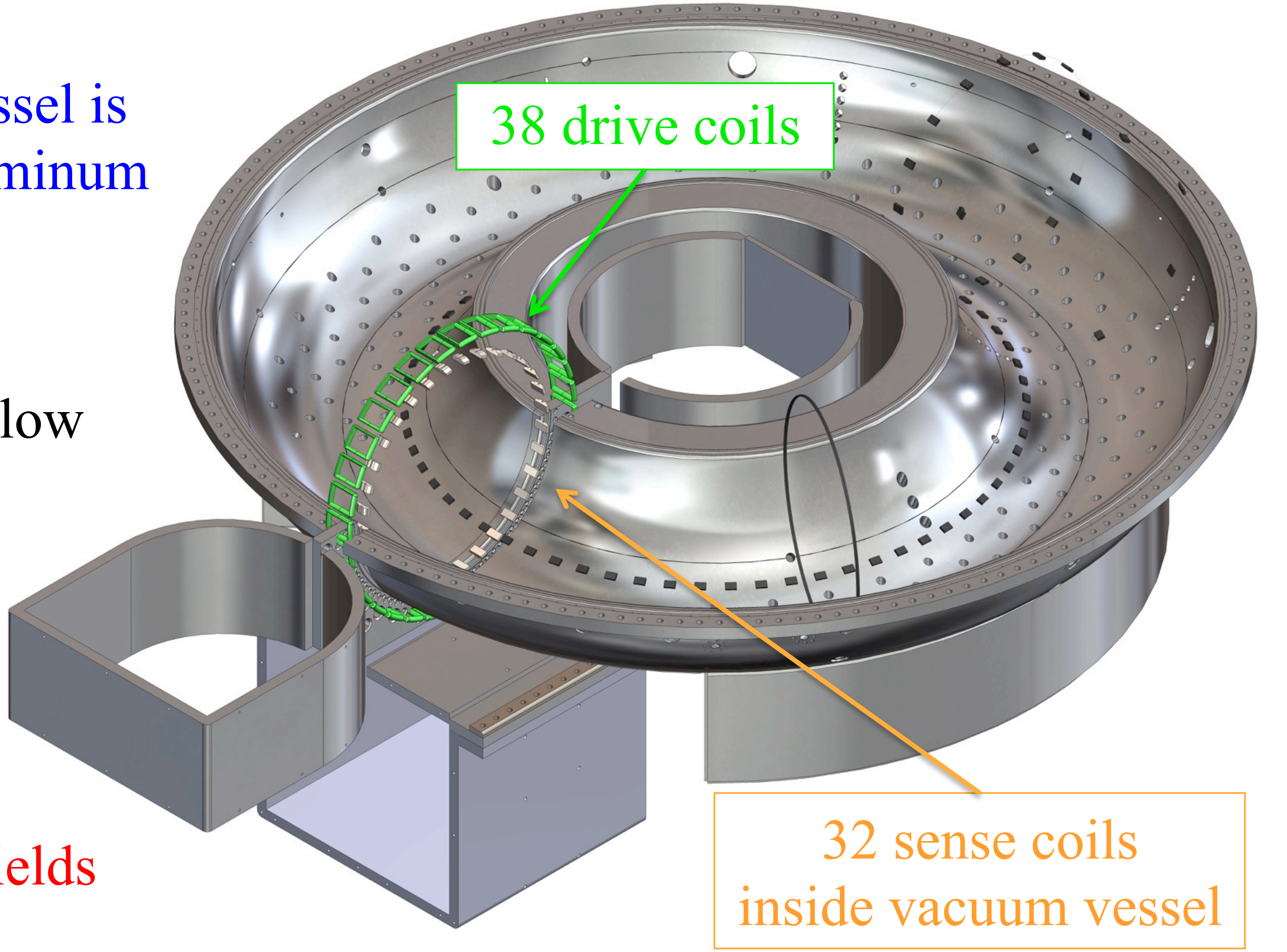
2. THE ACTIVE FEEDBACK SYSTEM TO APPLY RMP

Active feedback system to control the radial error field at the vertical gap

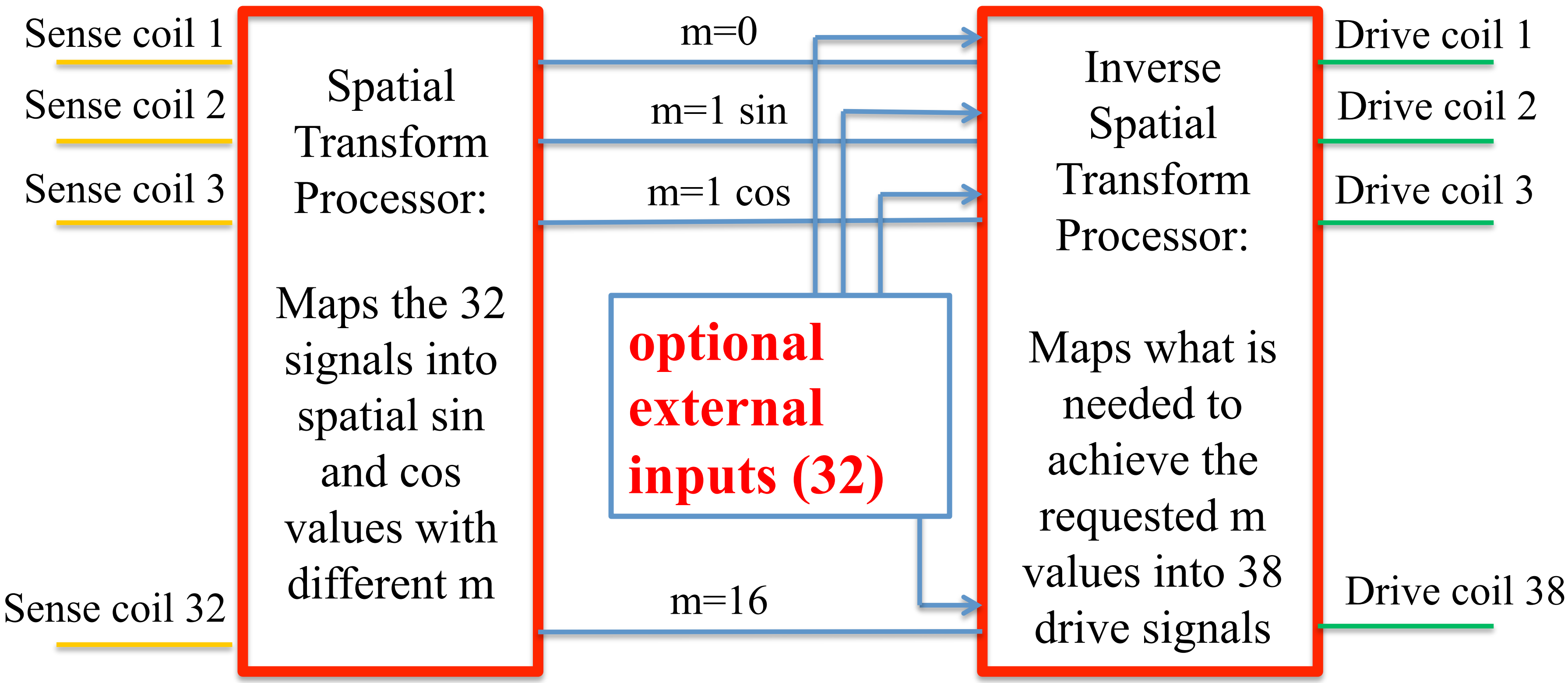
MST vacuum vessel is a 5 cm thick Aluminum shell

