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Fishbones and their Impacts on Core Confinement in MAST and MAST-U

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(5) Durham University, (6) Swiss Plasma Center EPFL, (7) Tokamak Energy

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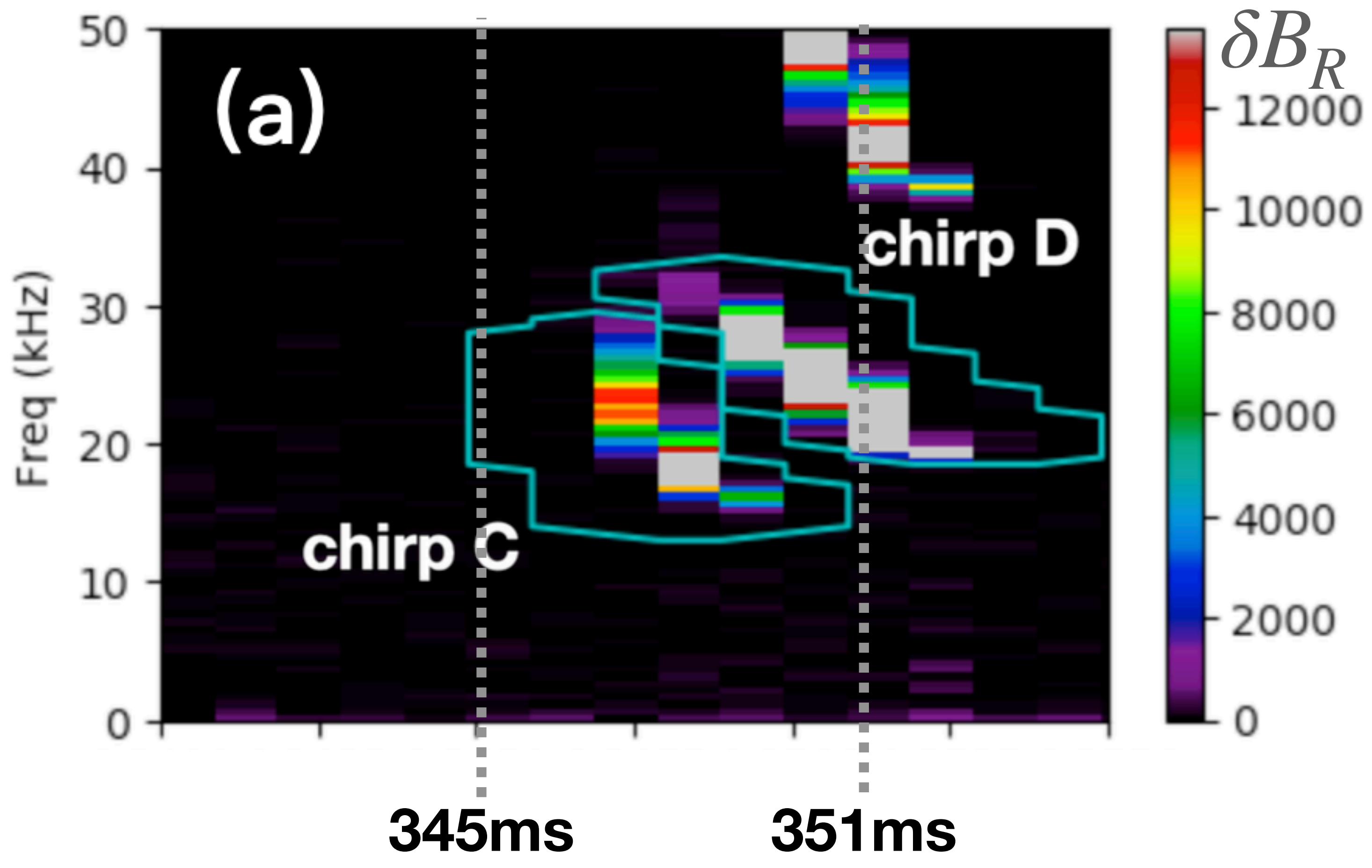
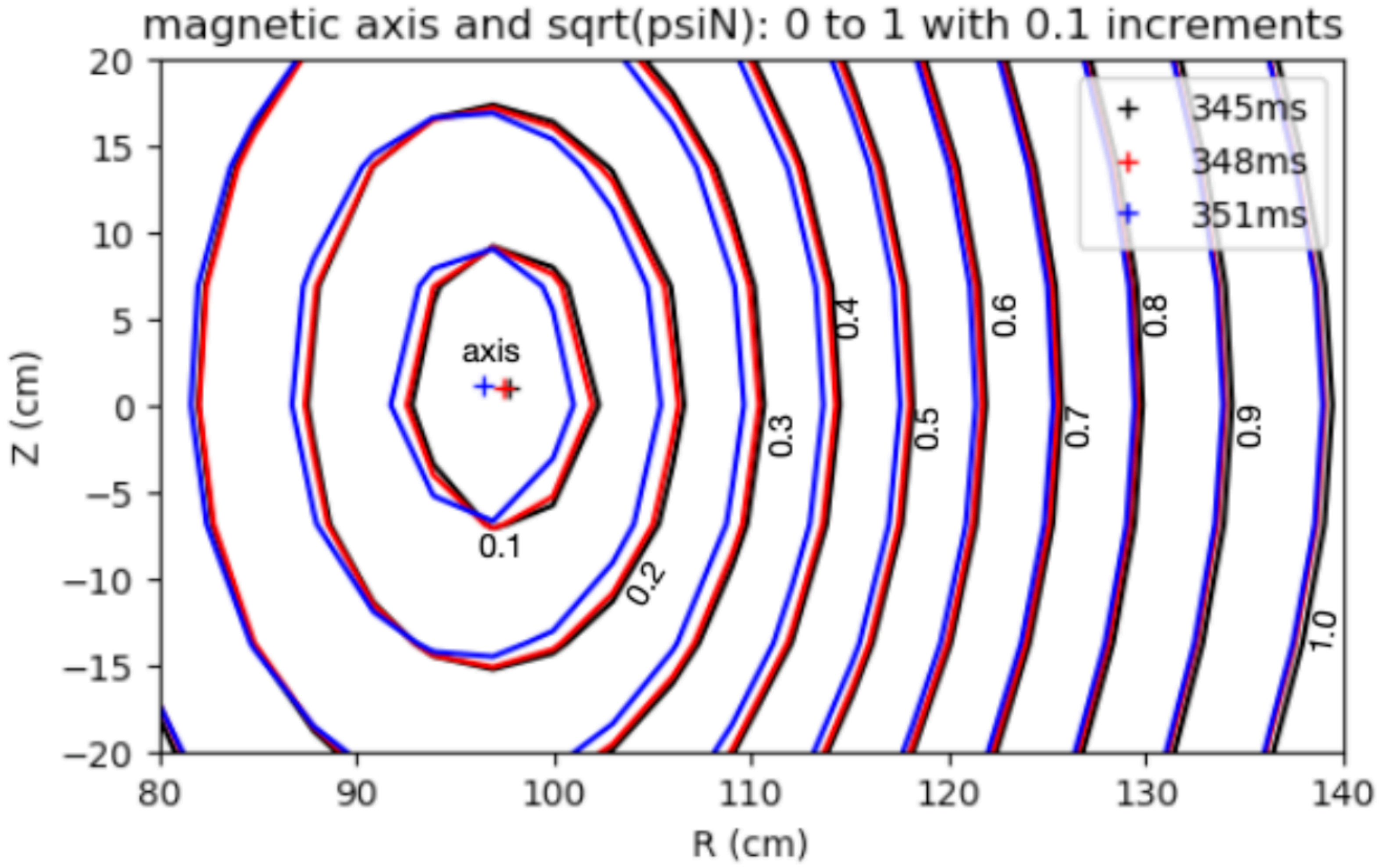
Summary: some fishbone instabilities in MAST/-U cause <u>both</u> fast and thermal species transports

- MAST - temporal phase variation between signals from two spatial separated diagnostics
- MAST-U - observe it again, alongside evidences of <u>significant fast ion and thermal species transports</u> and <u>equilibrium crashes</u>
  - (1,1)-kink , even-m mode-mode interactions cause the most significant crashes and transports among the FBs
- the even-m modes could possibly be:
  - (n,m) = (1,2) tearing mode
  - n > 1 modes (e.g. sawtooth, infernal modes)





Background on fishbone (FB) instabilities

- **kink mode being destabilized by beam-induced fast ions**
- kink modes could appear with or without $q = 1$ surface:
  - internal kink: $|q_{min}| < 1.0$
  - infernal kink / interchange mode: $|q_{min}|$ slightly above 1
    - usually $|q_{min}| \sim 1.1$ but we found infernal-like FBs with $|q_{min}| \sim 1.2$ (**high!**)

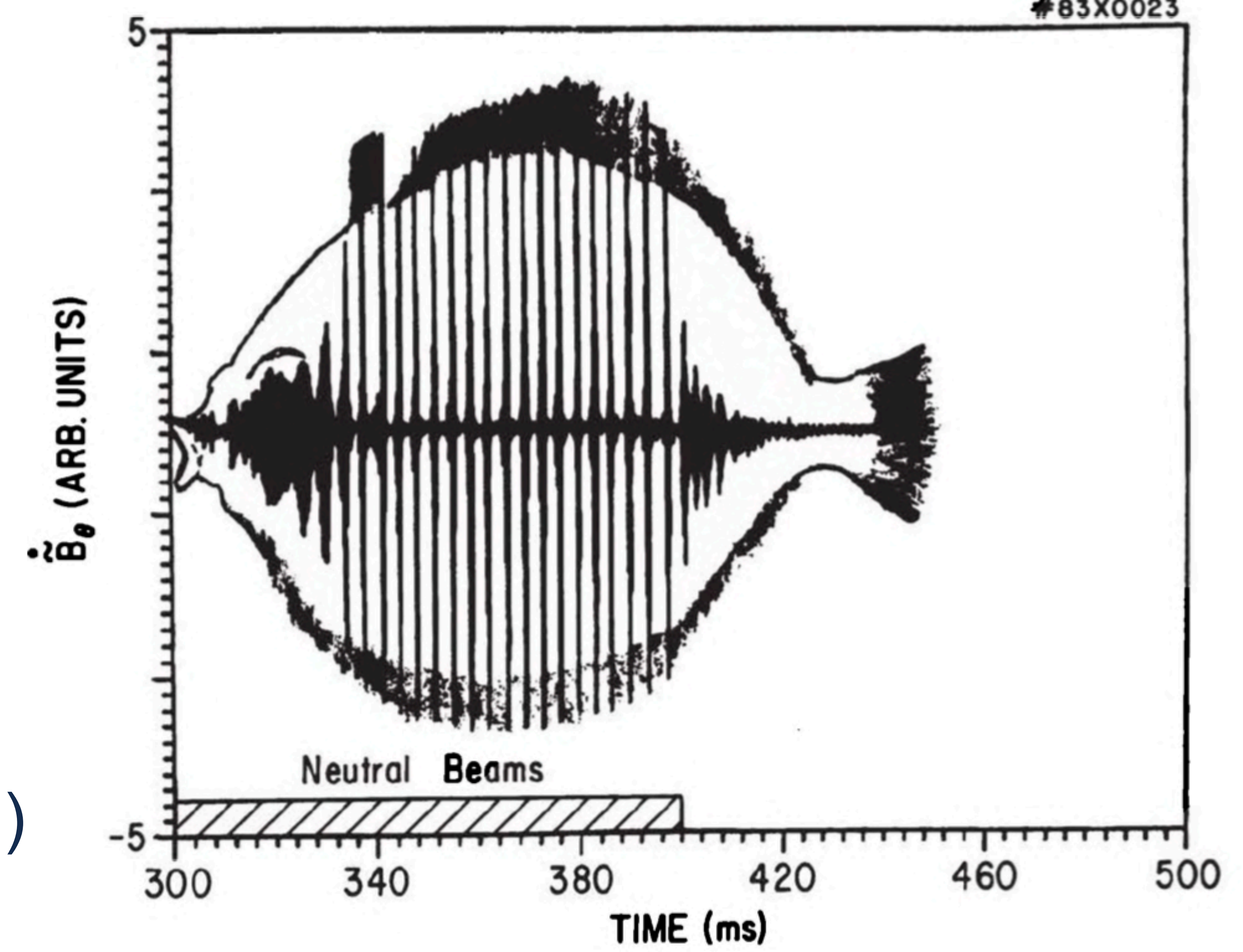


Fig. 6.1 Mirnov signal during fishbone mode, outline added by artist.

(R.B. White 2001)

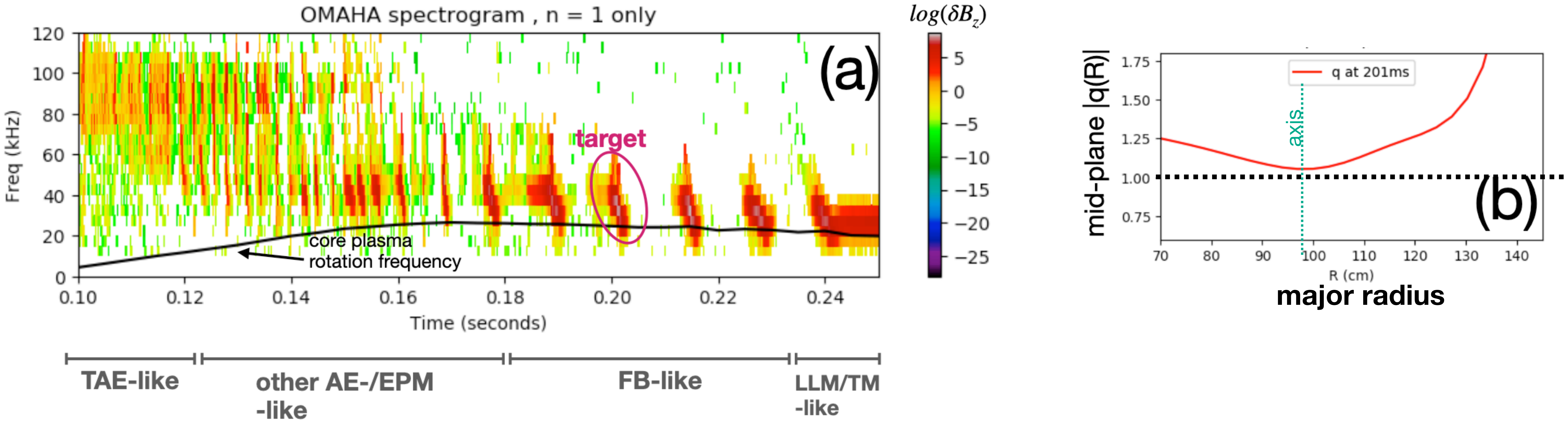
Why care about FB?

