Onset of strongly non-linear energetic-particle(EP)-driven modes in ASDEX Upgrade

Ph. Lauber with input from
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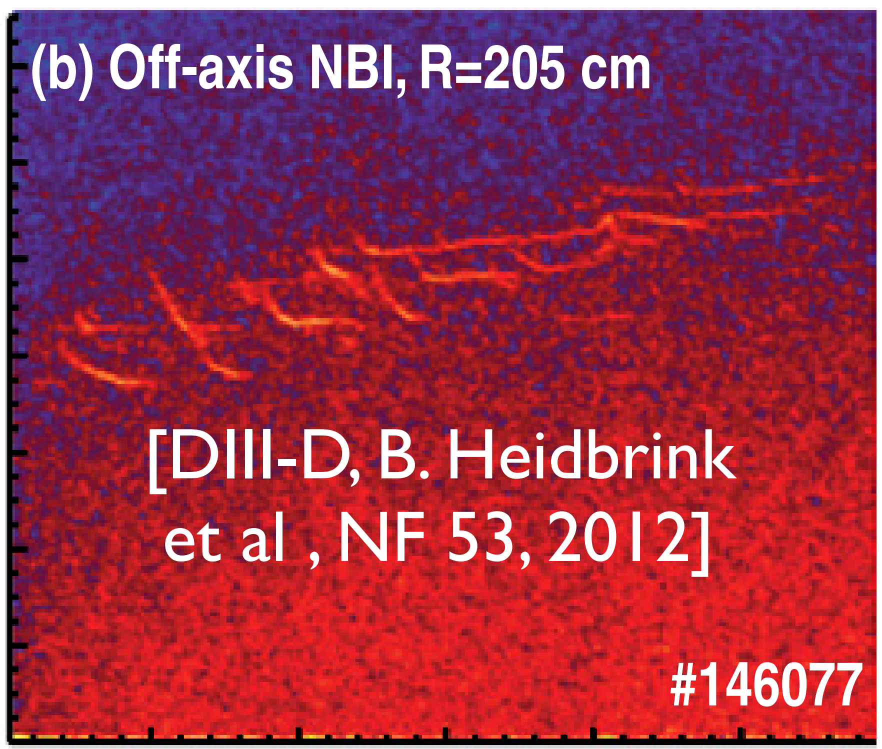
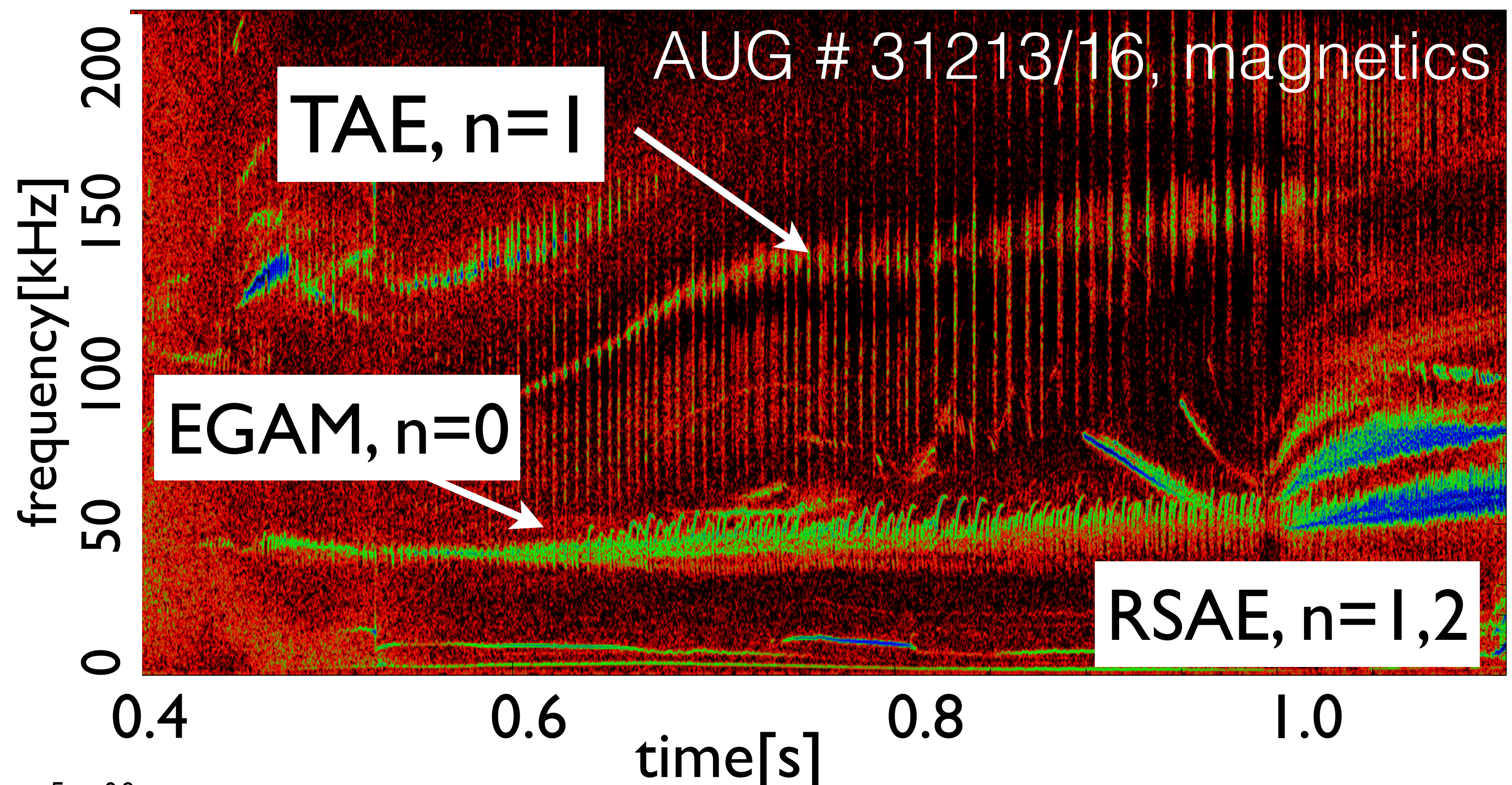
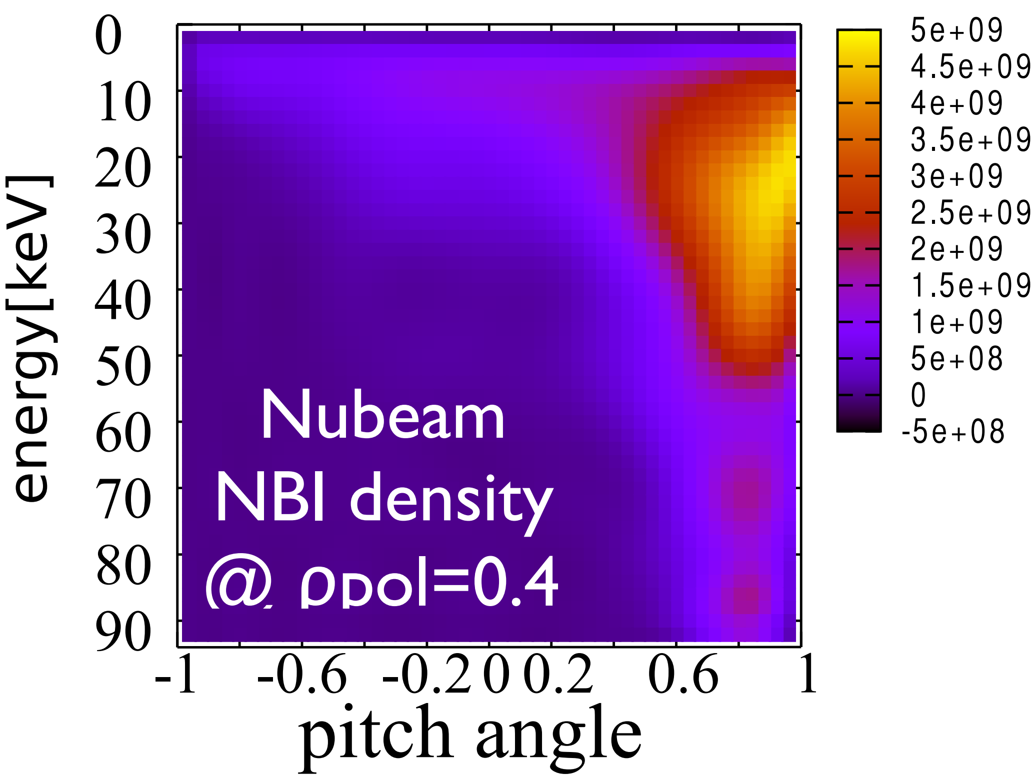