Vertical gap to allow plasma startup

Source of error fields

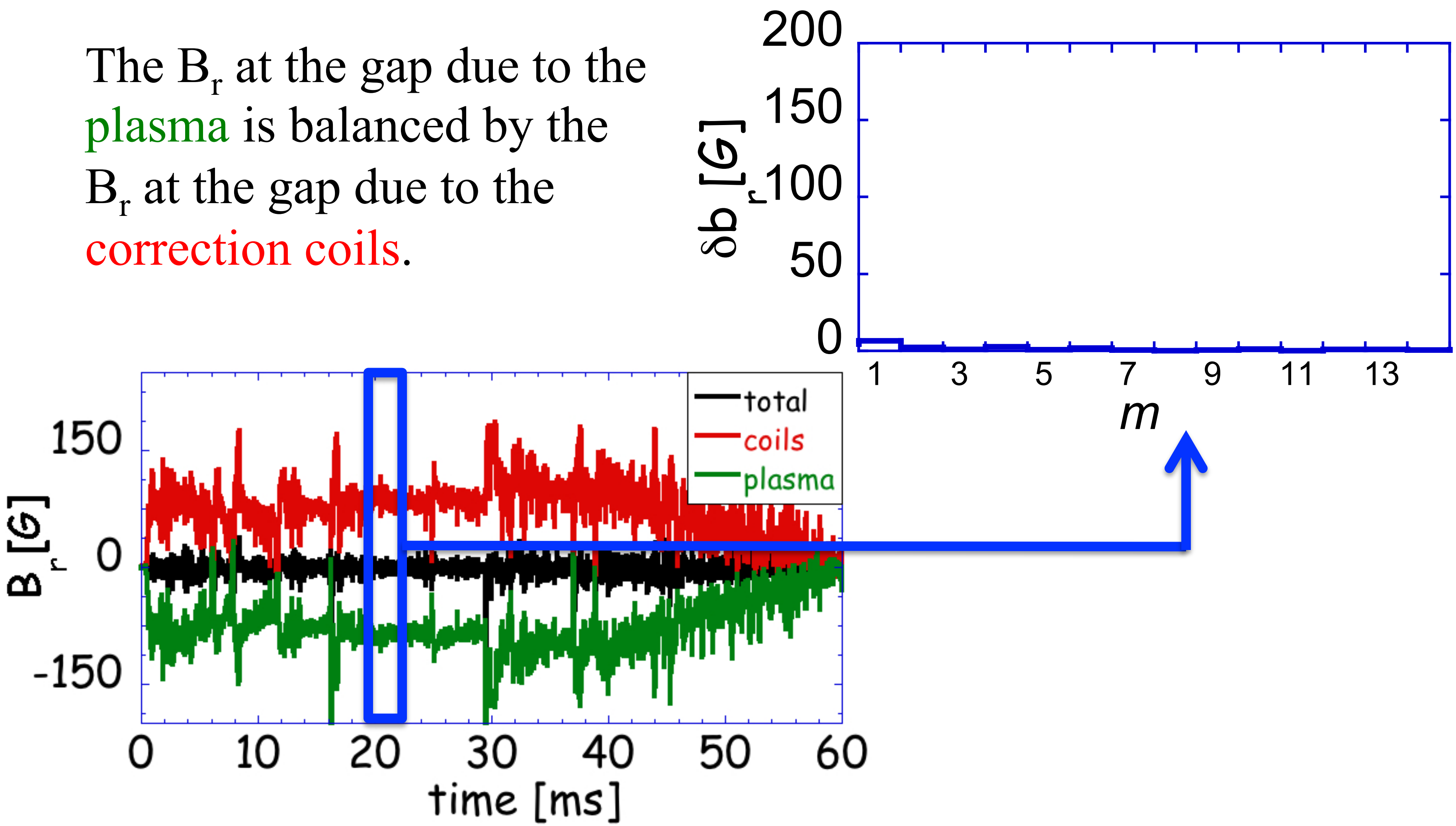


The Active Feedback system scheme



Active feedback is normally used to minimize the error fields

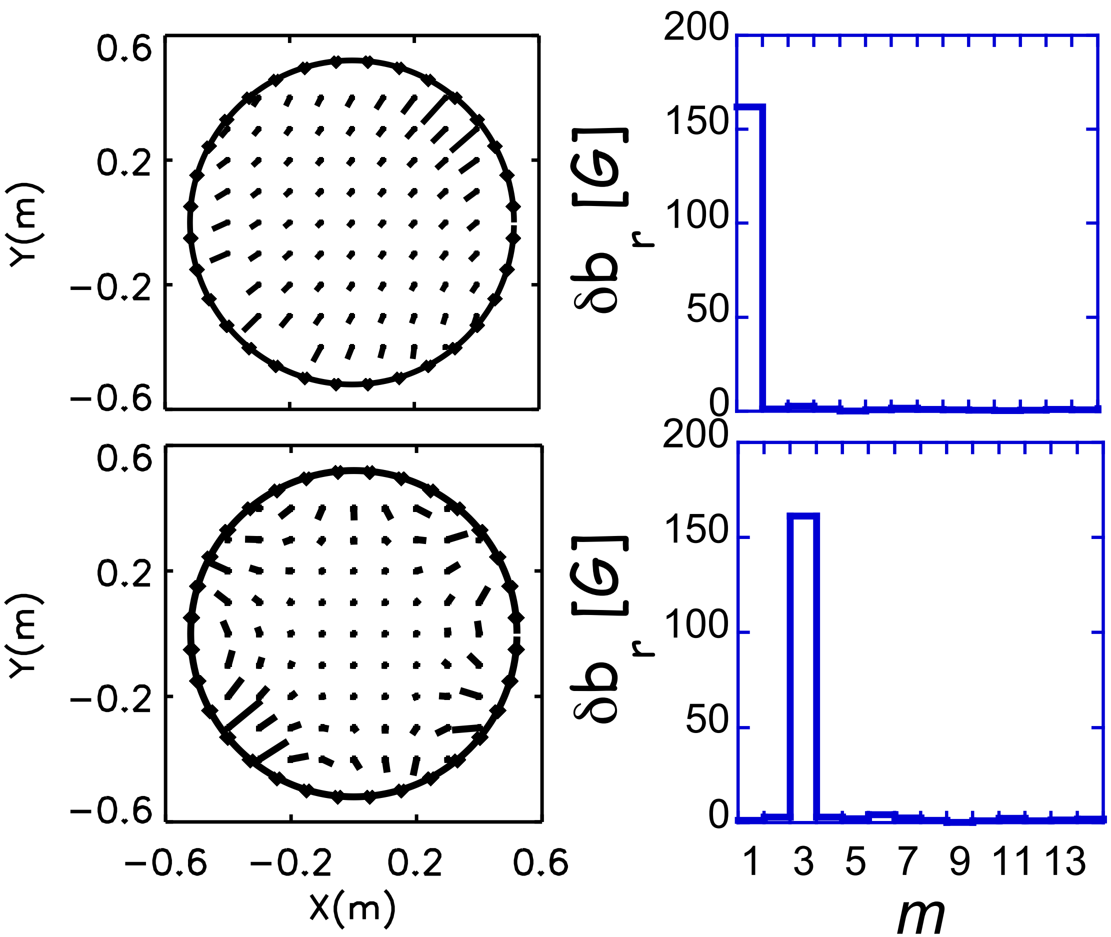
The B_r at the gap due to the plasma is balanced by the B_r at the gap due to the correction coils.



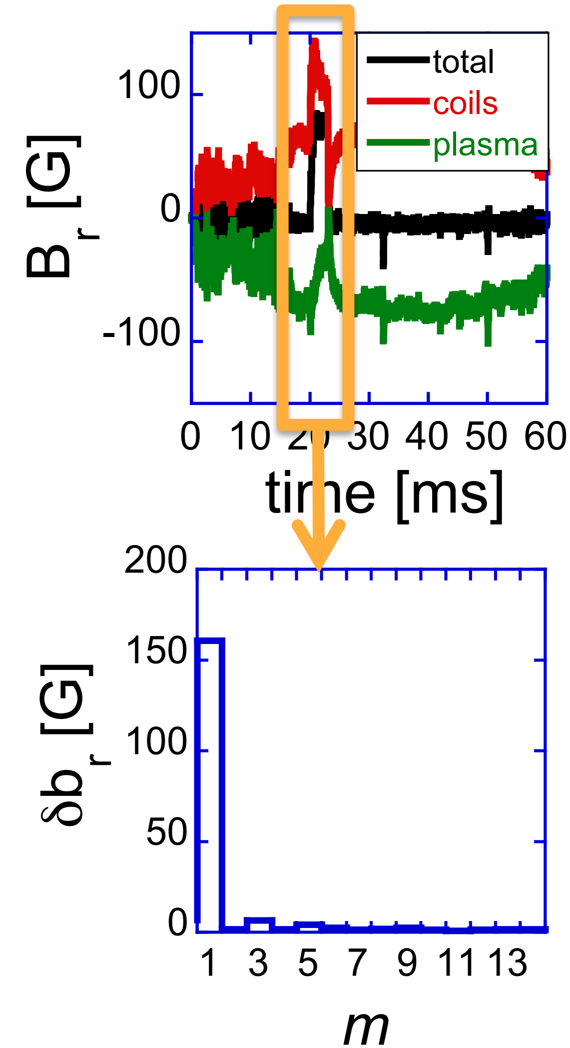
Active feedback used to produce RMPs - *m* spectrum

The *m* component produced by the RMP is well defined

in vacuum



in plasma



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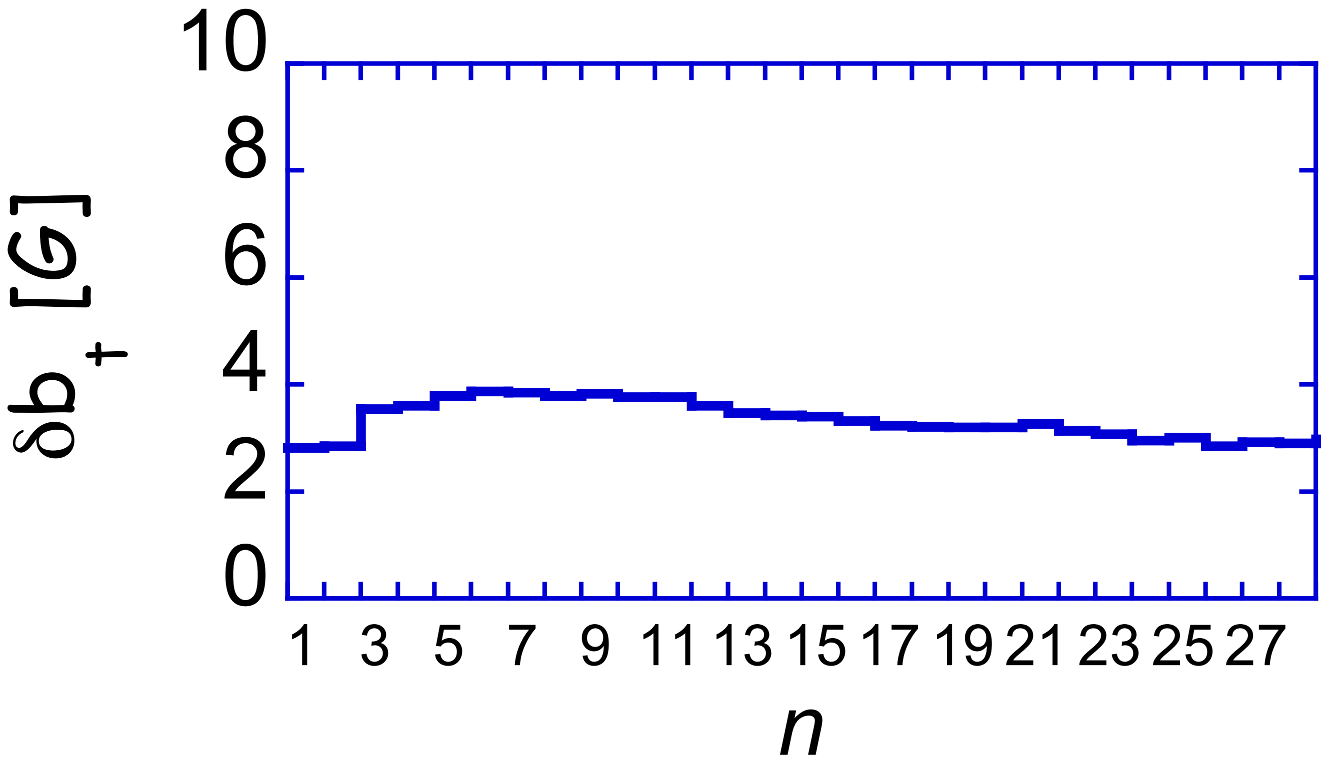
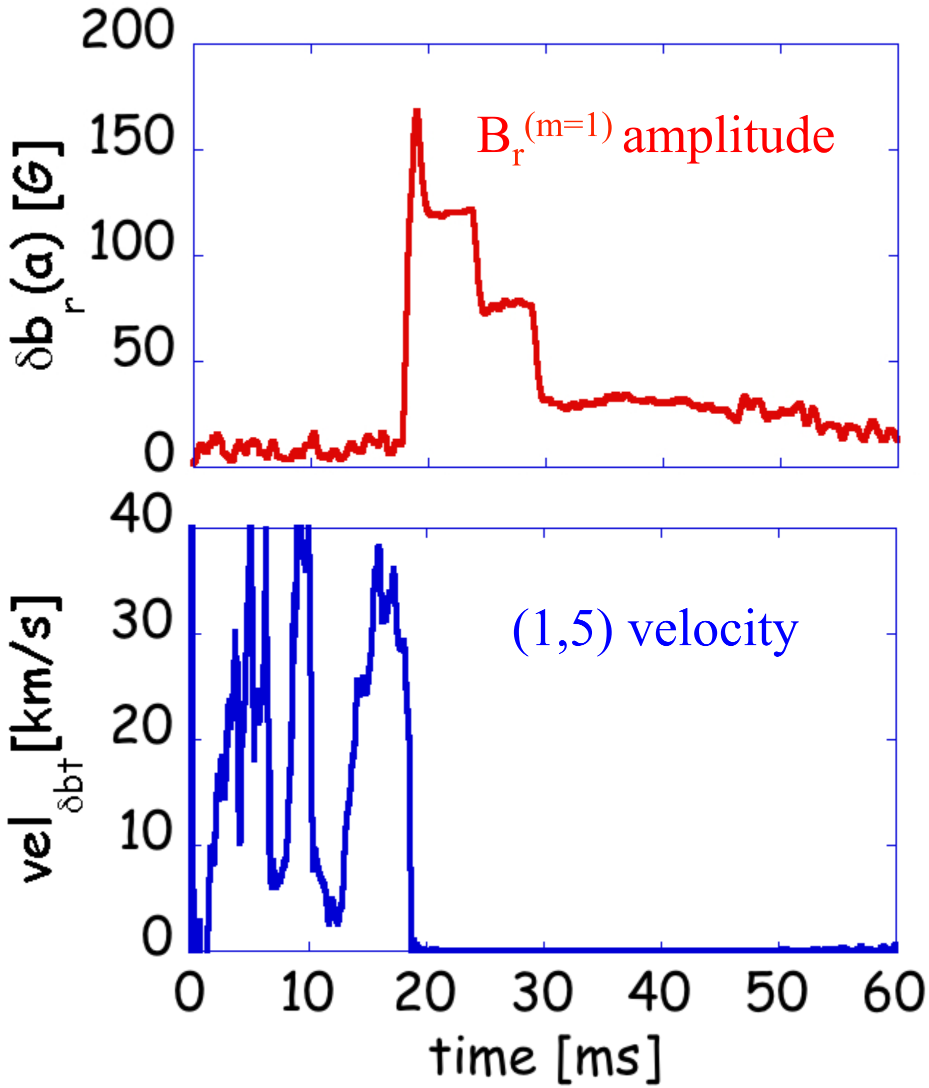