- cause fast ion transport/losses -> degrade fusion effectiveness + losses could damage wall components
- thermal transport (sometimes) -> affect core confinement and further reduce fusion effectiveness
  - also difficult to model

both internal and infernal kink regime FBs can be found in MAST plasma

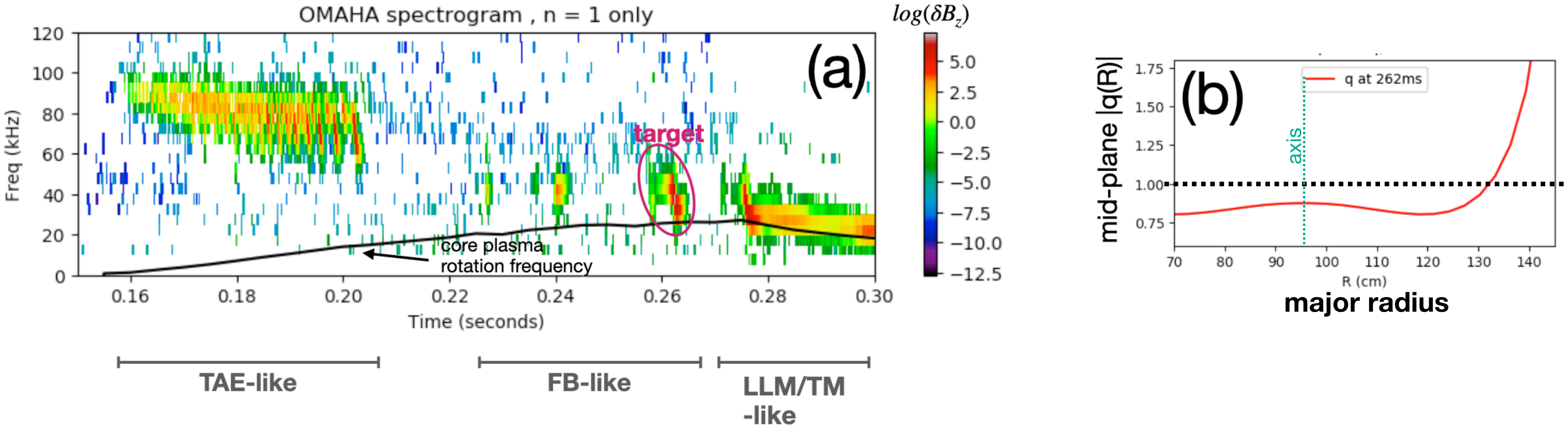
- similar in δB_z spectrograms (panels (a) and (b)), but different q profiles
- both FBs start at ~40kHz and then down chirping to ~20kHz (core rotation frequency)

MAST discharge 29976



- $|q_{min}| > 1$ (infernal-like)
- plasma current ~ 800kA
- beams power ~2.1MW SS, ~0.9MW SW

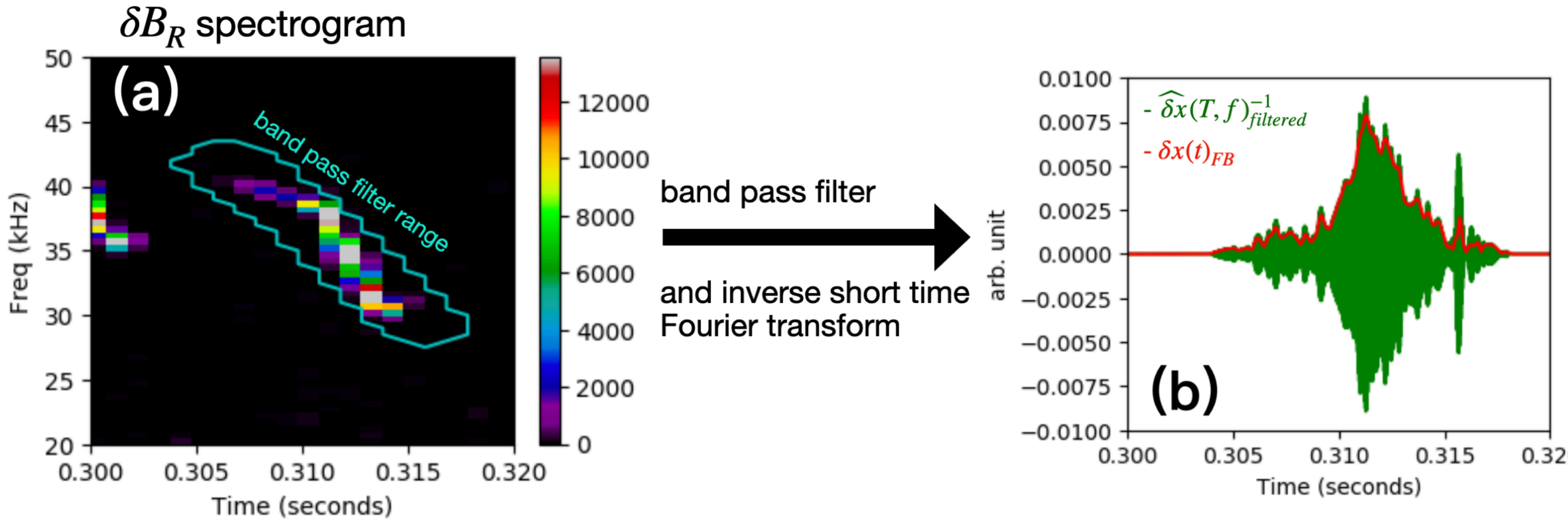
MAST discharge 26887



- $|q_{min}| < 1$ (internal-like)
- plasma current ~ 800kA
- beam power ~1.5MW

temporal phase variations (core SXR vs. edge δB_z) in MAST suggest distortion of mode

- SXR and BES structure measurements went through filters (band pass, linear regressions, etc) using δB as guideline
  - isolate global effects (by **eliminating turbulences**, etc)
  - **preserve phases between core SXR/BES vs. δB**

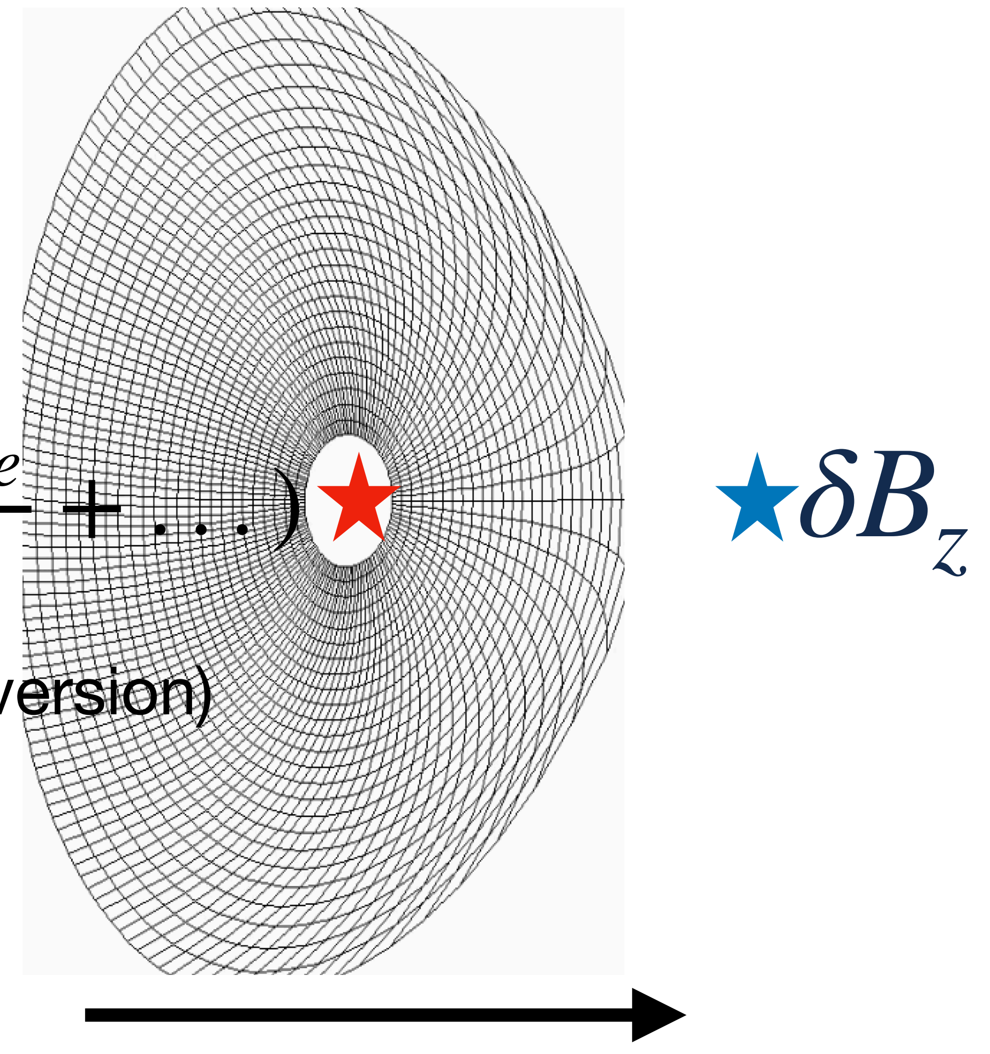


band pass filter

and inverse short time Fourier transform

- FB radial structures are typical -> peak around the axis
- (inverted) SXR - $\frac{\delta\epsilon}{\epsilon_0} = 2\frac{\delta n_e}{n_{e0}} + \left(\frac{1}{2}+\frac{E_{photon}}{T_{e0}}\right)\frac{\delta T_e}{T_{e0}} + \cancelto{\sim 0 \text{ for core}}{\frac{\delta Z_{eff}}{Z_{eff,0}}}$ near the core

- OMAHA - δB near edge
  - expect phase difference between radially separated measurements, but no temporal phase variation from linear theory with fixed equilibrium -> **distortion of mode**
  - **change in k_r and/or change in the equilibrium**



$$\delta\epsilon = \epsilon(2\frac{\delta n_e}{n_e} + \ldots)$$

(after inversion)

★δB_z

major radius

temporal phase variations (core SXR vs. edge δB_z) in MAST suggest distortion of mode (continued)

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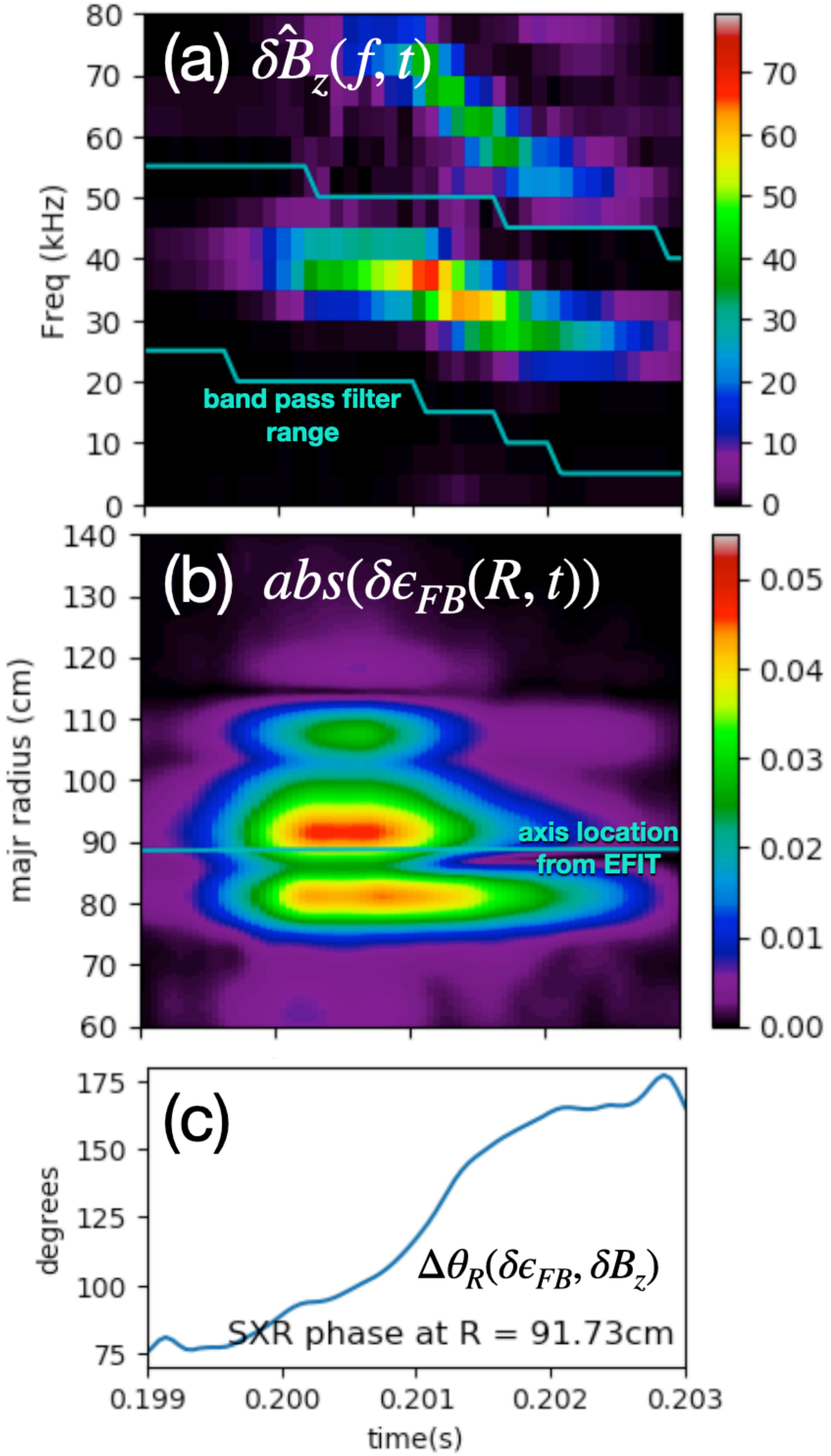
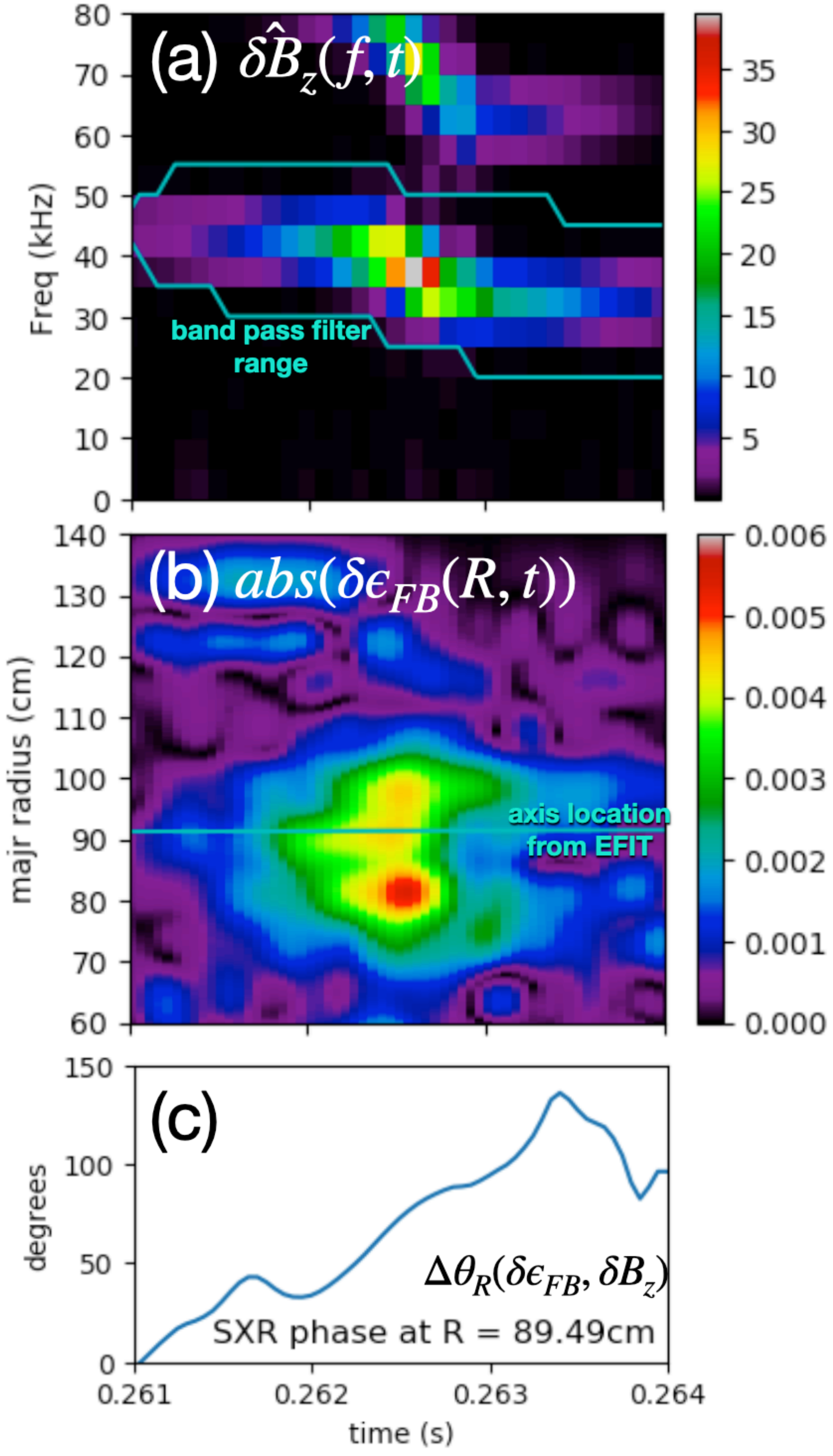
$q_{min} > 1$

MAST discharge 29976



$q_{min} < 1$

MAST discharge 26887



- distortions near the axis in both infernal and internal kink-like cases
- distortions are unlikely to be the results of beating/interaction with higher n modes due to sophisticated band-pass filtering
- both have dominated toroidal mode number n = 1 and mode associated fluctuations peak near the axis
  - -> both are **on-axis FBs**