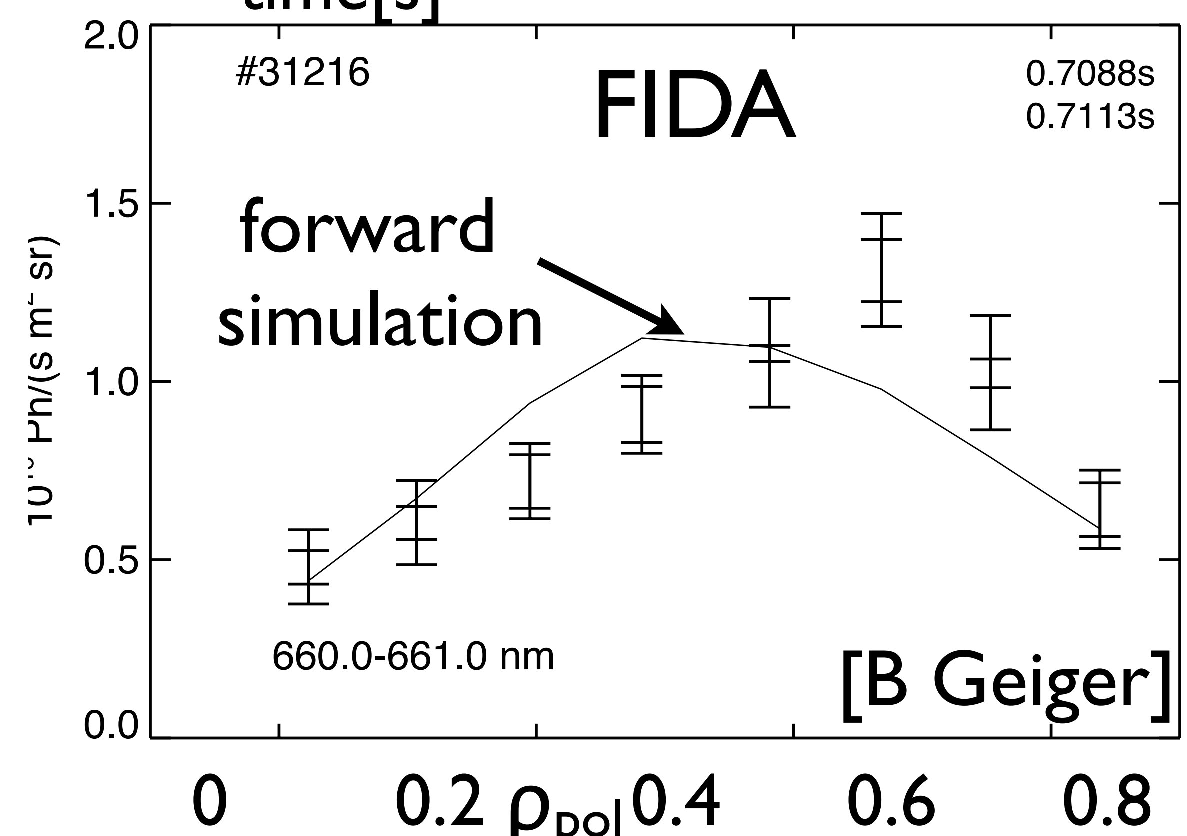
A. Bierwage, H. Wang, F. Palermo, P. Poloskei, G. Papp, G Pokol, M. Maraschek
and ASDEX Upgrade team