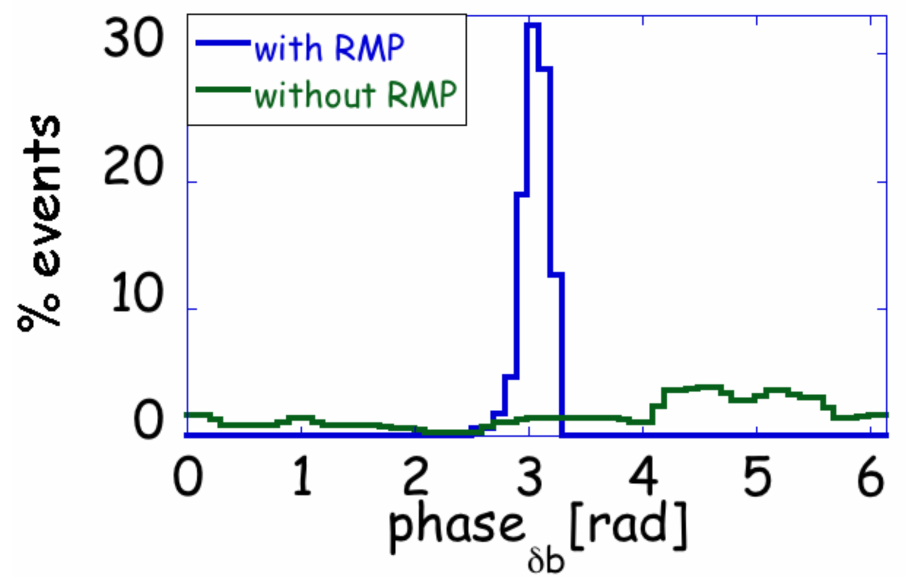
The RMP *n* spectrum is broad due to the vertical gap in front of the correction coils.

3. USE OF THE RMP FOR ORIENTATION CONTROL

m=1 RMP to lock the QSH



RMP couples with the m=1 tearing modes producing an electromagnetic torque

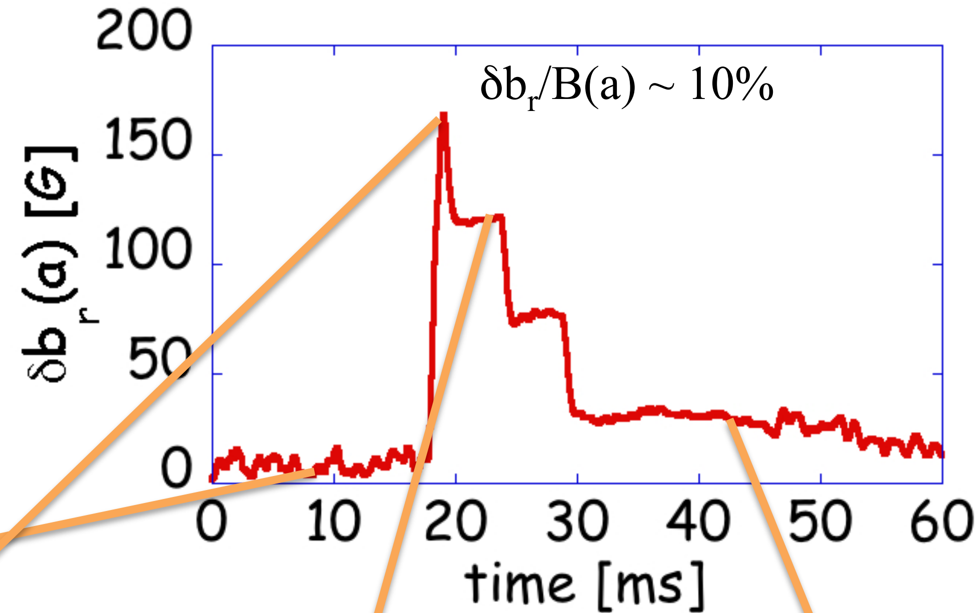


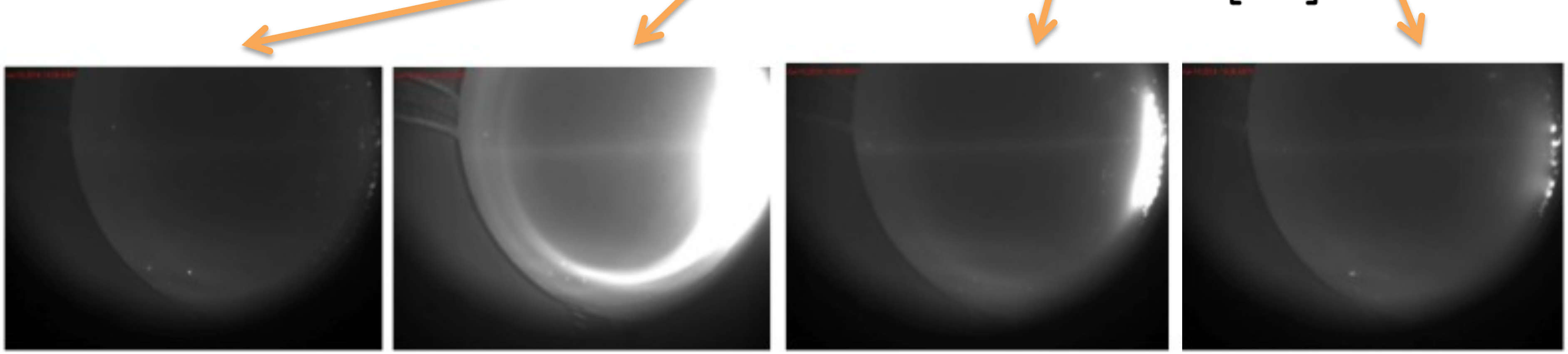
At the RMP application corresponds a strong PWI

Visible and IR emission observed at the vertical gap

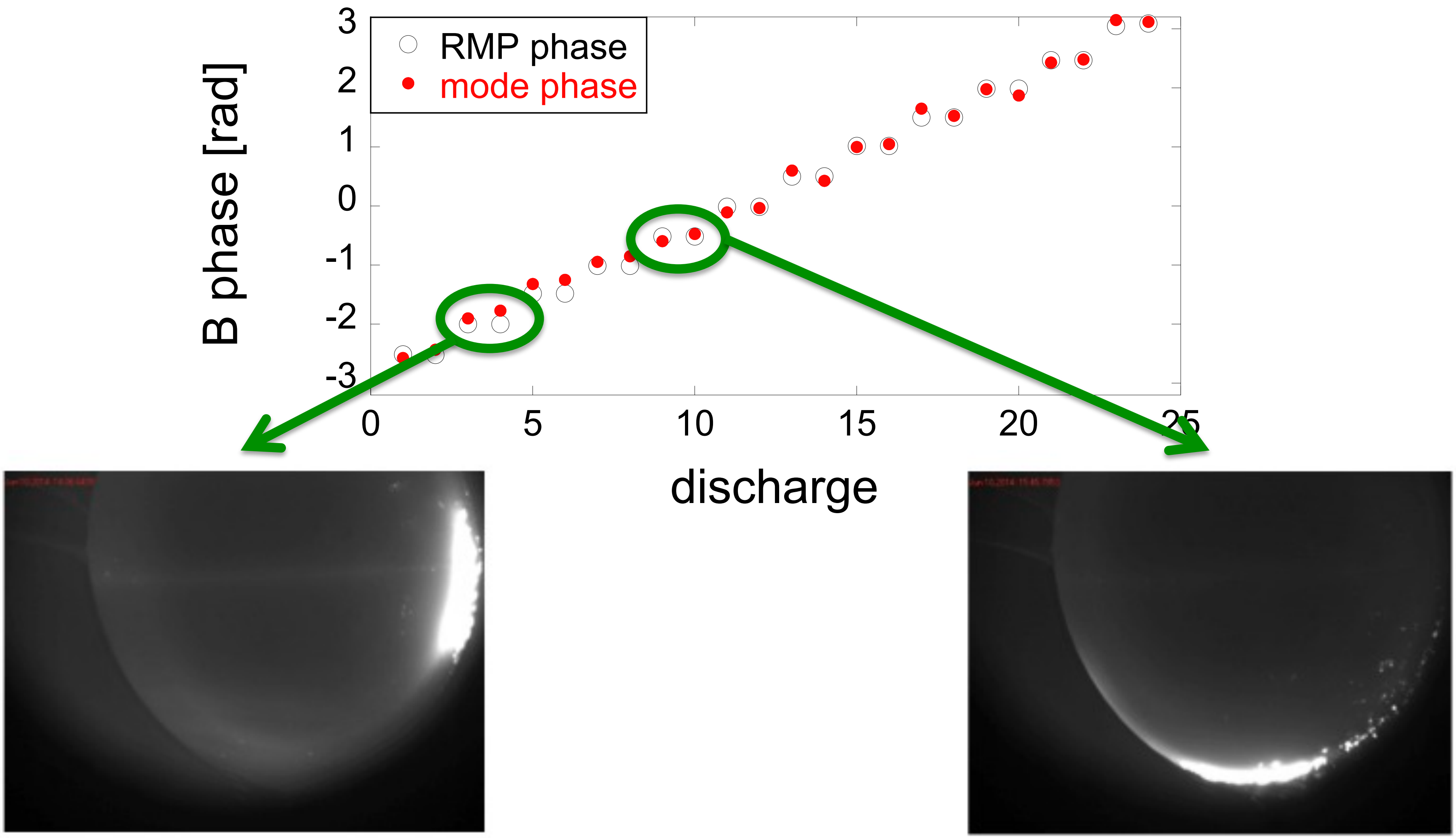
Strong emission during strong applied RMP periods