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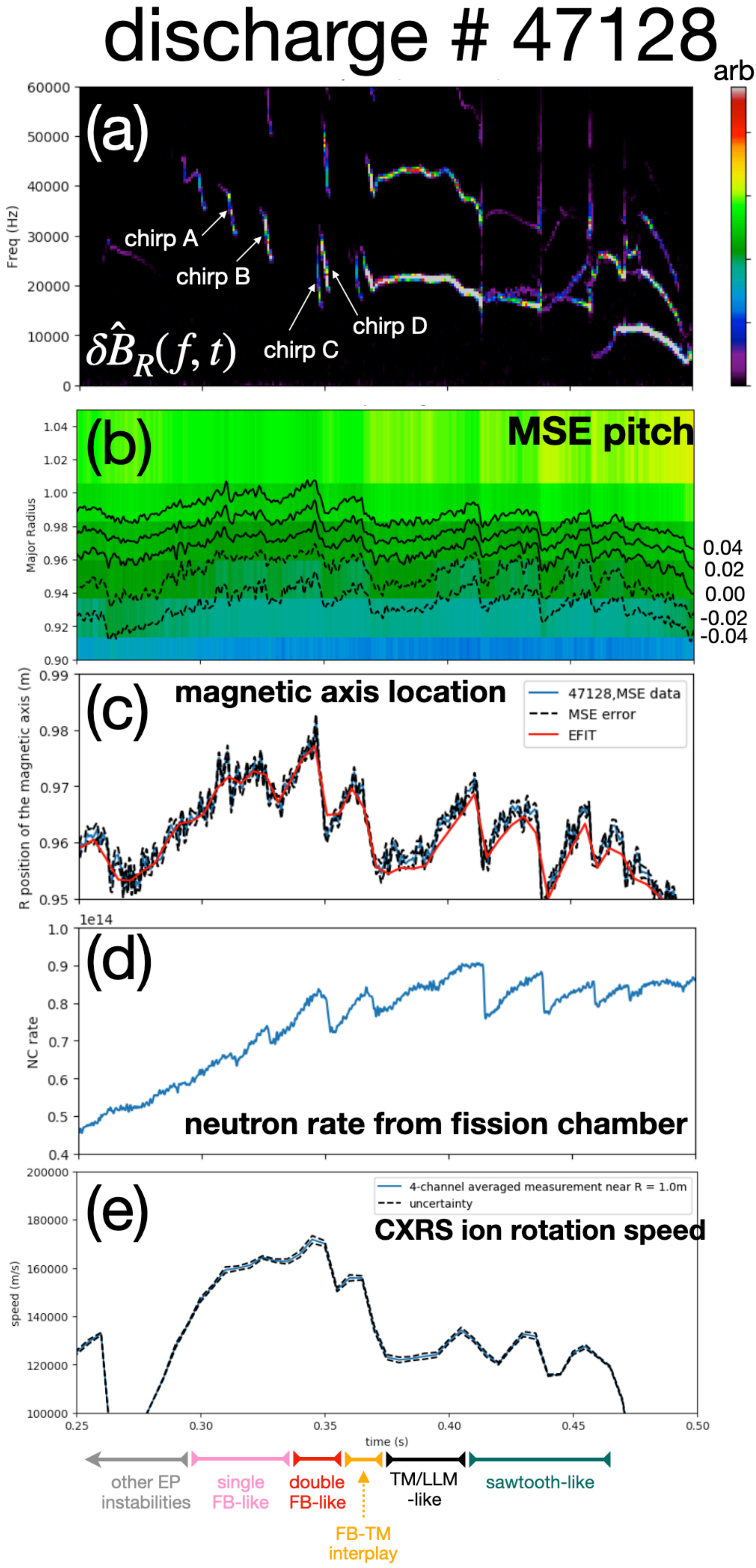
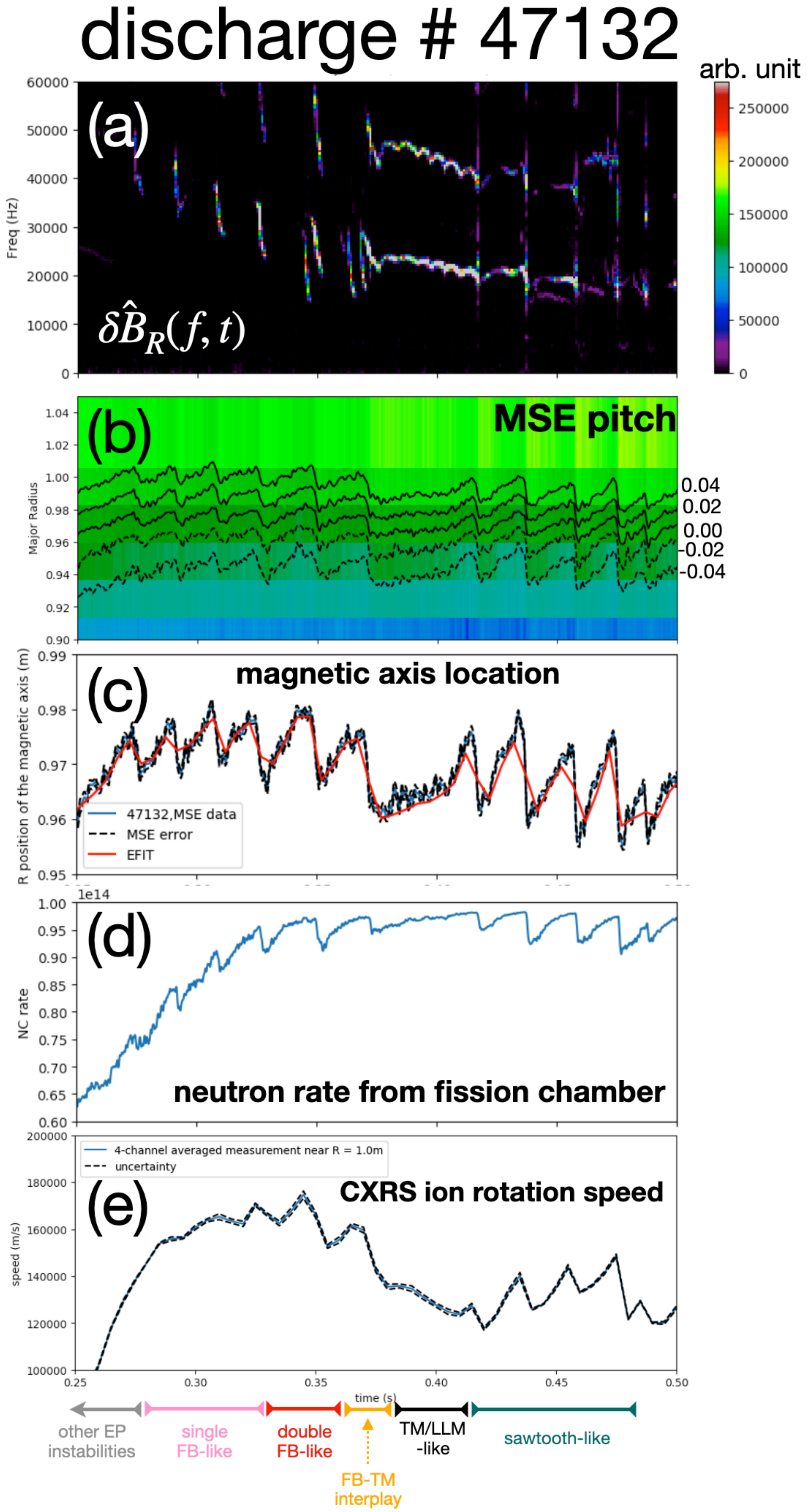
MAST mode distortion measurements inspired new experiment in MAST-U

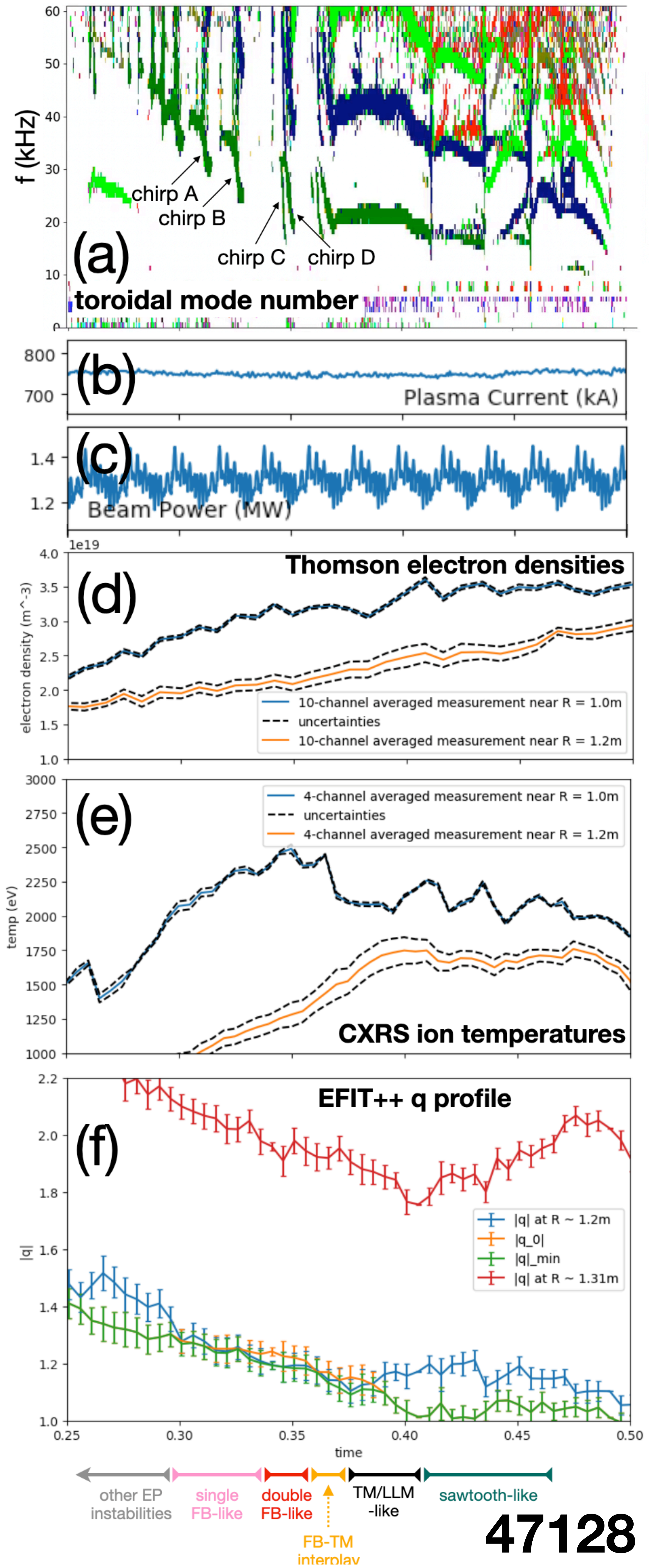


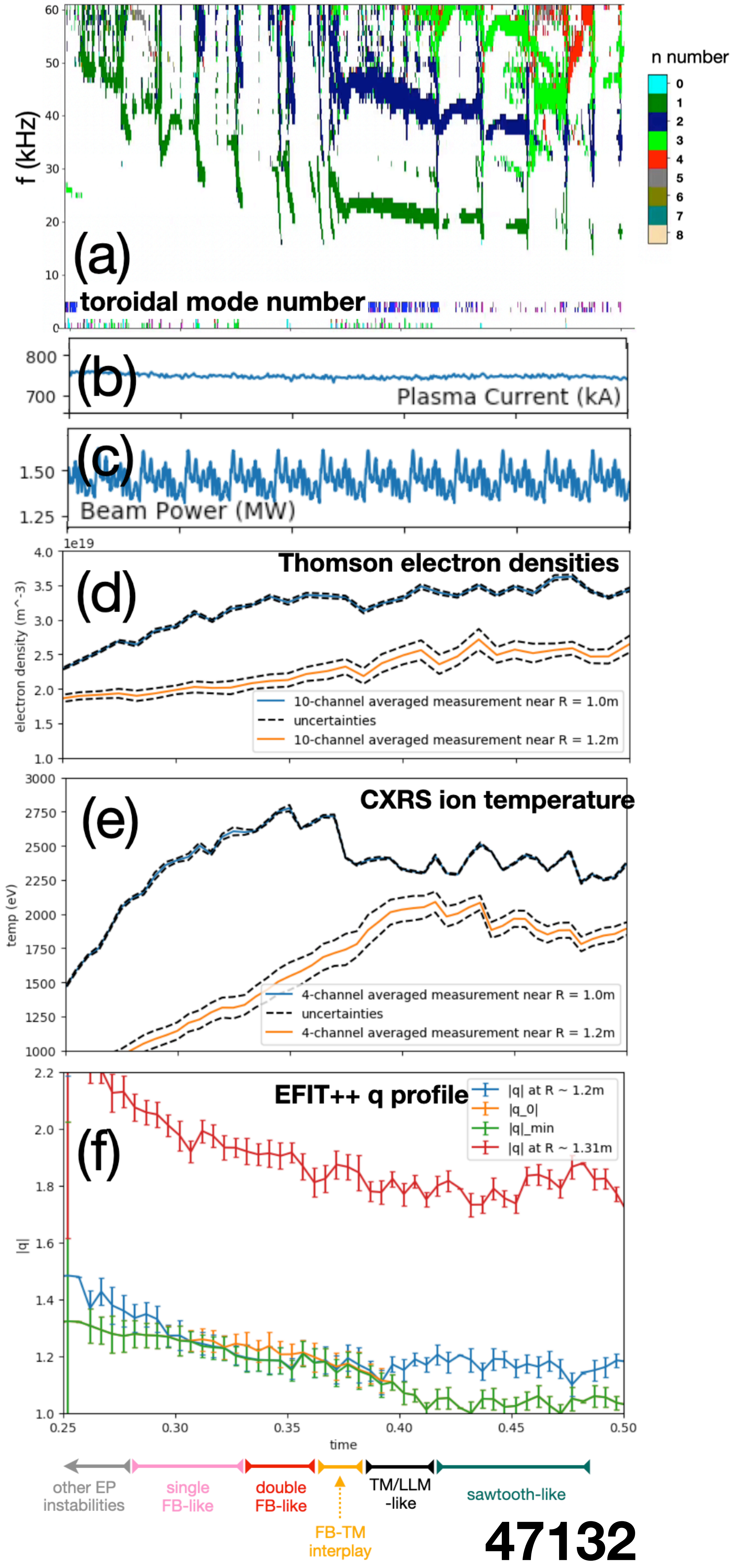


- new experiment in MAST-U aimed to study various low-frequency modes
- two shots (47128, 47132) have similar equilibria (densities, q profiles etc) **except 47132 has slightly higher beam power (1.5MW vs. 1.3MW)** and hence higher equilibrium temp. and neutron emissions

- modes appear in this order:
  - AE -> FB -> *double* FB -> TM -> Sawtooth
- tearing modes/LLMs dominate before q_{min} drop below 1 -> all FB-like bursts are **infernal-like**
- chirps A, B in 47128 -> single bursts
- chirps C, D in 47128 -> double bursts close proximity in time and frequency
- reserved shears become more pronounced before appearance of double FB-like bursts
- **significant axis movements, drops in neutron emission, drops in rotation speed during/after double FB-like bursts**
- **drops in central thermal ion temperature during double FB-like bursts**