off-axis drive, high beam energy (93keV, Q7)









the physics picture of this scenario:

- the accumulation of W in the core decreases the background Te, Ti and thus reduces the ion Landau damping of Alfvén eigenmodes (AEs); moves strong EP anisotropy in GAM frequency range

- often hollow Te profiles form

- large values of $R_0 \nabla \beta_\alpha / \beta_{back}$ can arise, off-axis peaked EP distribution function forms; AEs propagating in both ion and electron diamagnetic direction; anisotropy in pitch angle drives EGAMs

- central ECRH can counteract this accumulation; the increased temperatures (strong EP anisotropy is 'detuned'; increased Landau damping) bring the system below excitation threshold → threshold typically Ti ≲1.8keV for q≥2

- Emax/Ti,th ~90 is comparable to burning plasma parameters (ITER/DEMO: 3,5MeV/ 30keV)

- opens possibility to study experimentally the interaction between Alfvénic modes, EGAMs i.e. zonal structures and background turbulence: due to the EGAM excitation a direct channel from EPs to n=0 modes can be investigated

physics questions to be clarified:

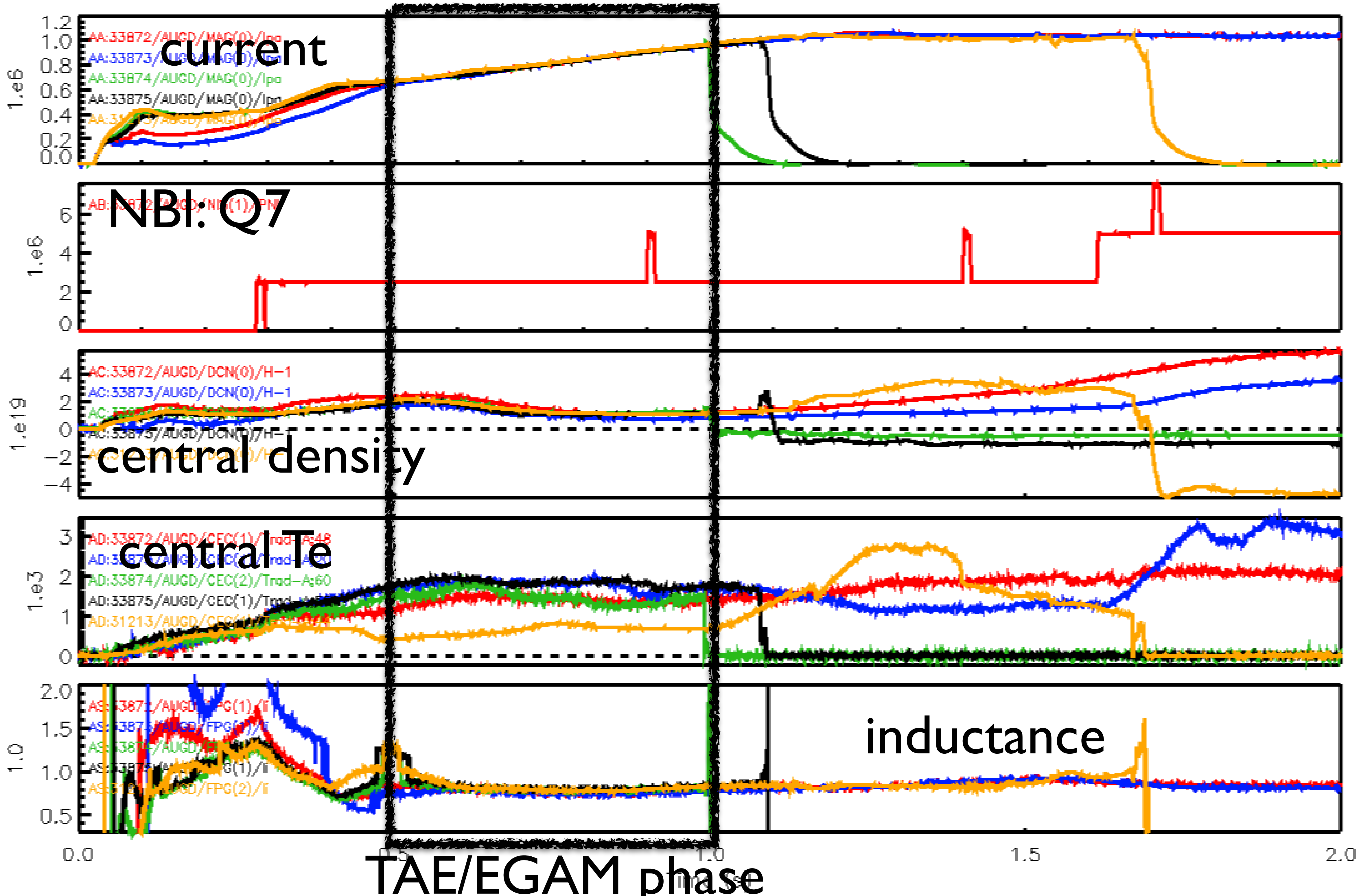
strongly non-linear EP dynamics at AUG for sub-Alfvénic neutral beam injection raises the following questions:

- experimental conditions?
- study non-linear evolution of various ES and EM modes
- study interaction between different modes (TAEs/RSAEs-EGAMs)
- study interaction of modes with turbulence [Zarzoso/Girardo 2015,Sasaki 2017;Duarte 2017]
- study scenarios that match projected DEMO parameters in β_{fast}/β_{th} and T_{fast}/T_{th}
- why can system arrive at state well above marginal stability (critical gradient models would not allow for that state)?

obtain confidence in models and codes towards understanding the self-organisation of a burning plasma;
low-β turbulence-EGAM interaction allows to use electrostatic limit

8 successful discharges: 33872,73,74,75; 34184/85/86/87

reference: 31213



well reproducible scenario

IPP

onset conditions for EGAMs (Ti ≲1.8keV;Te<Ti q≥2) confirmed by new experiments

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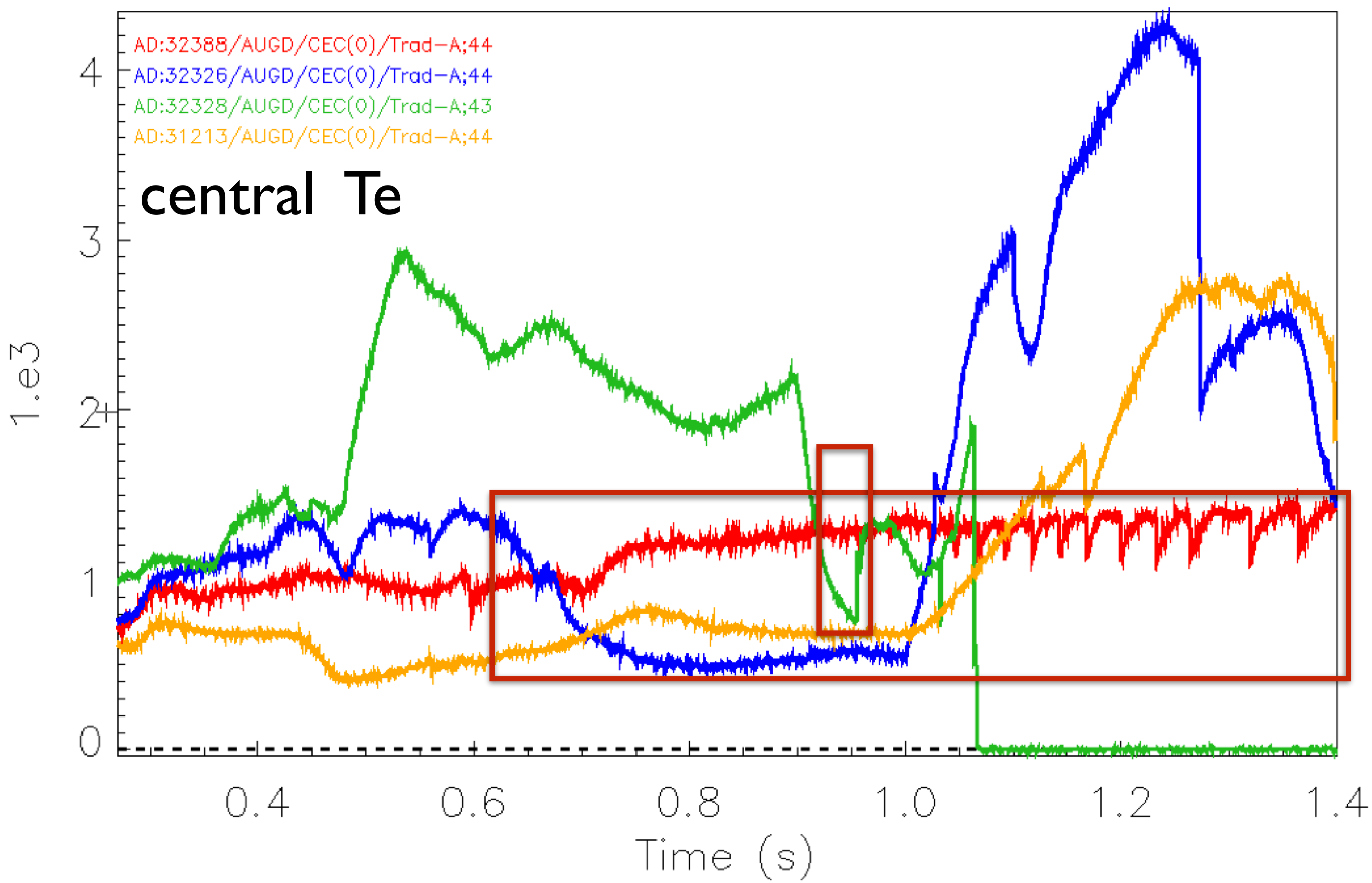
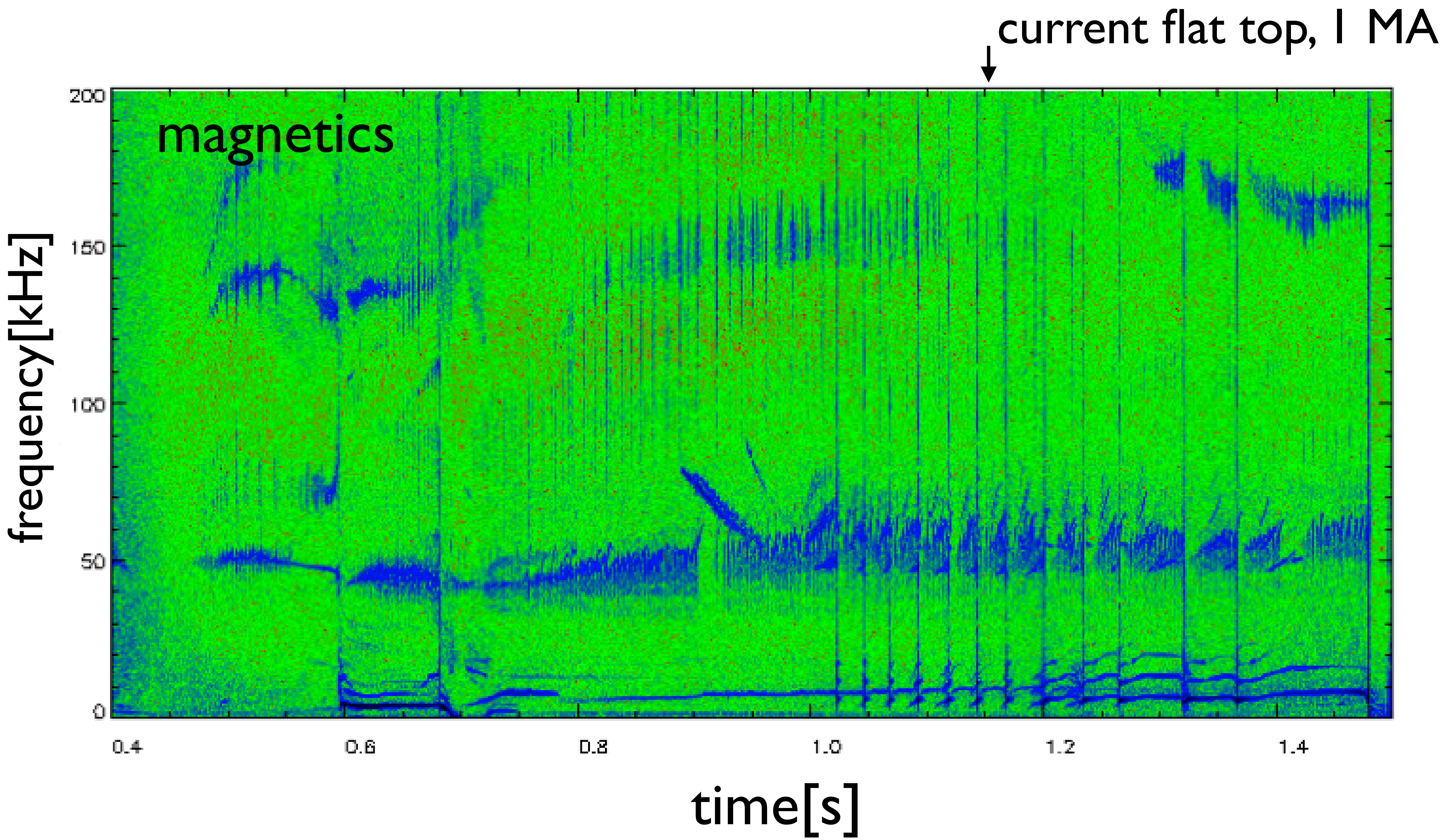