No impurities increase observed

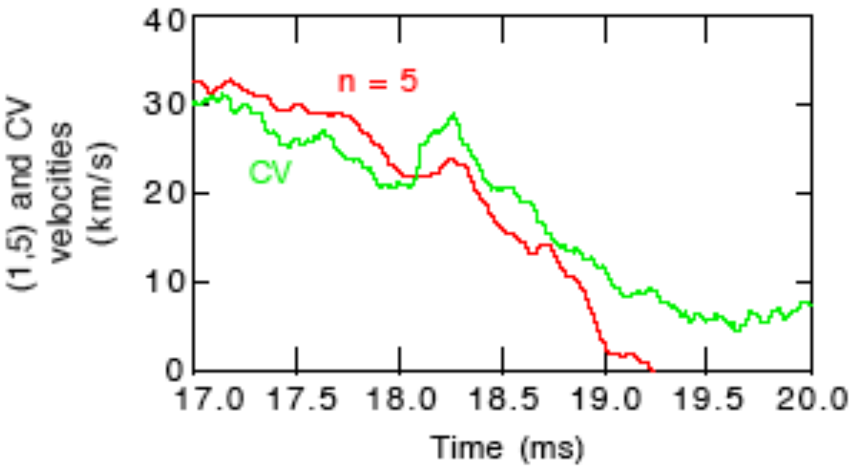




The applied RMP locks the structure at any desired angle

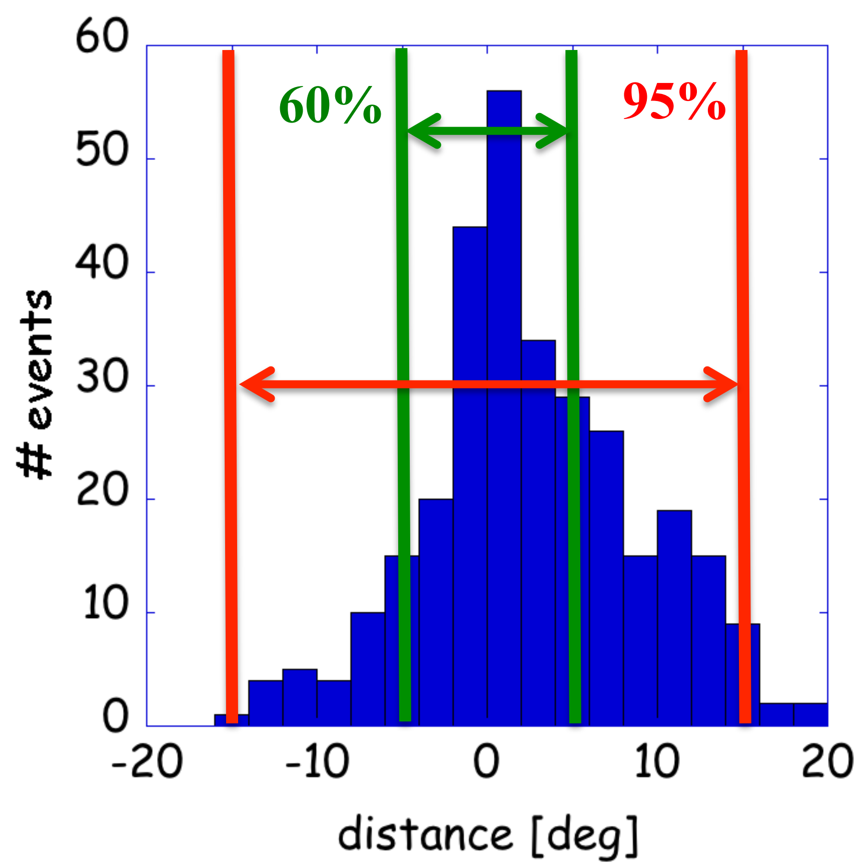


Optimizing RMP duration



A RMP of at least 8 ms is usually applied.

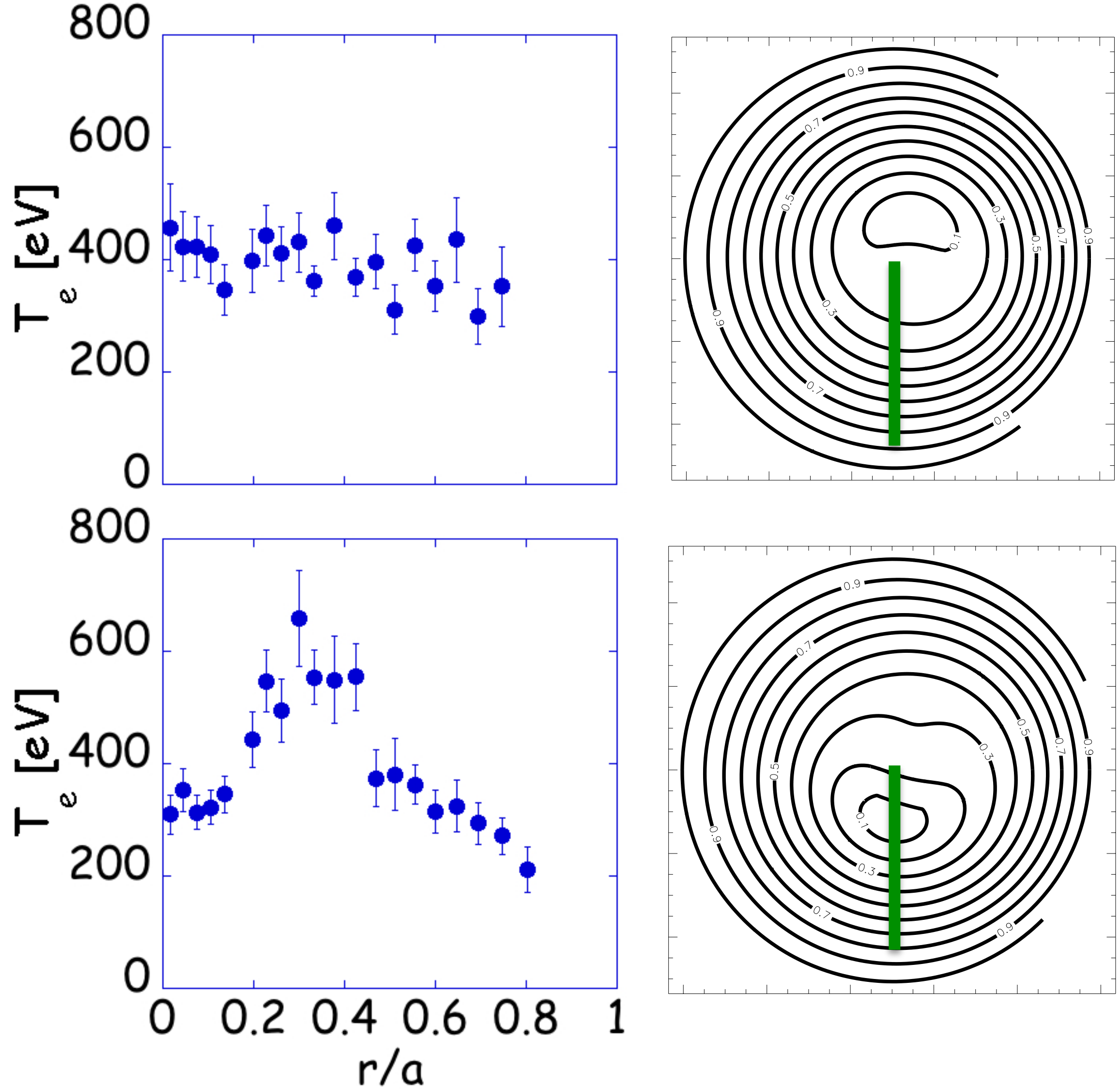
The longer the RMP is applied the less the mode drifts away from the requested phase.



4. APPLICATION OF RMP FOR THERMAL STRUCTURES STUDY

T_e profile with helix locked in front of the Thomson Scattering

TS provides T_e measurements from the bottom of the machine to the geometrical axis



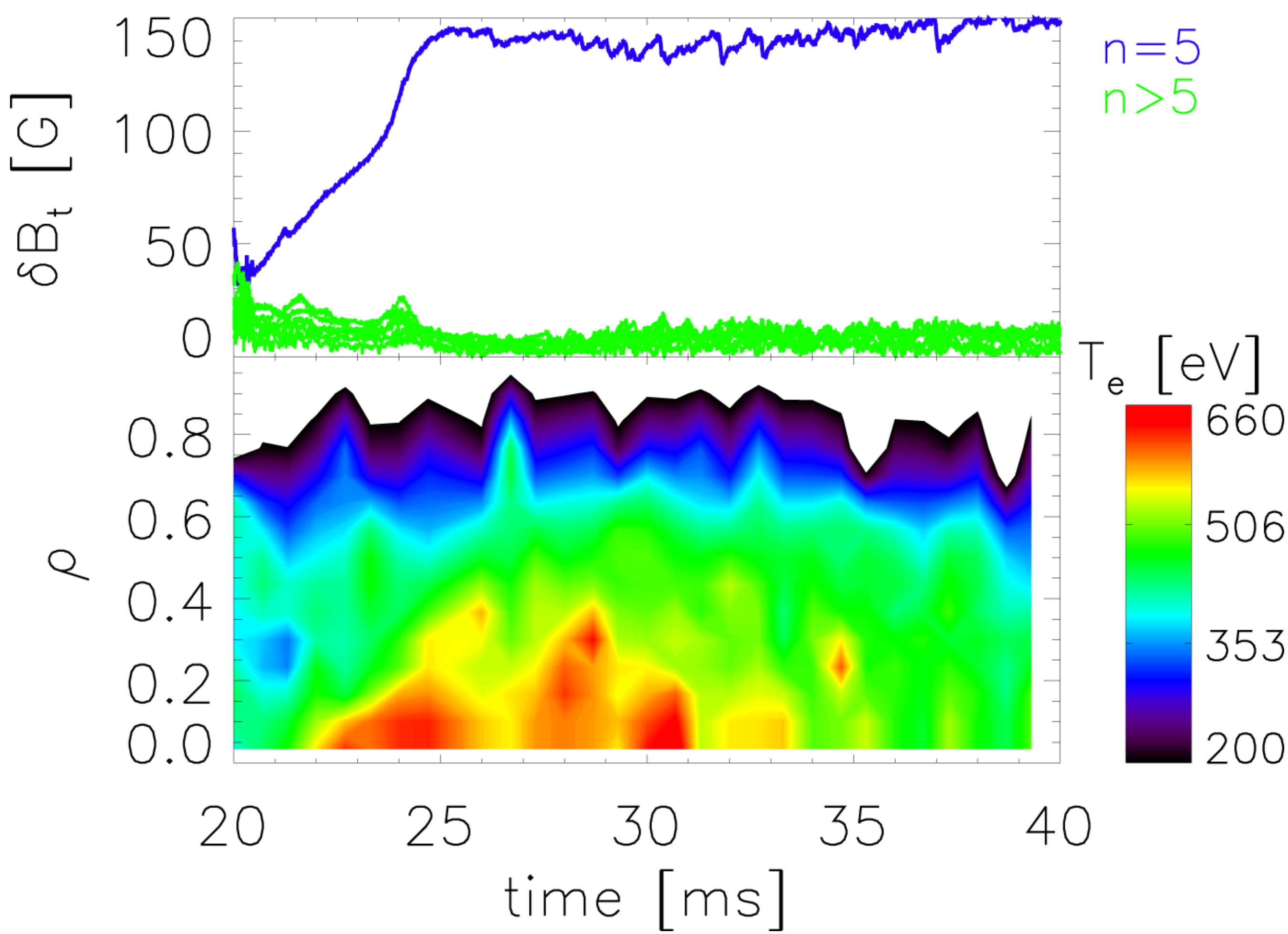
A thermal structure arises during QSH formation and disappears