MAST mode distortion measurements inspired new experiment in MAST-U





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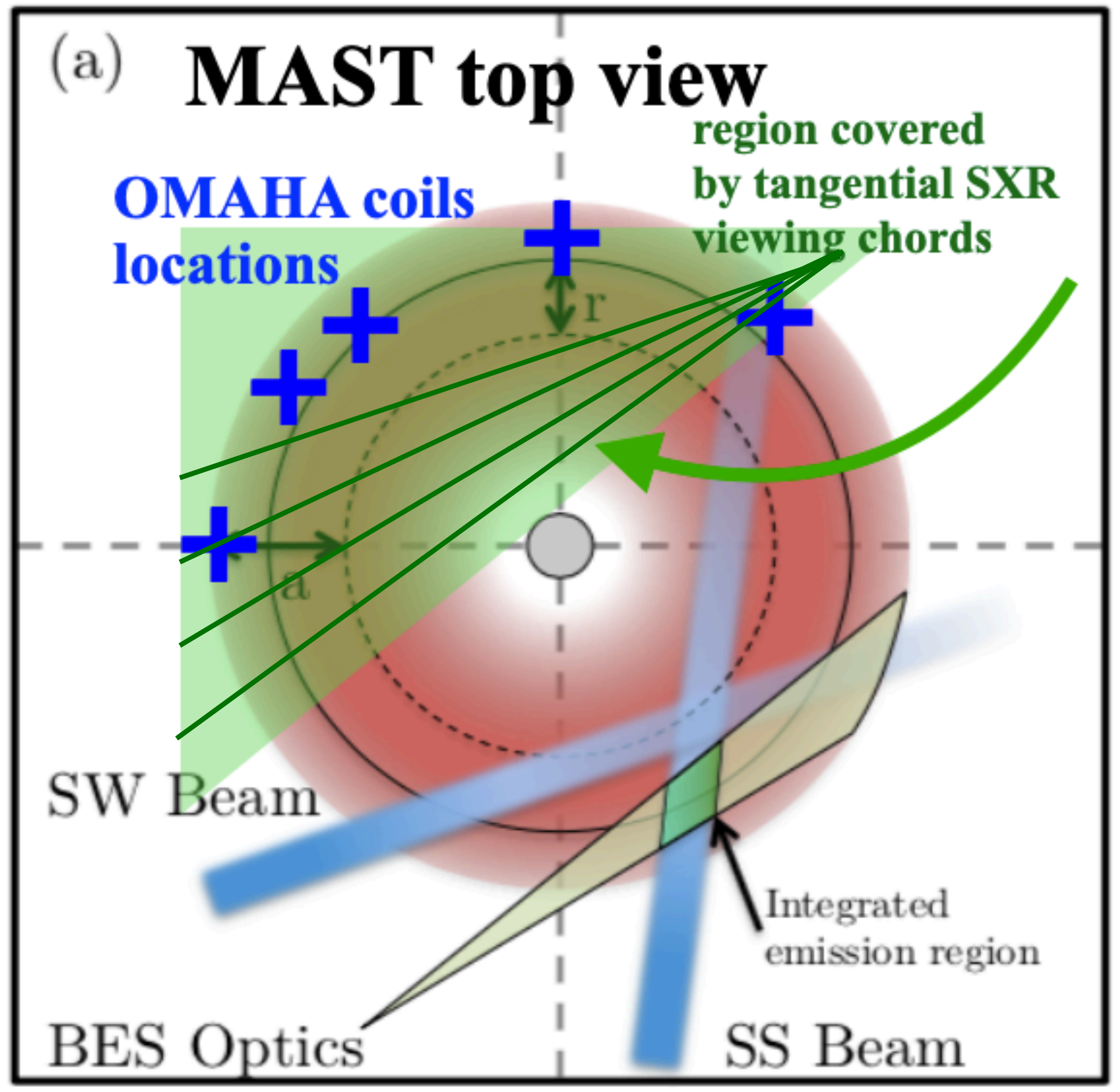
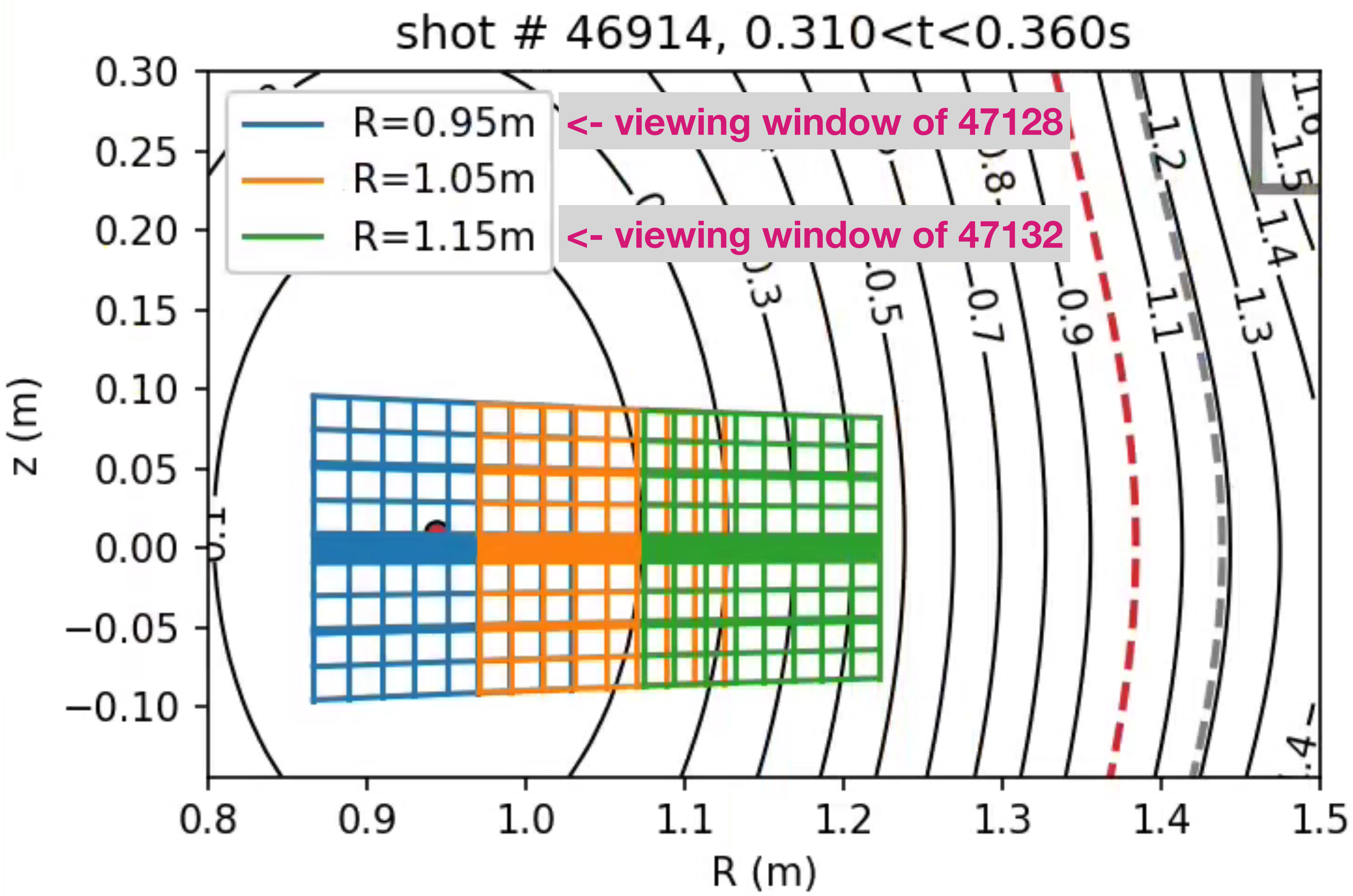
upgraded 2D BES used to measure FB associated mode structures

- no ECEI in MAST/-U due to low field strength
- complicated emissivity inversion of signals from poloidal SXR arrays (especially when equilibrium is disrupted)
  - rely on 2D Beam Emission spectroscopy (BES) for 2D mode structure measurements
- BES samples $\frac{\delta I}{I_0} \approx \frac{\delta n_e}{n_{e0}}$ (if there is no significant beam attenuation) near the core
- BES in MAST-U has 2D (~13cm x 15cm) window (movable radially).
- MAST-U has 2 NBIs. SS: on mid-plane; SW: vertically displaced
  - 2D BES captures emissions from the **SS beam**





<- viewing window of 47128

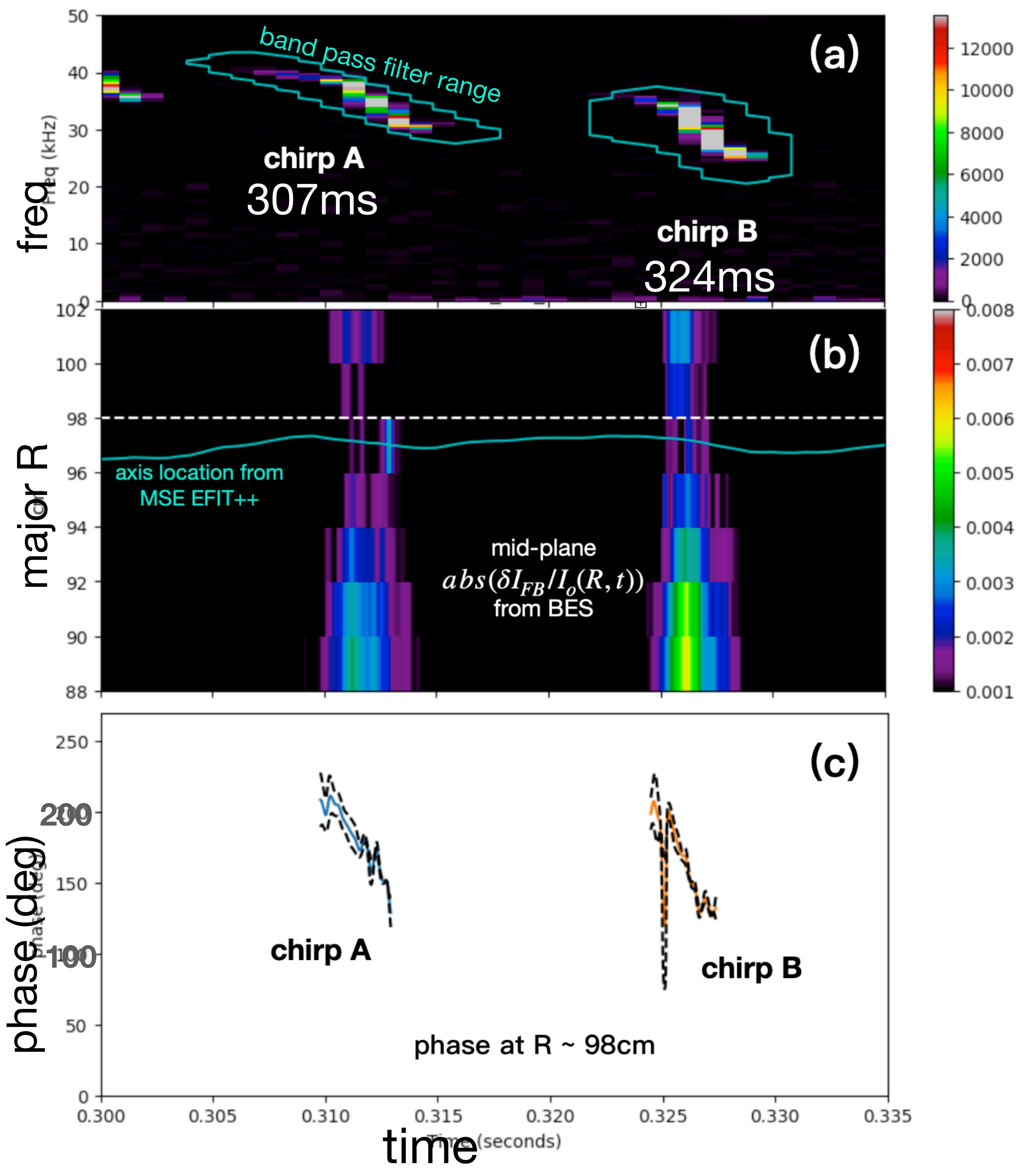
<- viewing window of 47132

temporal phase variations (core BES vs. edge δB_R) appear again in MAST-U

δB_R spectrogram discharge #47128

mid-plane $\delta I / I_o$ from BES

BES vs δB_R phase at R ~ 98cm, mid-plane



- chirp A: 30-40kHz (high for a FB)
- chirp B: 22-35kHz
- chirp B signals are stronger then chirp A for both δB_R and $\delta I / I_o$ + q_{min} is lower in chirp B
  - -> kink mode is less stable for chirp B
- smallest mid-plane $\delta I / I_o$ near the axis for both chirps

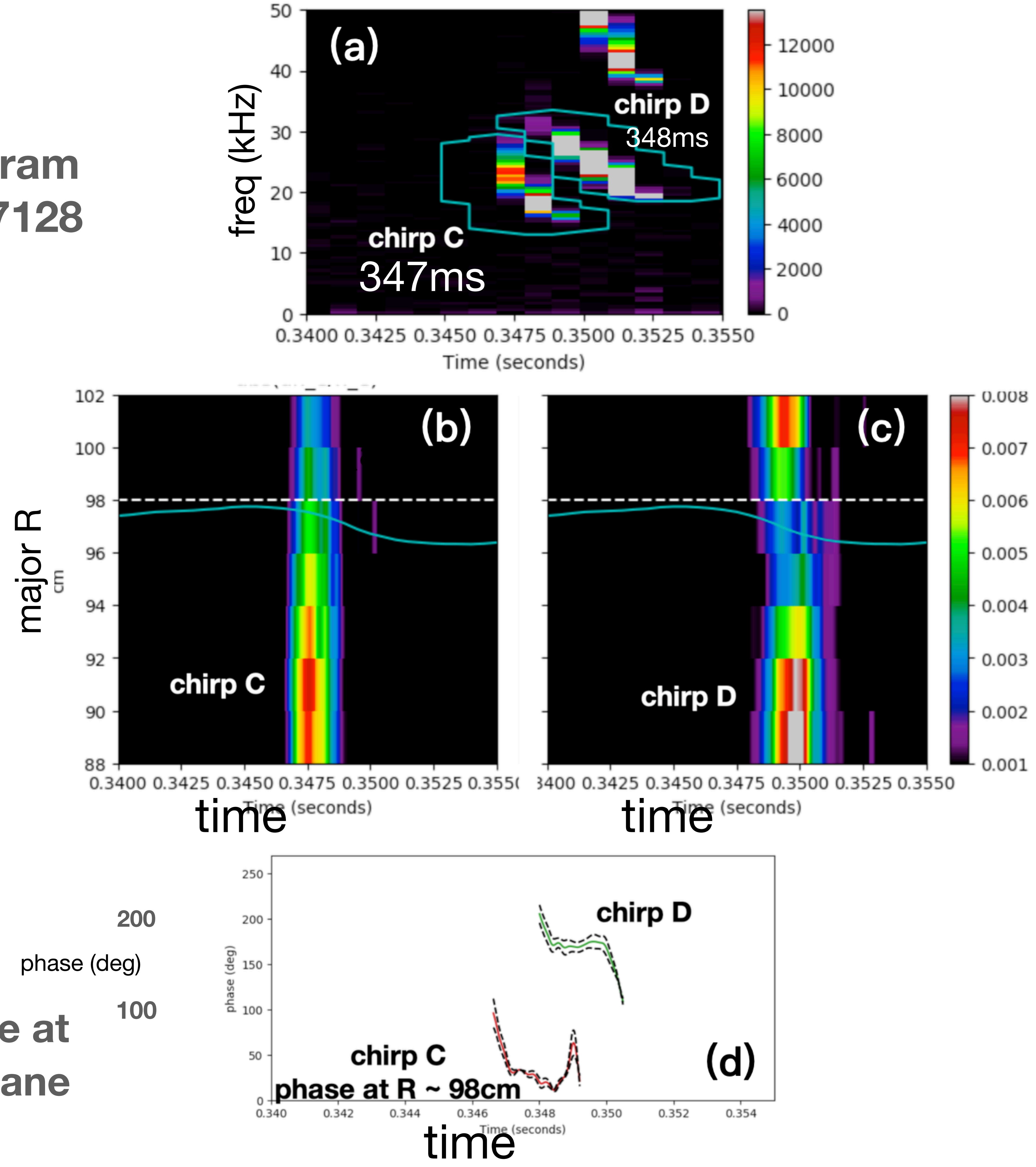
- BES vs. δB_R phase change over time observed again, similar to SXR vs. δB_z in MAST

temporal phase variations (core BES vs. edge δB_R) appear again in MAST-U (continued)

δB_R spectrogram discharge #47128

mid-plane $\delta I_{FB}/I_o$ from BES

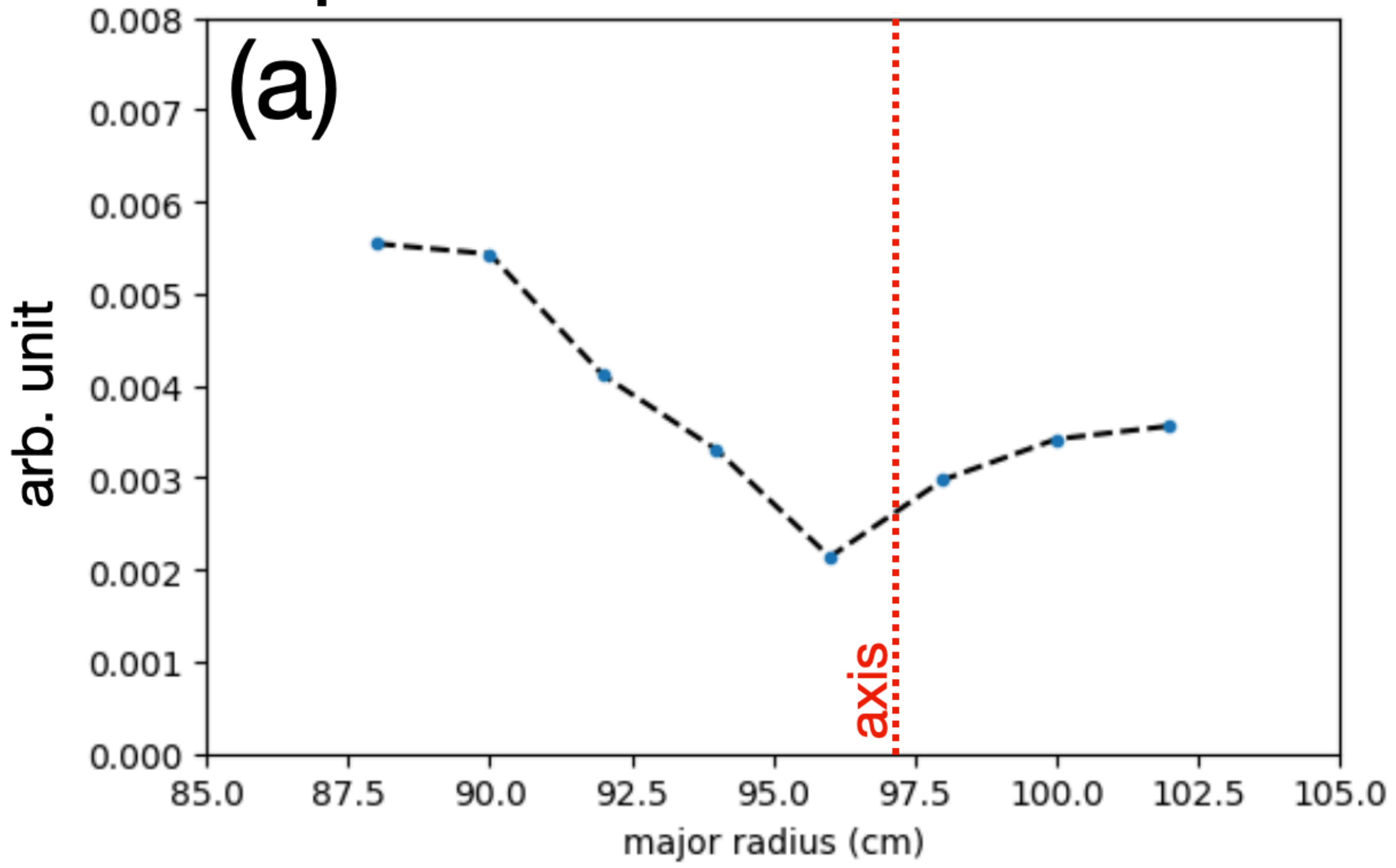
BES vs δB_R phase at R ~ 98cm, mid-plane



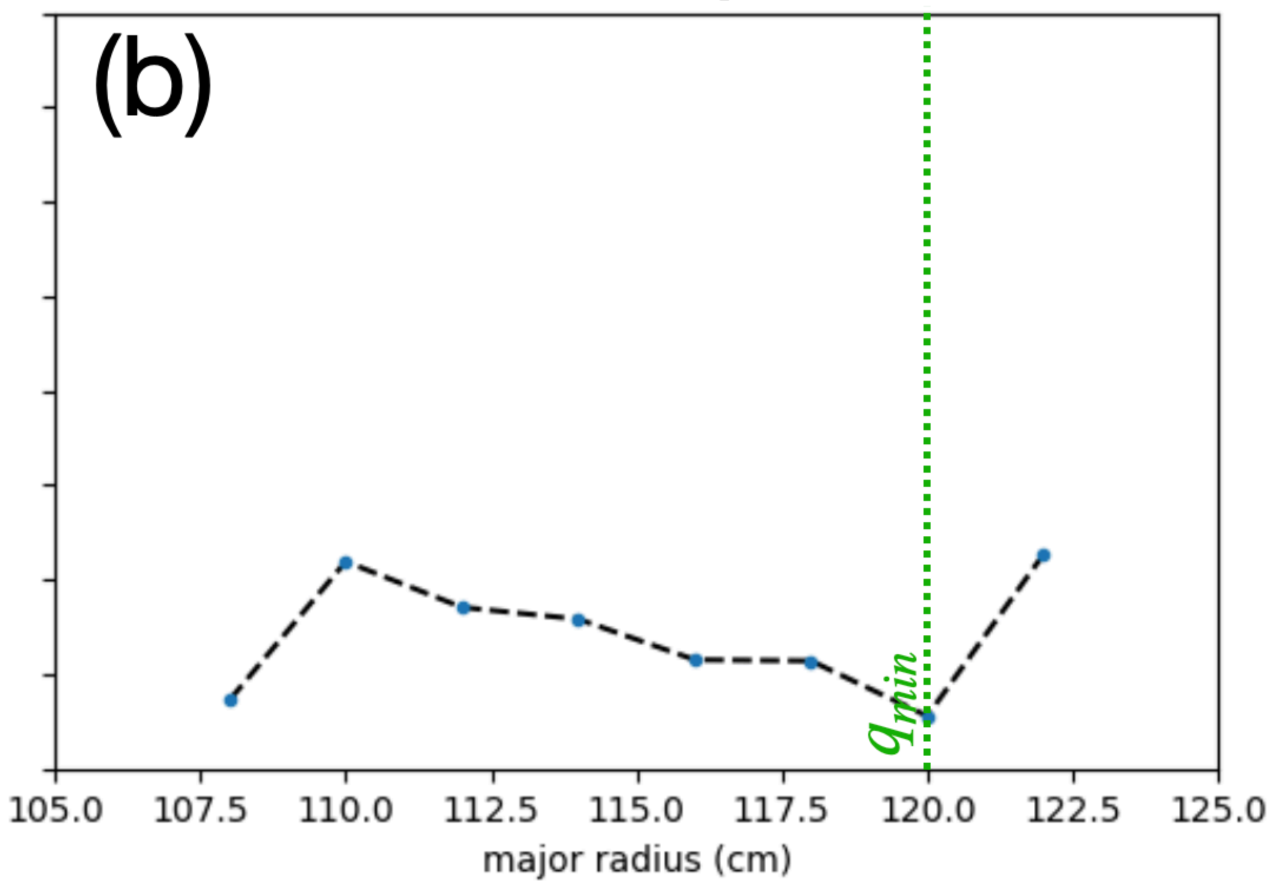
- chirps C and D: close proximity in time and frequency
- chirp C has slightly lower frequency then chirp D
- chirp D has radial structure similar to A and B
- BES vs. δB_R phase change over time
- chirp C phase starts at ~120 degrees lower then D

- phase and structure suggest chirps C is fundamentally different from other FB-like chirps in 47128

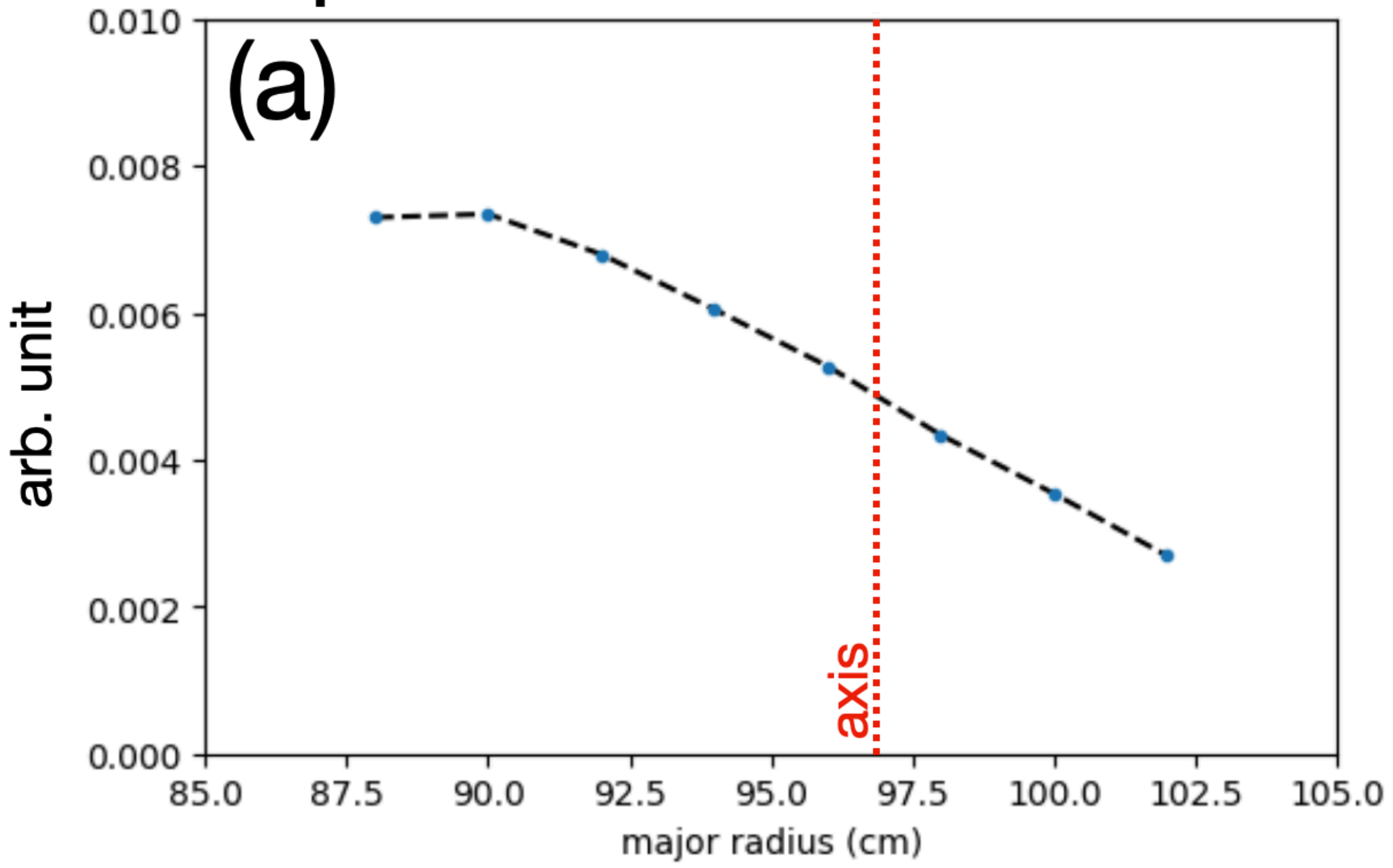
FB-like bursts likely peak between axis and q_{min} locations



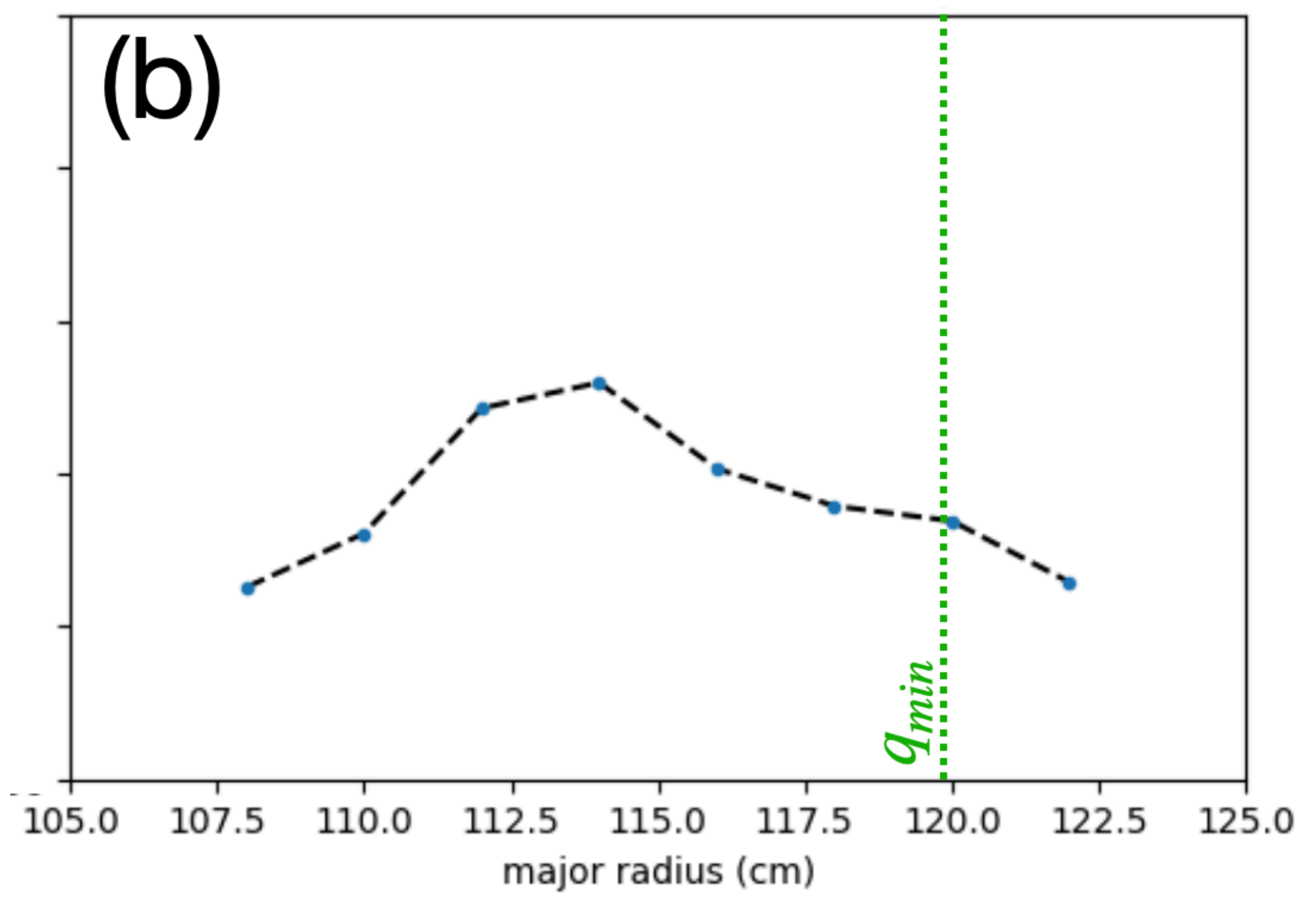
discharge # 47128, t ~ 325.9ms
mid-plane $abs(\delta I/I_0)$ from BES
chirp B



discharge # 47132, t ~ 326.2ms
mid-plane $abs(\delta I/I_0)$ from BES
the burst similar to chirp B in 47128