TS allows up to 25 kHz for 30 time points per discharge

a structure emerges during the growing of the QSH

the structure is intermittent during the flat-top

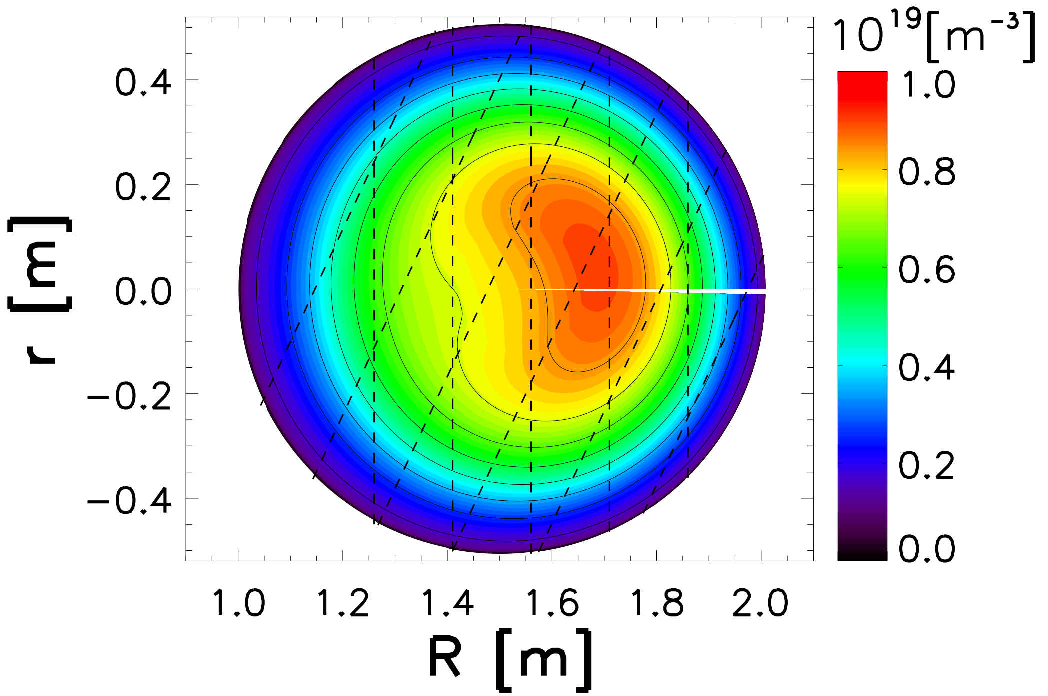
it vanishes before the end of the QSH

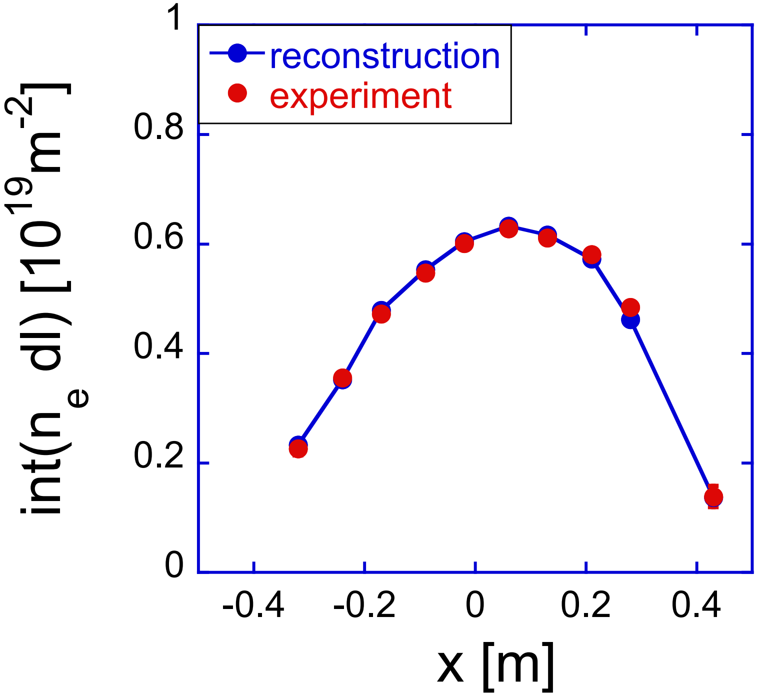


Electron density is obtained from interferometric measurements

11 chords in two adjacent toroidal positions

density reconstructions mapping data on flux surfaces

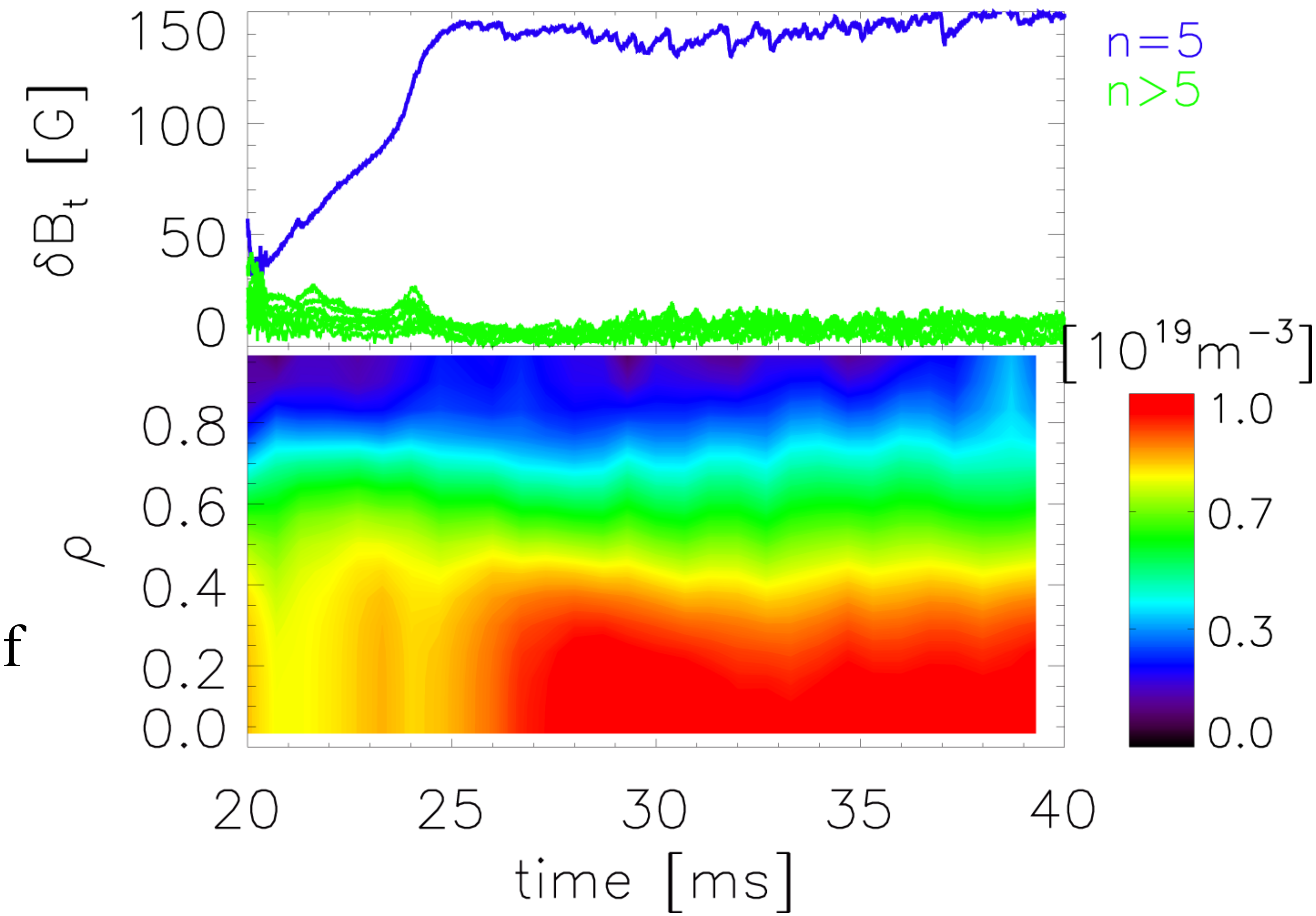




The density structure persists throughout QSH

Electron density increases in the core once the QSH is well established

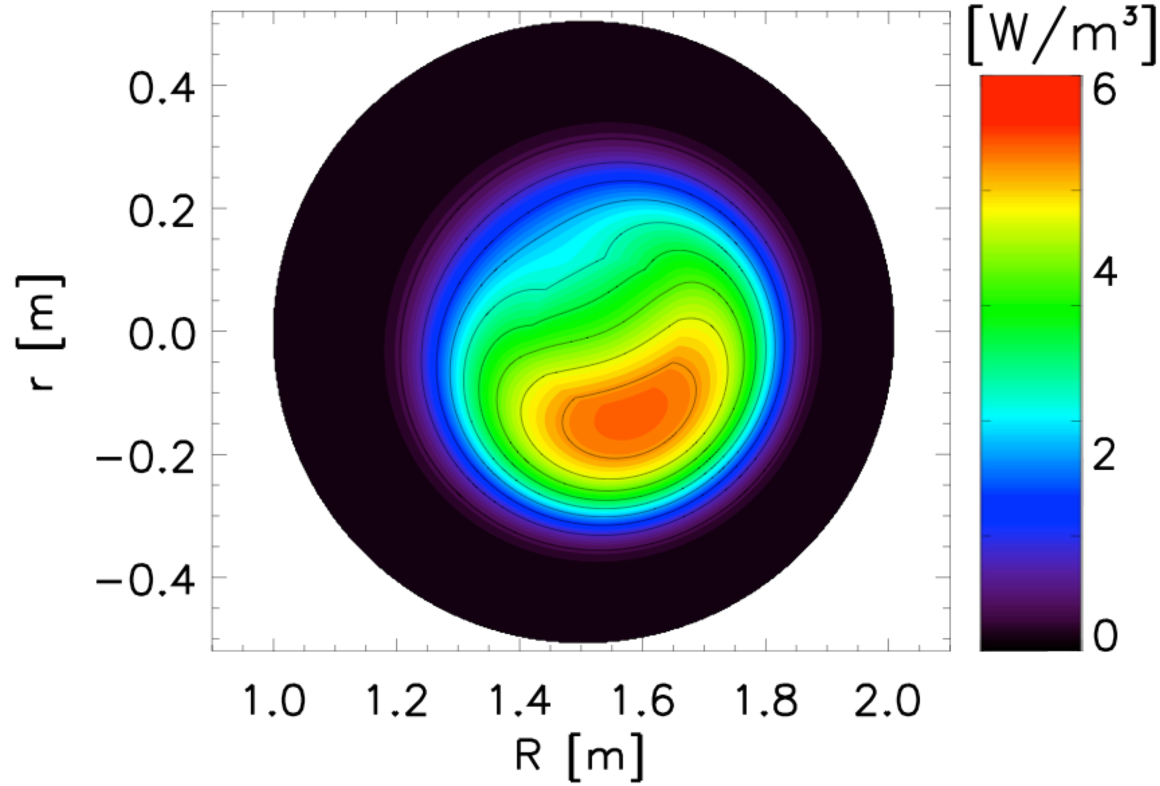
It persists for the whole duration of the QSH