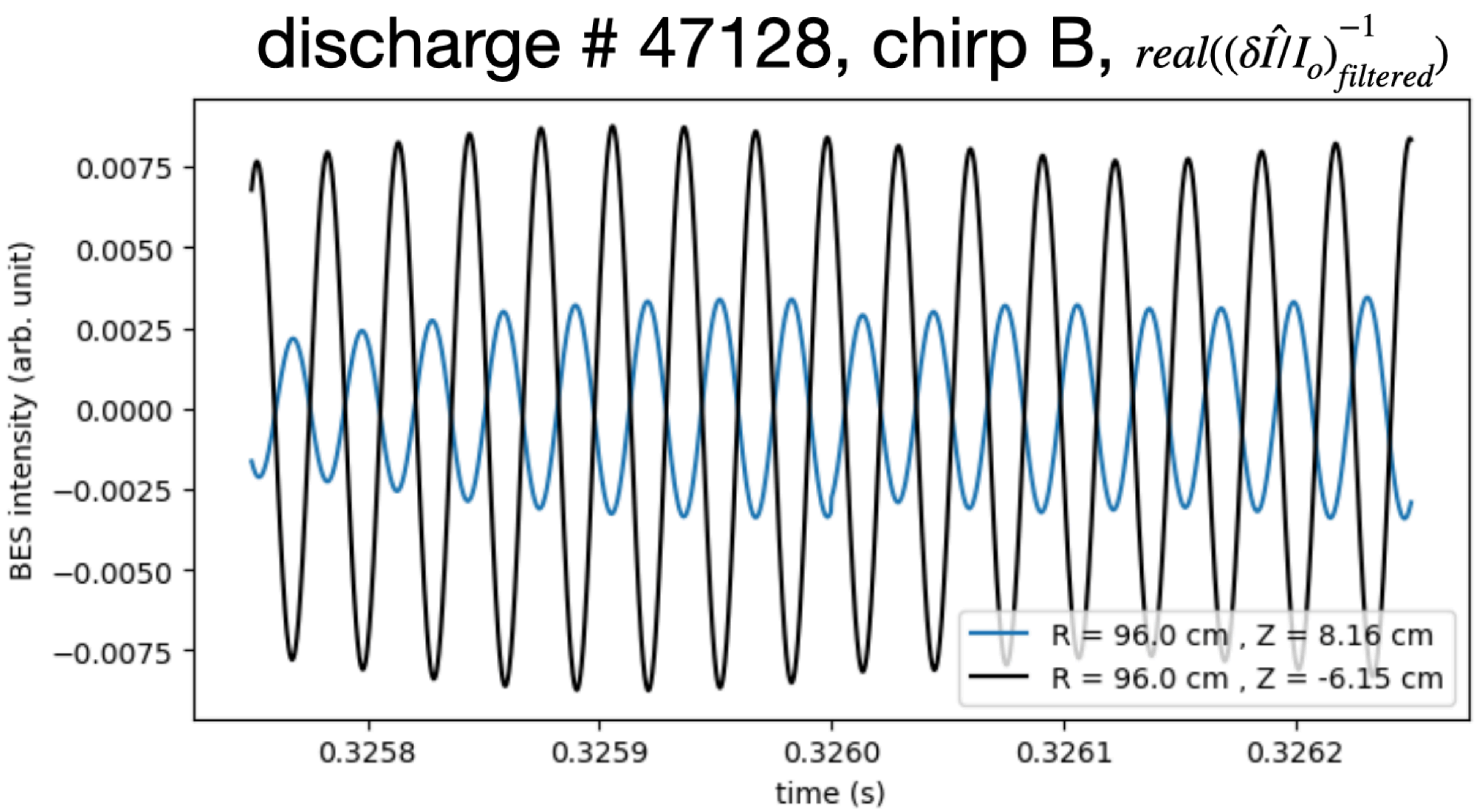
discharge # 47128, t ~ 347.5ms
mid-plane $abs(\delta I/I_0)$ from BES
chirp C



discharge # 47132, t ~ 348ms
mid-plane $abs(\delta I/I_0)$ from BES
first burst of the double FB-like bursts

- axis: R ~ 97cm; q_{min}: ~120cm; q = 2: ~128cm
- if any of the bursts are off-axis FBs, then we expect stronger fluctuations in outer radii (i.e. BES from 47132 greater than 47128) but this isn't the case
- also don't see the BES signals increase when R increases in 47132
  - the FBs are likely to be on-axis FBs

signals from vertically separated BES channels unveil m-parities of FB-like bursts

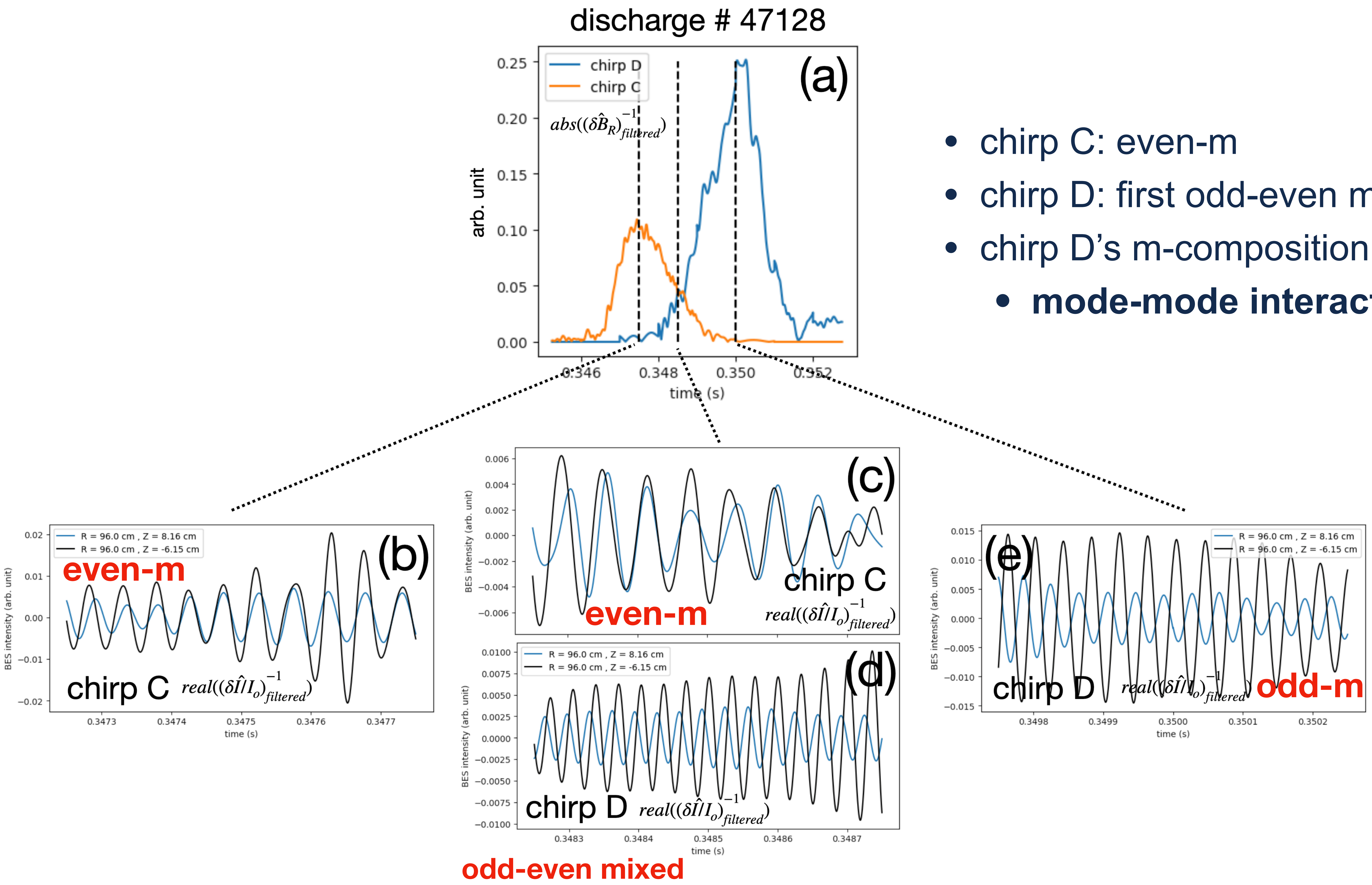


discharge # 47128, chirp B, $real((\delta\hat{I}/I_o)^{-1}_{filtered})$

- 2 BES ch. (R,Z) = (96, 8.16)cm , (96, -6.15)cm
- plasma is 1cm displaced vertically -> both 7cm away from the axis
- if $real(\delta I/I_0)$ from these 2 ch. are in-phase -> **even-m**
- if out of phase -> **odd-m**

- for example, chirp B has odd-m
  - **-> most likely to be (n,m) = (1,1) mode**

signals from vertically separated BES channels unveil m-parities of FB-like bursts (continued)



- chirp C: even-m
- chirp D: first odd-even mixed, then odd-m -> (n,m) = (1,1) ?
- chirp D’s m-composition is probably affected by chirp C
    - **mode-mode interactions during double FB-like bursts**

odd-m / even-m mode interactions cause disruptions

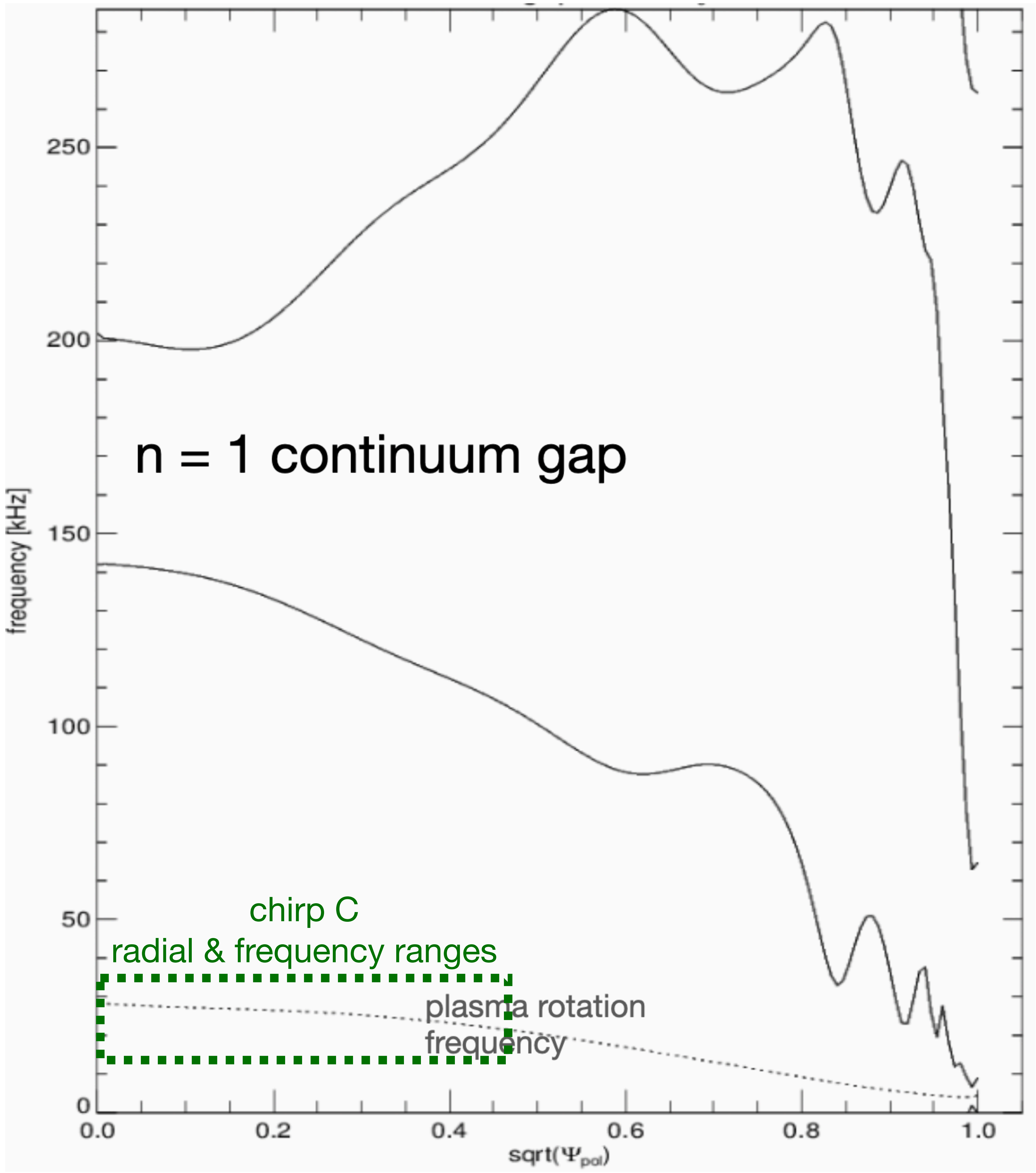
- fast ion transports (neutron emission, plasma rotations, axis movements), and drops of central ion temperature associated to double FB-like bursts (e.g. chirps C and D in 47128) the strongest among other FBs
- chirp C -> even-m; chirp D -> odd-m since the peak of burst, (n,m) = (1,1)?

- (1,1)-kink & even-m mode interaction
- 3D MHD sim. for NSTX case shows (1,1) mode alone could make field near q_{min} stochastic.
- single bursts (e.g. chirps A & B) - near flat central q; double bursts (e.g. C & D) - reserved shear q
- likely that **the presence of these two modes make the field in a reserved shear plasma more stochastic than other FBs**
  - **-> cause more significant disruptions compared to single bursts**

LIU, C. *et al.*, Thermal ion kinetic effects and landau damping in fishbone modes, Journal of Plasma Physics **88** (2022).

the even-m mode is unlikely to be RSAE

discharge # 47128, t = 346ms



- the even-m modes appear after the plasma becomes more reserved shear
- but the frequency of mode is <u>well below</u> n = 1 TAE gap
- mode doesn’t peak at q_{min} location
  - not RSAE?

Possible nature of the even-m mode

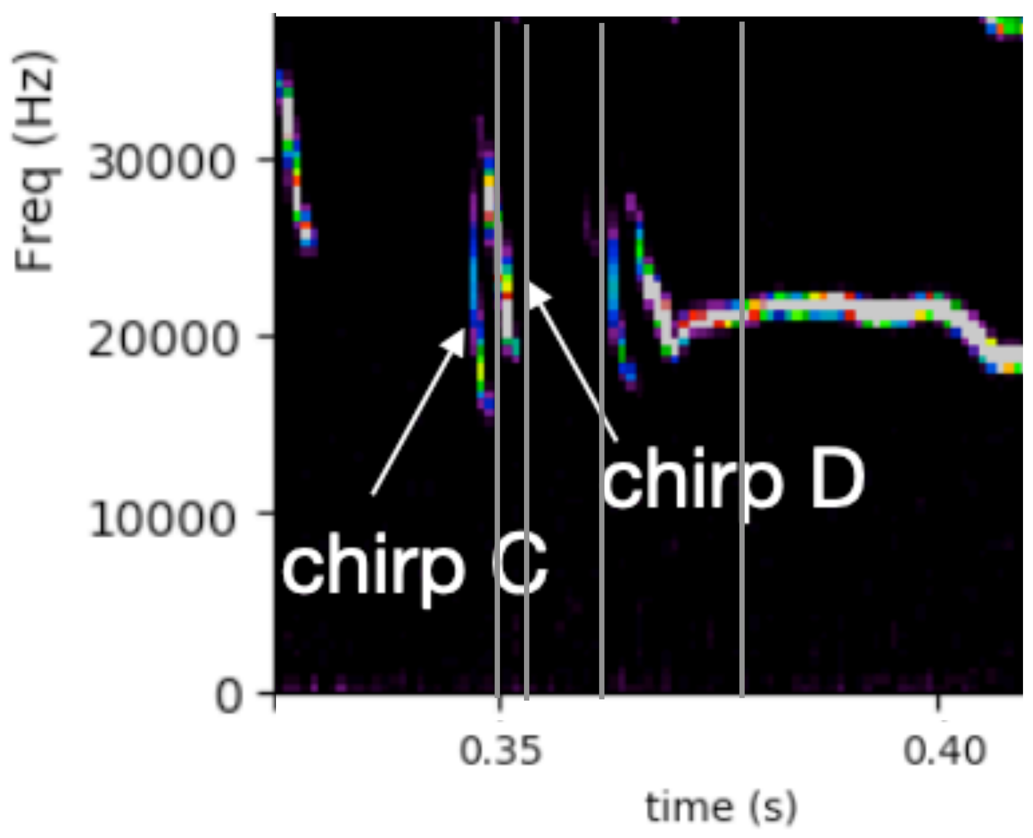
(n,m) = (1,2) tearing mode

GERHARDT, S. *et al.*, Relationship between onset thresholds, trigger types and rotation shear for the m/n = 2/1 neoclassical tearing mode in a high-β spherical torus, Nucl. Fusion **49** (2009) 032003.