SXR tomographic reconstructions

40 lines of sight divided between 2 cameras at the same toroidal position

SXR emissivity reconstructions as function of the flux surfaces

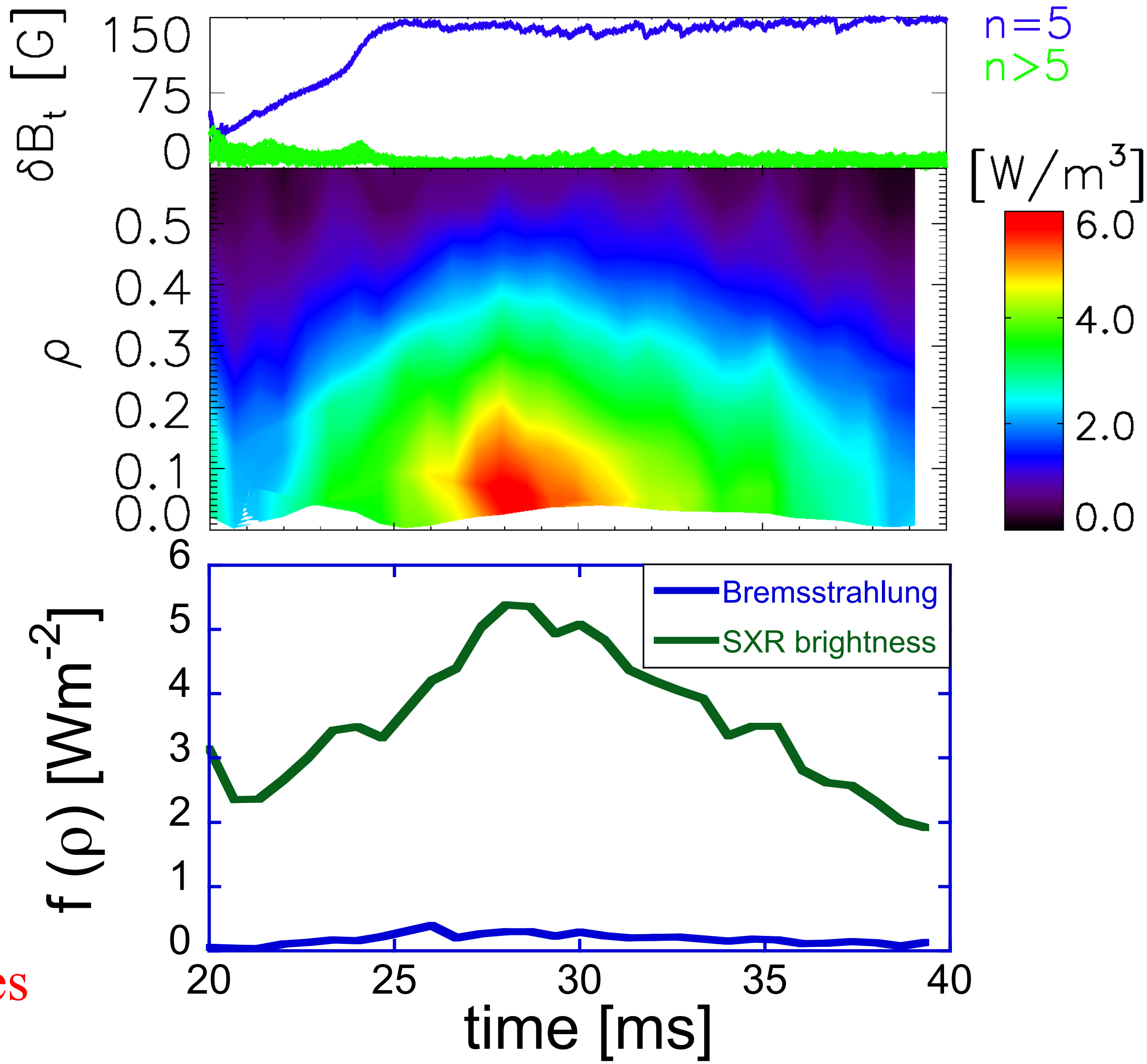


SXR emission is mostly from impurities

A peak in the SXR brightness is observed during the QSH flat–top

Due to the low T_e, thin Be filters are required

Emissivity signal only from impurities

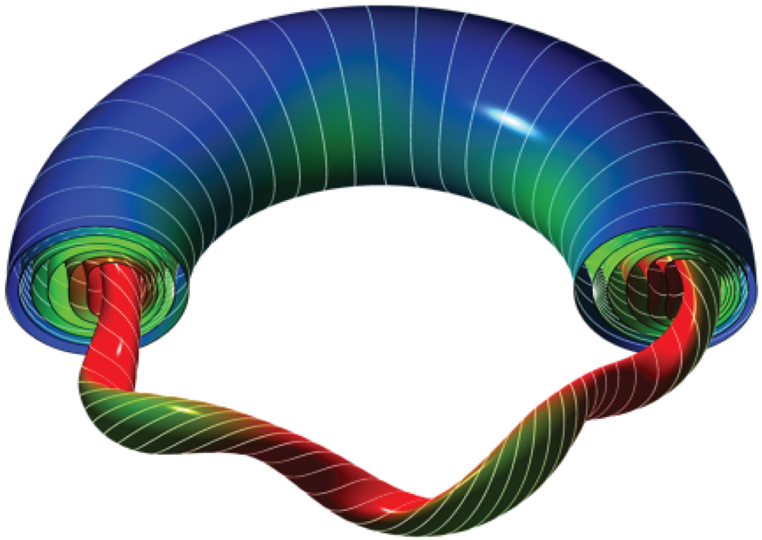


TS, FIR and SXR are good constraints to perform equilibrium reconstruction

V3FIT

The code tries the best fit of VMEC equilibrium and several diagnostics to perform equilibrium reconstruction in 3D plasmas.

Hanson et al, Nucl. Fusion 2009



- Magnetic reconstruction with fixed boundary successfully applied.

The orientation control allows the positioning of the helix in a sweet spot for all these 3 diagnostic together.

- Recently conducting shell boundary implemented to better fit temperature and density profiles.

5. RUNAWAY ELECTRON SUPPRESSION WITH RMP

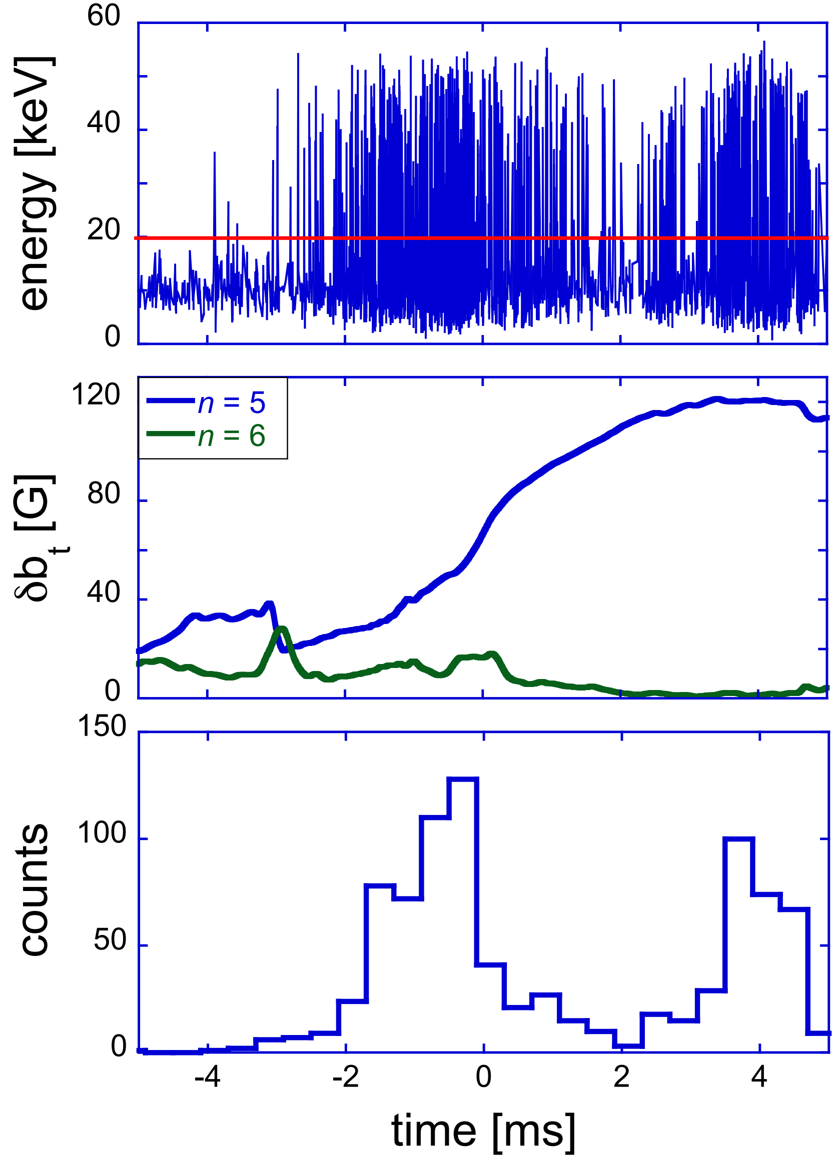
High energy electrons are generated during the formation of the QSH

The detector is set up to observe X-rays with energy in the range from ~ 10 to 50 keV.

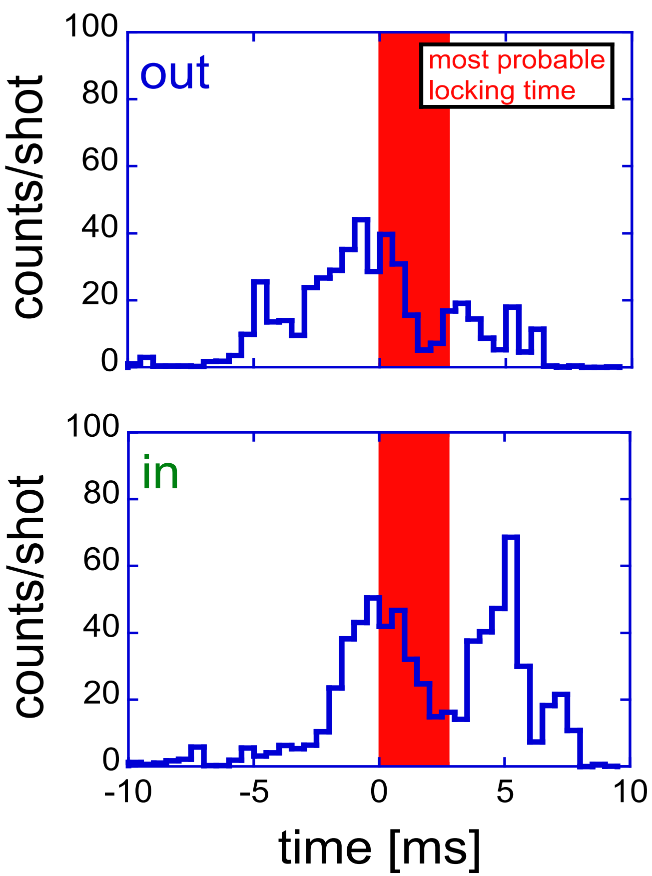
Any spike in the signal corresponds to a detected X-ray.

An increase of X-ray detection is associated with the transition to a QSH state

Data analysis done counting the X-rays with energy > 20 keV detected within 0.5 ms interval.



Phase dependence of the high energy X-ray detection



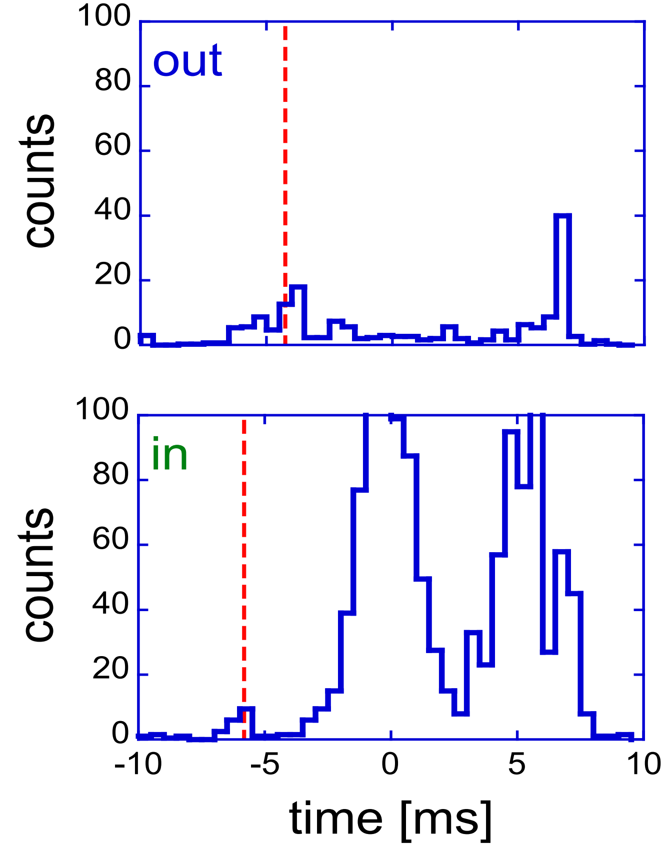
The detection of high energy X-rays is affected by the 3D nature of the QSH state.

RMP is not applied

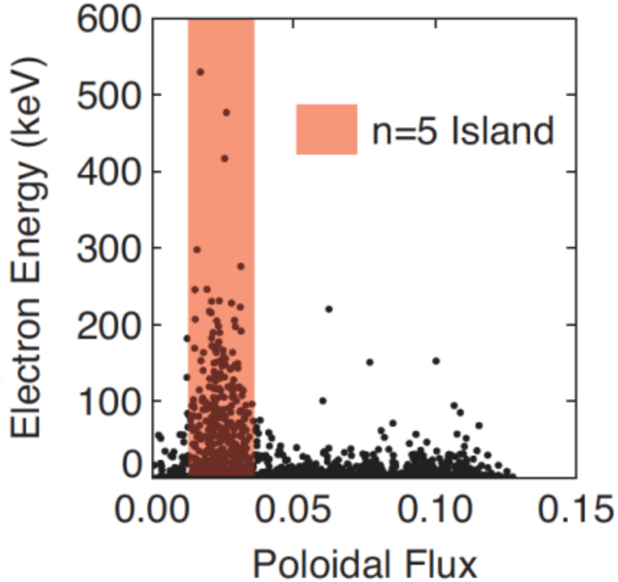
The mode locking usually happens after t = 0

When the modes are locked before the transition takes place the phase dependence is more clear.

Early locking time (single shot)



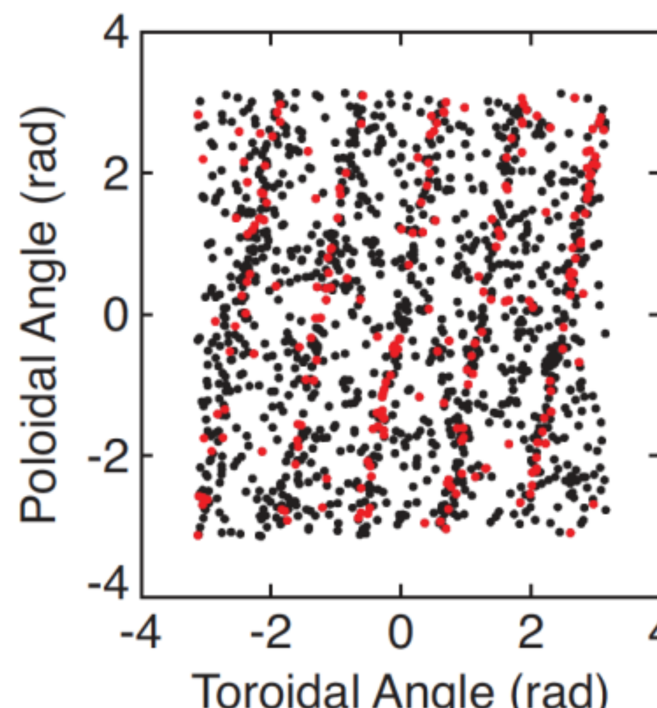
Simulations predict the presence of high energy electrons inside the island



- 1k particles placed within the island
- Initial temperature of 250 eV.
- $E_{toroidal}$ = 1.5 V/m was applied.

After 2 ms when the particle trajectories were free to evolve:

1. The highest energy electron are located inside the island region
2. Particles with energy > 40 keV have a m=1,n=5 spatial distribution

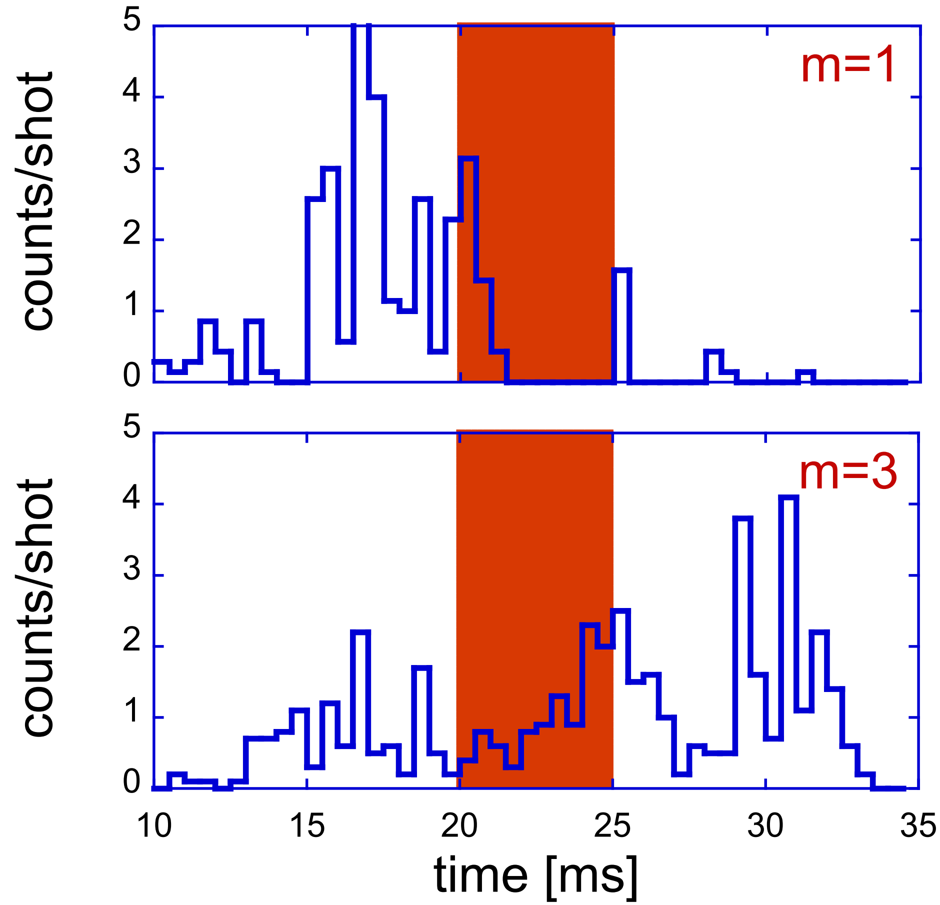


The presence of a m=1 magnetic perturbation suppresses the RE

As observed in several Tokamak experiments, also in MST RMPs inhibit the presence of high energy electrons

The generation of these electrons is unaffected by non-resonant perturbations.

The suppression of the high energy electrons only by resonant perturbations may reflect a change to the central magnetic topology.