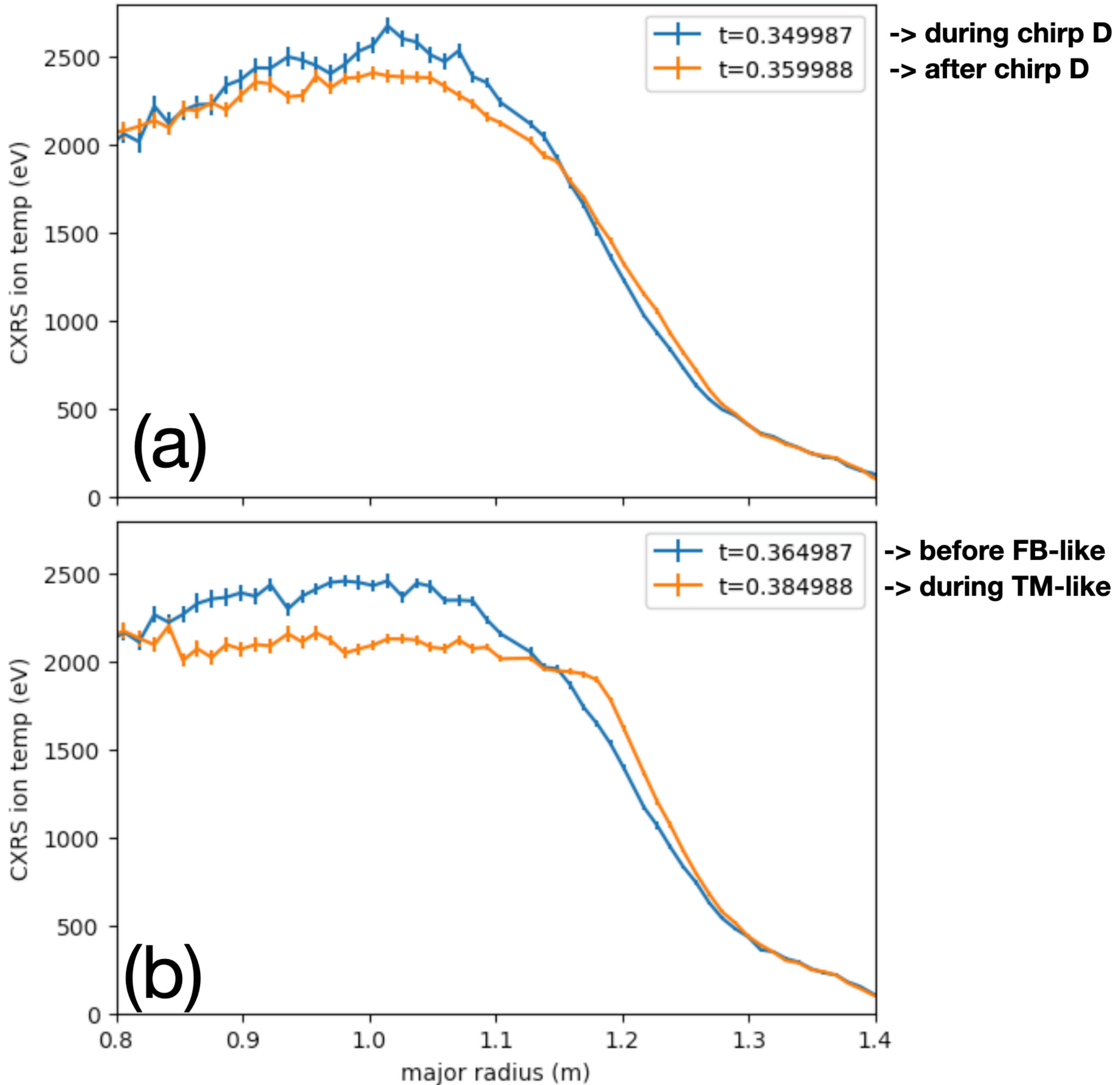
WANG, F. & FU, G. Y. & BRESLAU, J. A. & TRITZ, K., and LIU, J. Y., Simulation of non-resonant internal kink mode with toroidal rotation in the national spherical torus experiment, Phys. Plasmas **20** (2013).

YANG, J. & PODESTÀ, M., and FREDRICKSON, E. D., Synergy of coupled kink and tearing modes in fast ion transport, Plasma Phys. Control. Fusion **63** (2021) 045003.

- (n,m) = (1,1) mode triggers and interact with higher (n,m) modes (e.g. with (1,2) at q = m/n = 2)
- observed in multiple NSTX/-U case
- evidence of (1,1) + (1,2) interaction affecting confinements in MAST-U



discharge # 47128, CXRS ion temperature



<u>but…</u>

- very mild central temperature drop and no obvious flattening after chirp D
- tearing mode interplay model: (n,m) = (1,1) seeds the (1,2)
    - but chirp C (even-m) appears <u>before</u> the (1,1)

Possible nature of the even-m mode

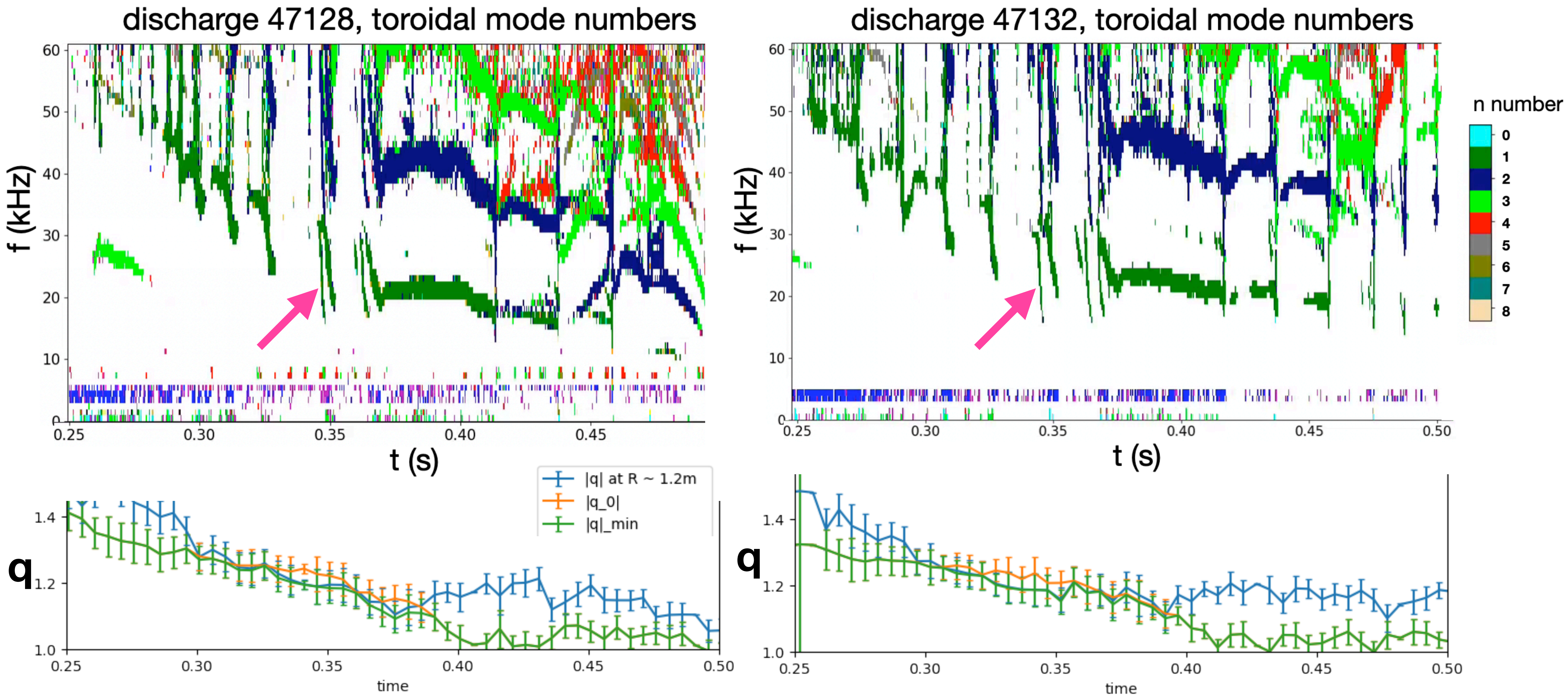
n > 1 MHD modes

- for example:
  - new sawtooth model: (1,1)-mode keeps q > 1 and n = m = 2 mode cause crash of central temperature

JARDIN, S. C. & KREBS, I., and FERRARO, N., A new explanation of the sawtooth phenomena in tokamaks, Phys. Plasmas **27** (2020).

  - unable infernal modes in q = m/n surface flatten/lower the temp. profile without creating magnetic islands

JARDIN, S. C. el al., Ideal MHD induced temperature flattening in spherical tokamaks, Phys. Plasmas **30** (2023).
BOOZER, A. H., The rapid destruction of toroidal magnetic surfaces, Phys. Plasmas **29** (2022)


discharge 47128, toroidal mode numbers

discharge 47132, toroidal mode numbers

but…

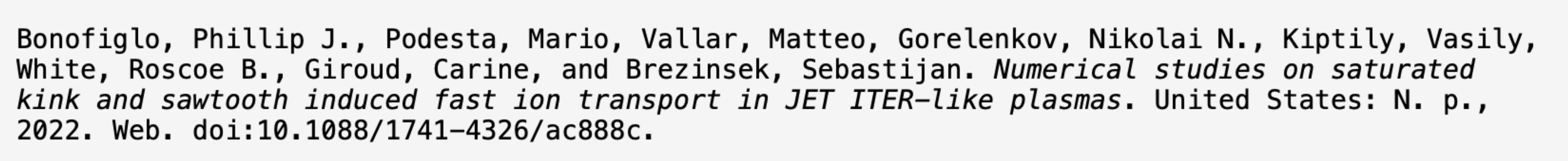
- n number identifications suggest chirp C in 47128 and the similar burst in 47132 have n = 1

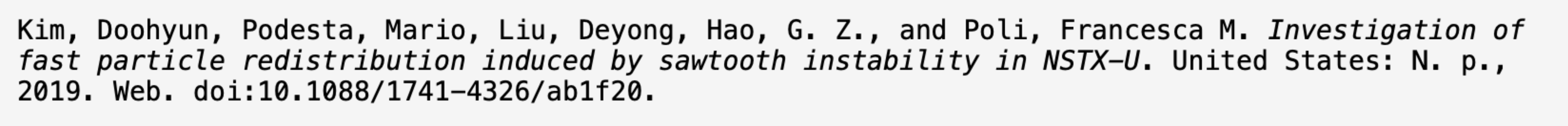
Conclusion & open questions

- (1,1) and even-m FB-like modes interactions cause significant disruption comparable to other MHD events (sawtooth, tearing mode, etc)
- The nature of the even-m FB-like modes is still unclear. They have similarities but don't look exactly like tearing modes, sawtooth, higher order infernal modes, etc)
- Regardless of the nature of the even-m mode, the presences of mode-mode interaction and associated equilibrium crash bring challenges to future simulation efforts
  - self-consist models need to allow evolution of equilibrium (q, mesh, magnetic island, etc) AND handle mode-mode interaction well to fully capture and predict the consequences of these (1,1) and even-m FB-like modes

Future efforts

- try measuring magnetic islands near core and |q| ~ 2 surface in future MAST-U experiments
  - MAST-U *(no ECEI, alternatives needed, e.g. BES again)*
  - NSTX-U: with high time-res Thomson scattering
    - alternatively, identify (n,m) = (1,2) TMs using poloidal coil array
- fast ion transport calculation and compare with diagnostics
  - e.g. ORBIT-Kick interpretive calculation using input inferred from measurements, regardless the natures of the modes


Bonofiglo, Phillip J., Podesta, Mario, Vallar, Matteo, Gorelenkov, Nikolai N., Kiptily, Vasily, White, Roscoe B., Giroud, Carine, and Brezinsek, Sebastijan. *Numerical studies on saturated kink and sawtooth induced fast ion transport in JET ITER-like plasmas*. United States: N. p., 2022. Web. doi:10.1088/1741-4326/ac888c.


Kim, Doohyun, Podesta, Mario, Liu, Deyong, Hao, G. Z., and Poli, Francesca M. *Investigation of fast particle redistribution induced by sawtooth instability in NSTX-U*. United States: N. p., 2019. Web. doi:10.1088/1741-4326/ab1f20.

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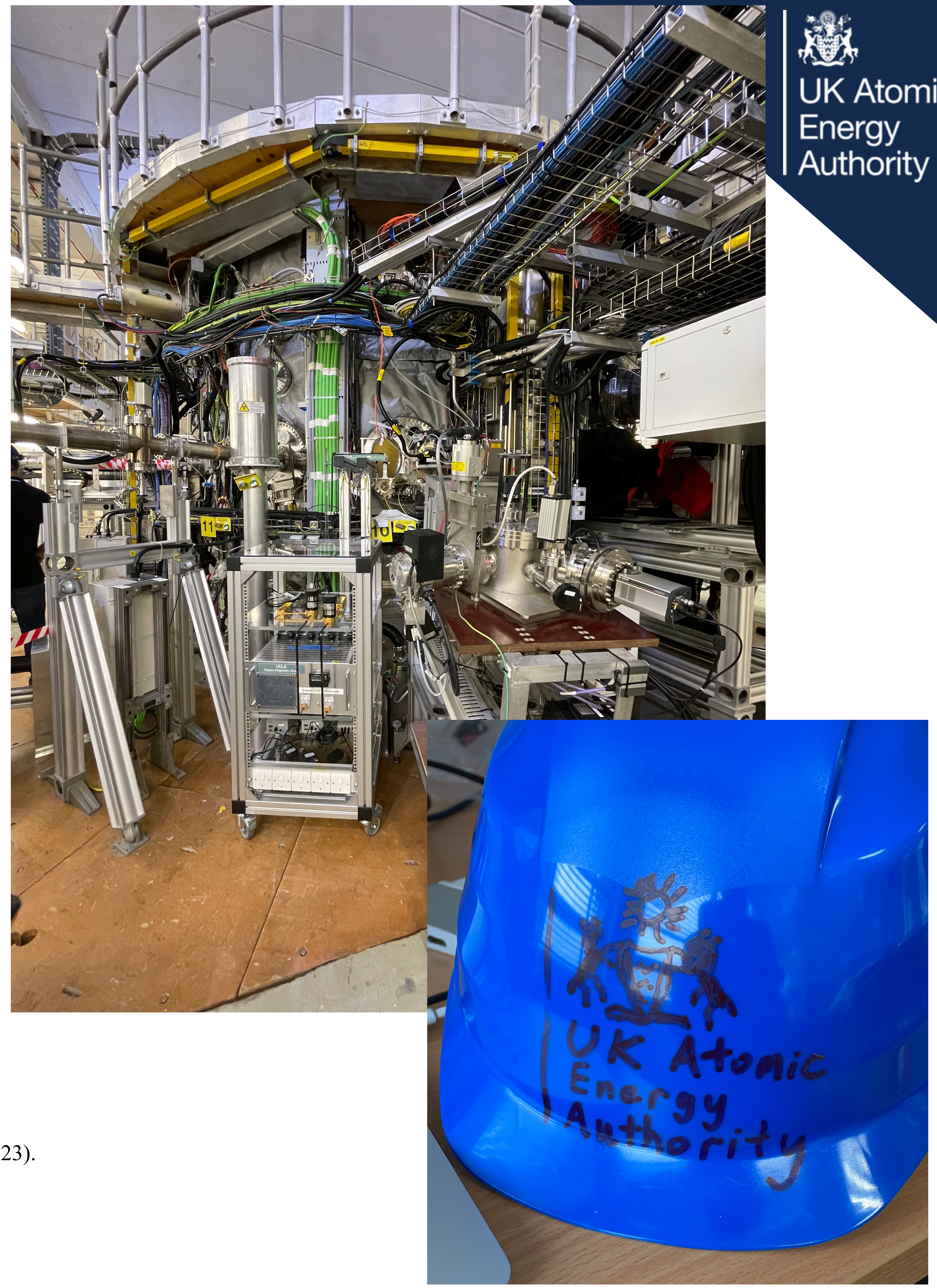

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- tearing modes in NSTX/-U:
  - GERHARDT, S. *et al.*, Relationship between onset thresholds, trigger types and rotation shear for the m/n = 2/1 neoclassical tearing mode in a high-β spherical torus, Nucl. Fusion **49** (2009) 032003.
  - WANG, F. & FU, G. Y. & BRESLAU, J. A. & TRITZ, K., and LIU, J. Y., Simulation of non-resonant internal kink mode with toroidal rotation in the national spherical torus experiment, Phys. Plasmas **20** (2013).
  - YANG, J. & PODESTÀ, M., and FREDRICKSON, E. D., Synergy of coupled kink and tearing modes in fast ion transport, Plasma Phys. Control. Fusion **63** (2021) 045003.
- (1,1) & (1,2) affecting confinement in MAST-U:
  - CECCONELLO, M. *et al.*, First observations of confined fast ions in mast upgrade with an upgraded neutron camera, Plasma Phys. Control. Fusion **65** (2023) 035013.
  - HARRISON, J. *et al.*, 2023 29th iaea fusion energy conference, ().
  - RIVERO-RODRÍGUEZ, J. *et al.*, Overview of fast particle experiments in the first mast upgrade experimental campaigns, Nucl. Fusion (2024) in progress.