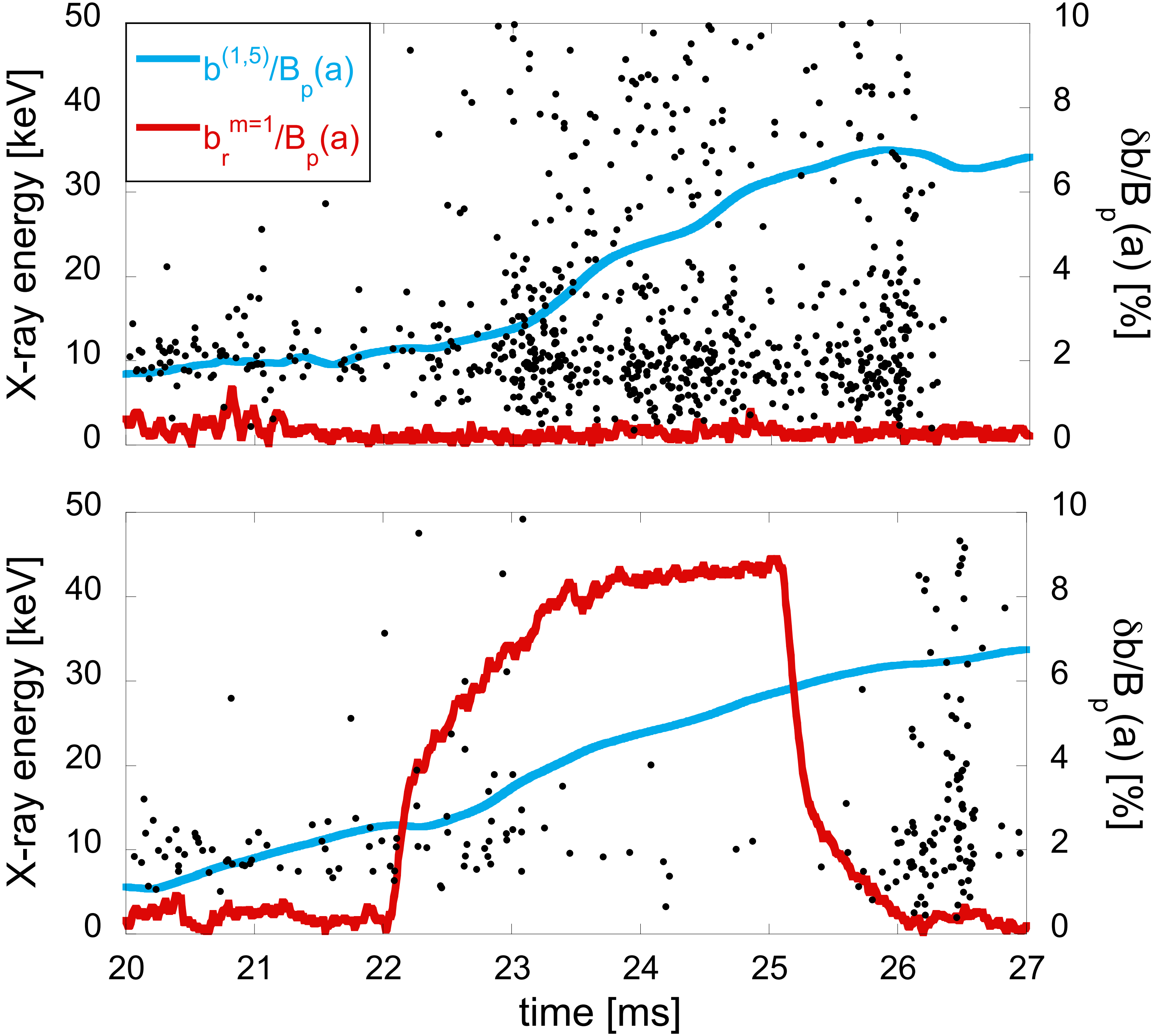
Summary

i. In RFP at high I_p the equilibrium becomes 3D

ii. Active feedback system used to generate RMP that controls orientation of the helix

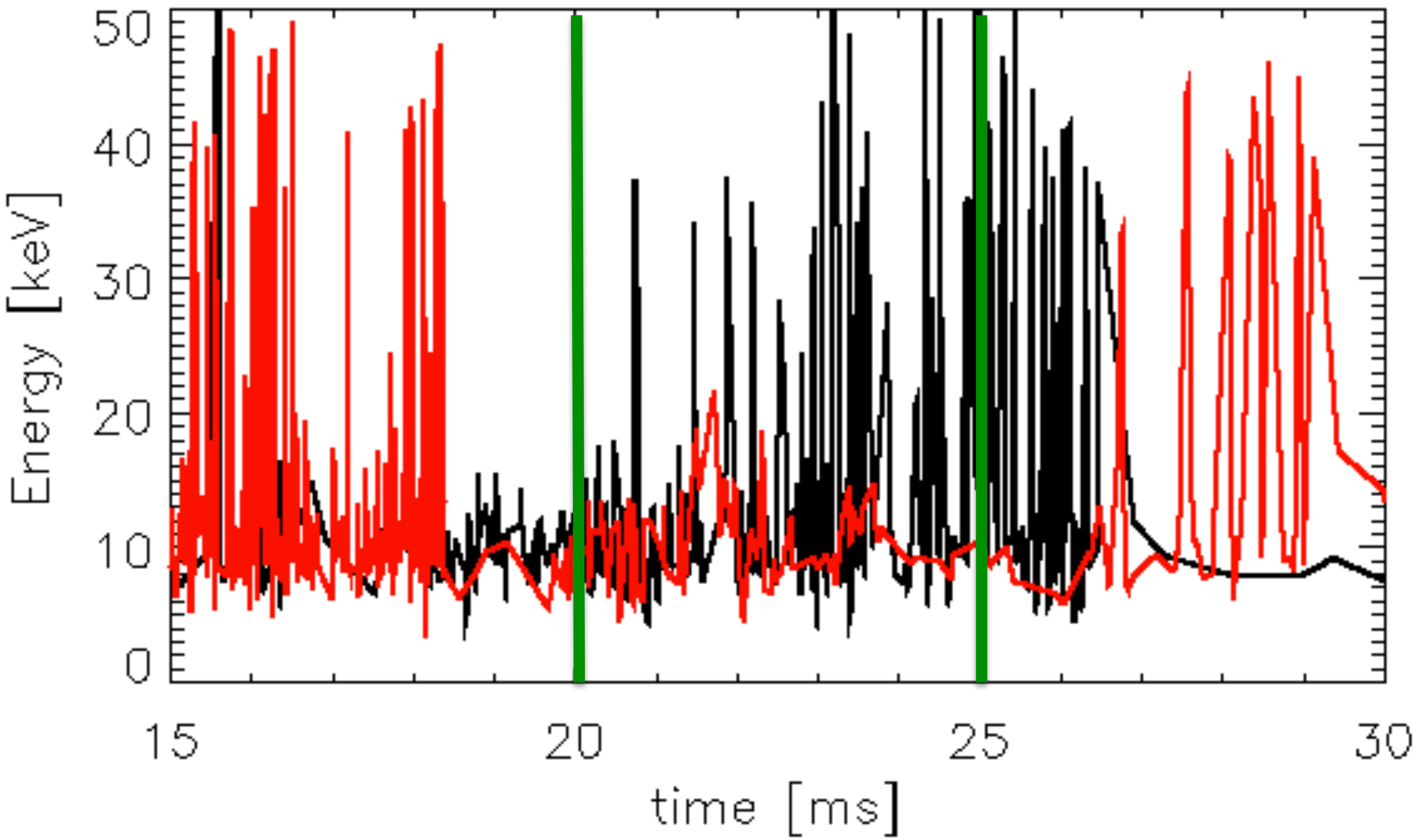
iii. Orientation control used to study time evolution of thermal structures

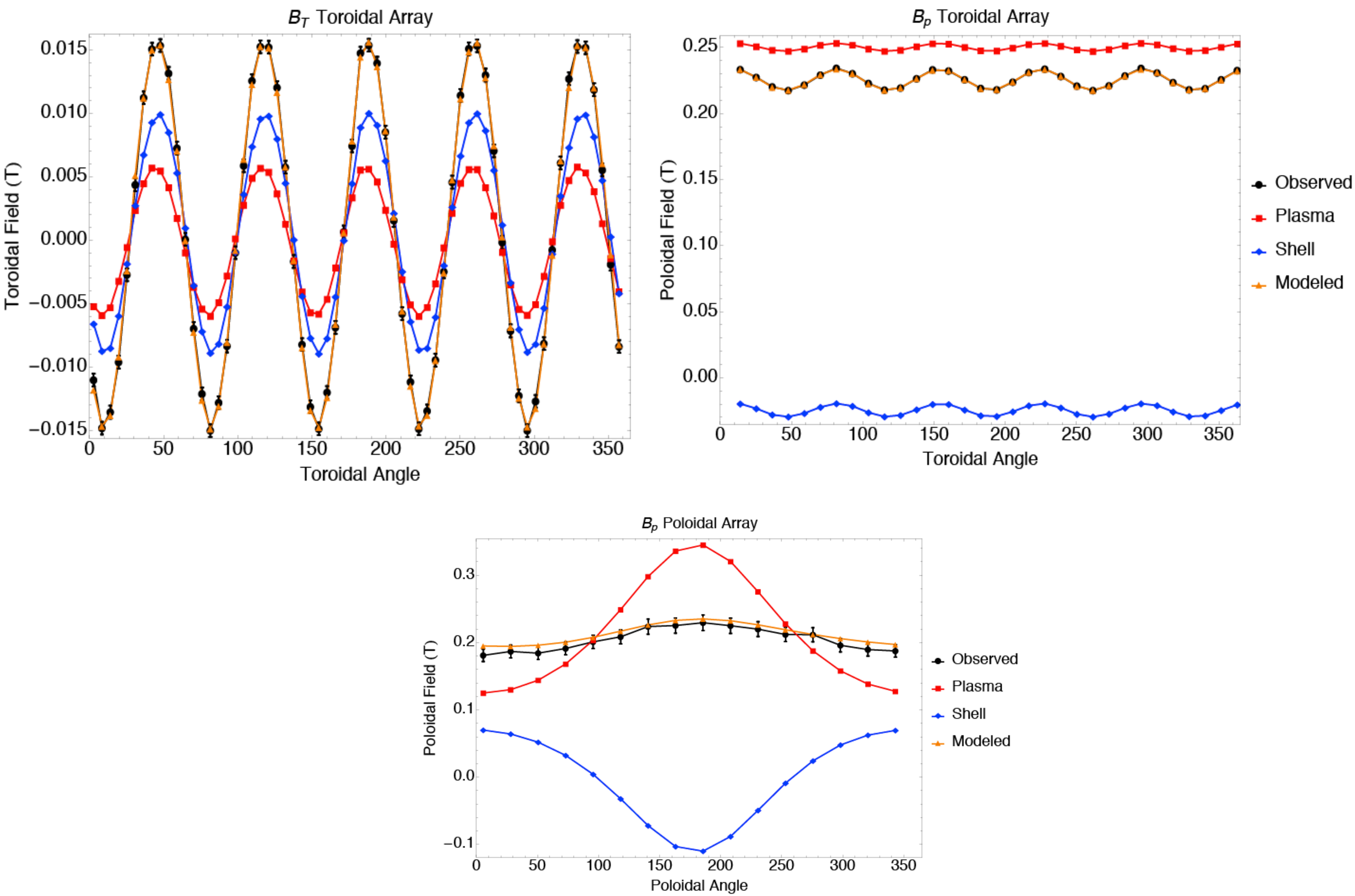
iv. RMP may change the central magnetic topology



X-ray energy [keV]
δb/B$_p$(a) [%]
$b^{(1,5)}/B_p(a)$
$b_r^{m=1}/B_p(a)$
time [ms]

m=1 and m=3 single shot comparison




B_T Toroidal Array
Toroidal Field (T)
Toroidal Angle
B_p Toroidal Array
Poloidal Field (T)
Toroidal Angle
Observed
Plasma
Shell
Modeled
B_p Poloidal Array
Poloidal Field (T)
Poloidal Angle
Observed
Plasma
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