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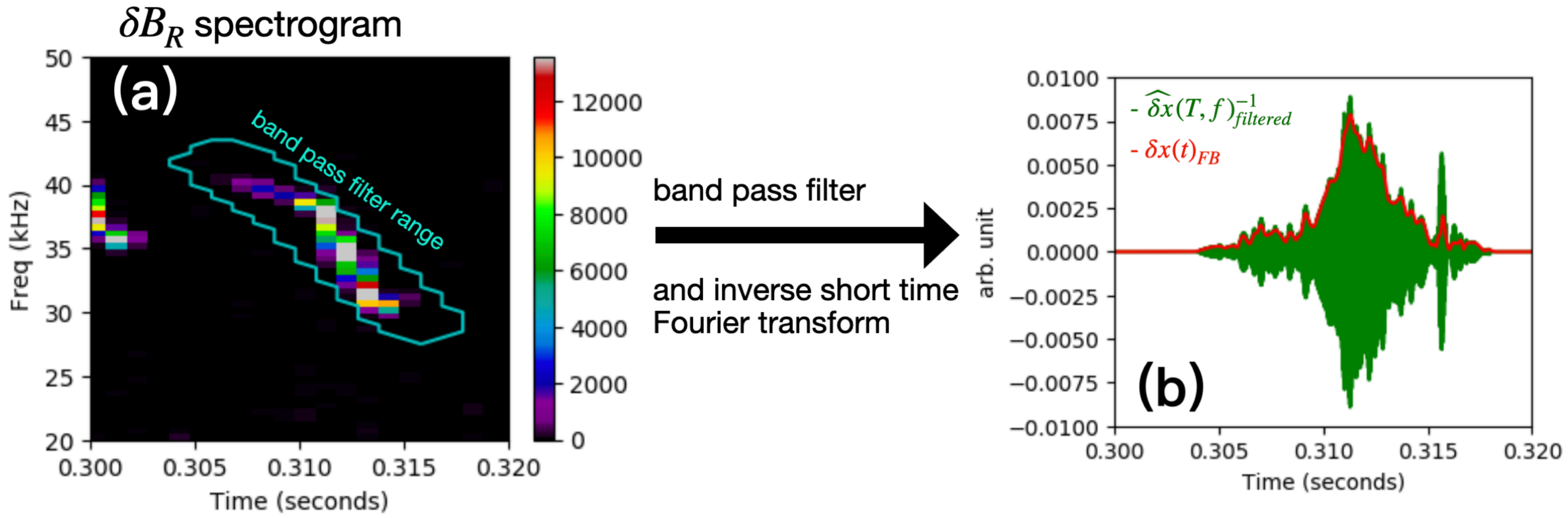
Linear regression model used to isolate global effects

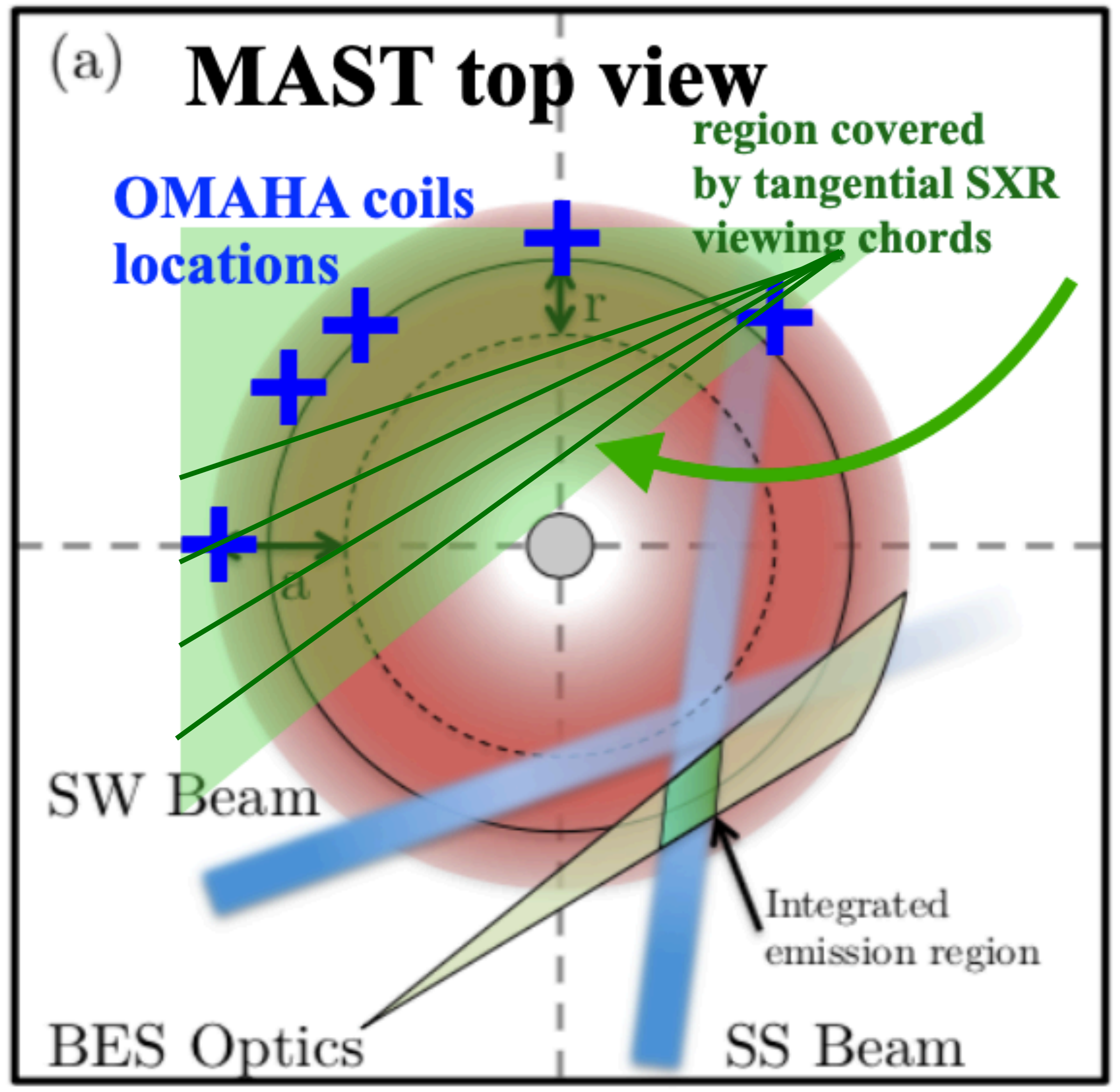
(backup)

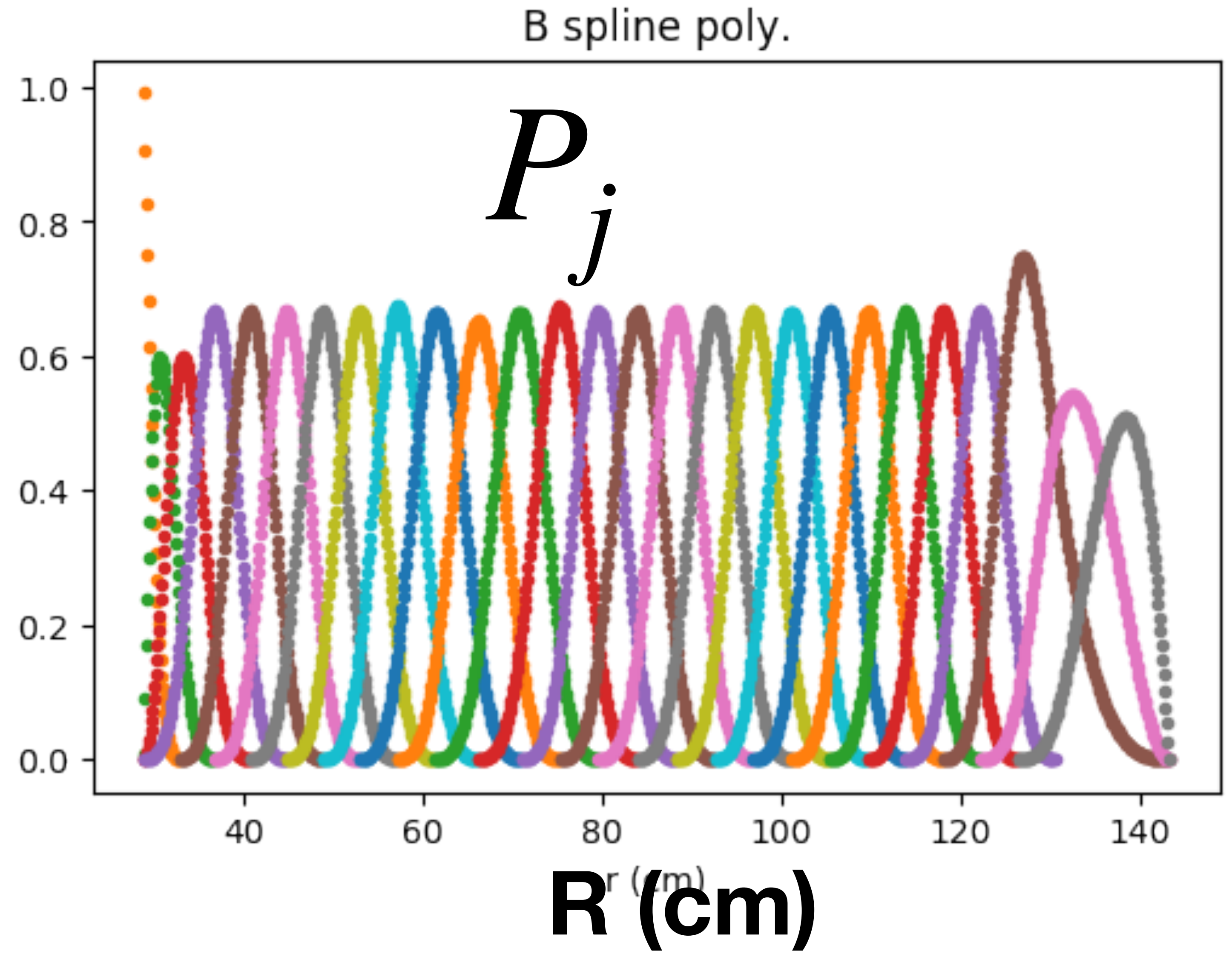


- diagnostics might capture non-global effects (e.g. noise and turbulences) while FB is a global mode
- assume $\delta x(t) = L_x(\overrightarrow{\delta B}(t)) + $ noise;
  - x: either soft x-ray (SXR) or Beam Emission spectroscopy (BES) signal; L_x : unknown linear function
- band pass filter is also applied to $\delta x(t)$, become $\widehat{\delta x}(T,f)^{-1}_{filtered}$
- linear regression: $\delta x(t)_{FB} = \dfrac{LP(\widehat{\delta x}(T,f)^{-1}_{filtered} * (\widehat{\delta B_z}(T,f)^{-1}_{filtered})^{\dagger})}{LP(\widehat{\delta B_z}(T,f)^{-1}_{filtered} * (\widehat{\delta B_z}(T,f)^{-1}_{filtered})^{\dagger})^{1/2}}$

Line integrated tangential SXR signals are inverted to radial emissivities *(backup)*

- could use the following least square method or Abel inversion (K G McClements et al 2021 Plasma Res. Express)
- SXR captures fluctuations: $\delta I_{SXR,i} = \int_{L_i} (\delta\varepsilon) e^{in\xi} dL_i$, where $\delta\epsilon = \epsilon_0 (2\frac{\delta n_e}{n_{e0}} + (\frac{1}{2} + \frac{E_{photon}}{T_{e0}})\frac{\delta T_e}{T_{e0}} + \frac{\delta Z_{eff}}{Z_{eff,0}})$
- inversion by assuming $\delta I_{SXR} = XC, \quad X_{ij} = \frac{1}{L_i}\int_{L_i} P_j dL_i$,





Beam Emission Spectroscopy in MAST-U

(backup)

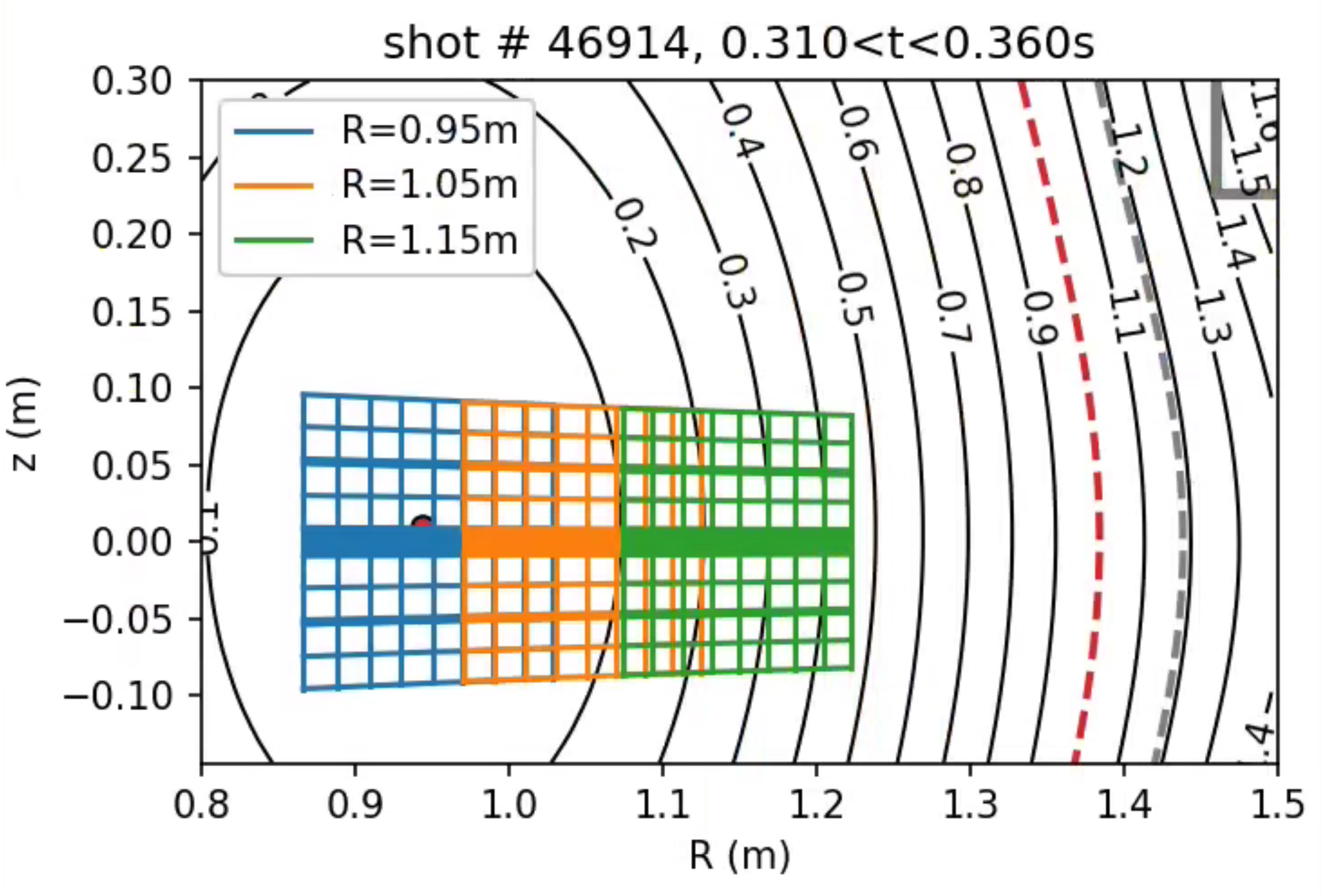
$I = n_e n_{beam} \sigma$

assume $I = I_0 + \delta I$, $n_e = n_{e0} + \delta n_e$, $n_{beam} = n_{beam,0} + \delta n_{beam}$

X_0: DC part; δX: fast varying part. $n_{e0} >> \delta n_e$
but NOT always the case for $n_{beam,0}$ and δn_{beam}

$$\frac{\delta I}{I_0} = \frac{\delta n_e}{n_{e0}} + (1 + \frac{\delta n_e}{n_{e0}})\frac{\delta n_{beam}}{n_{beam,0}} \qquad \frac{\delta I}{I_0} \approx \frac{\delta n_e}{n_{e0}}$$

if $\delta n_{beam} \approx 0$



- 2D view with ~13cm x 15cm (change slightly in different viewing radii)