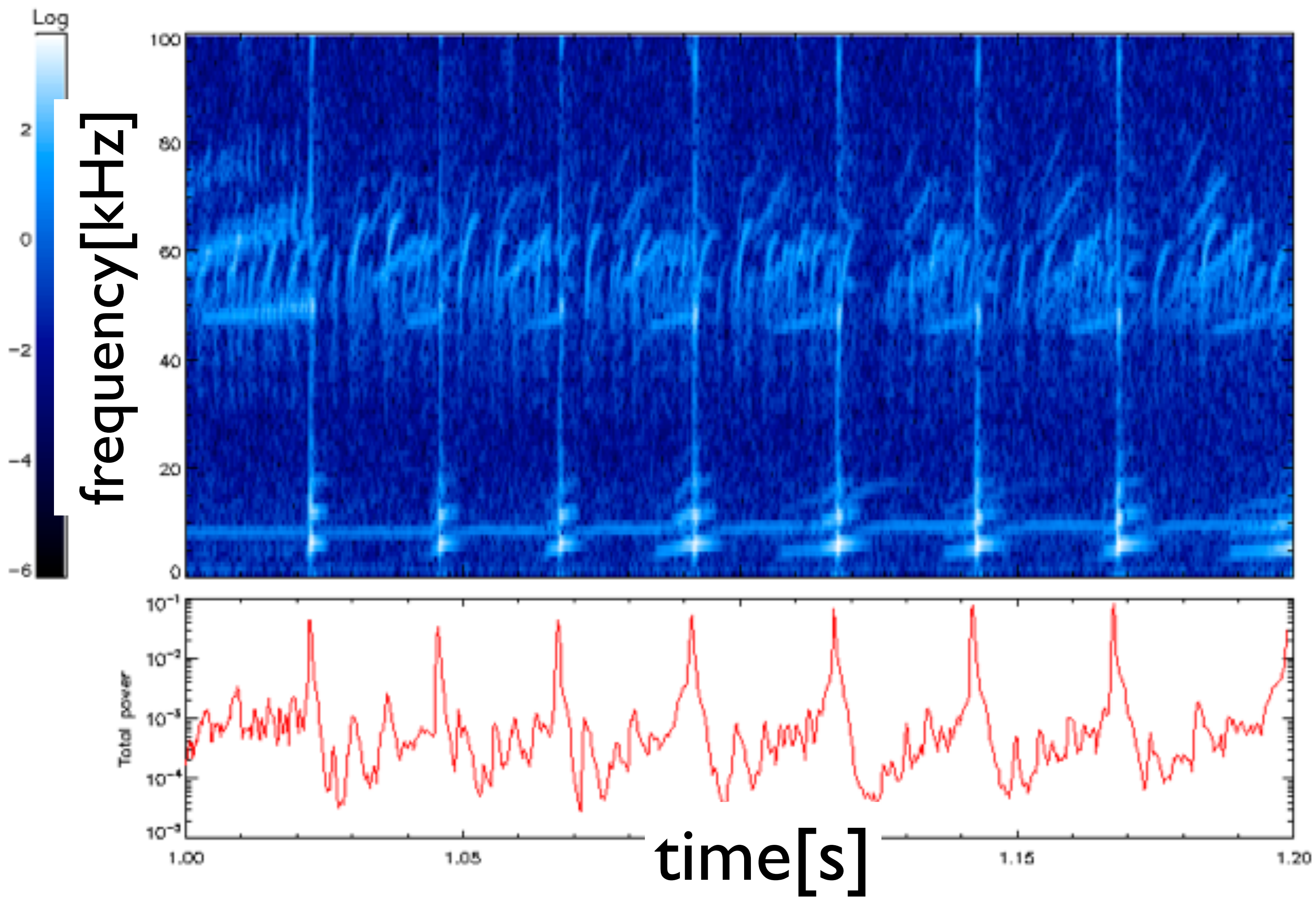
longer, more stable phases with EGAMs in new experiments

scenario developed further (I)

- slightly higher density: more stable transition through $q=2/q_{edge}=4$ region
- optimised beam blips for measuring Ti



regular sawtooth like crashes at q=2 surface



- q=2 sawtooth crashes like in 2001-05 JET/JT60U discharges (current holes) - is this how advanced scenarios JT-60SA will look like? [A Bierwage, 2016/17]
- EGAMs persistent during these crashes
- surprisingly no variation of EGAM onset frequency - constant Ti!

instability threshold for EGAM observed
no Te inversion

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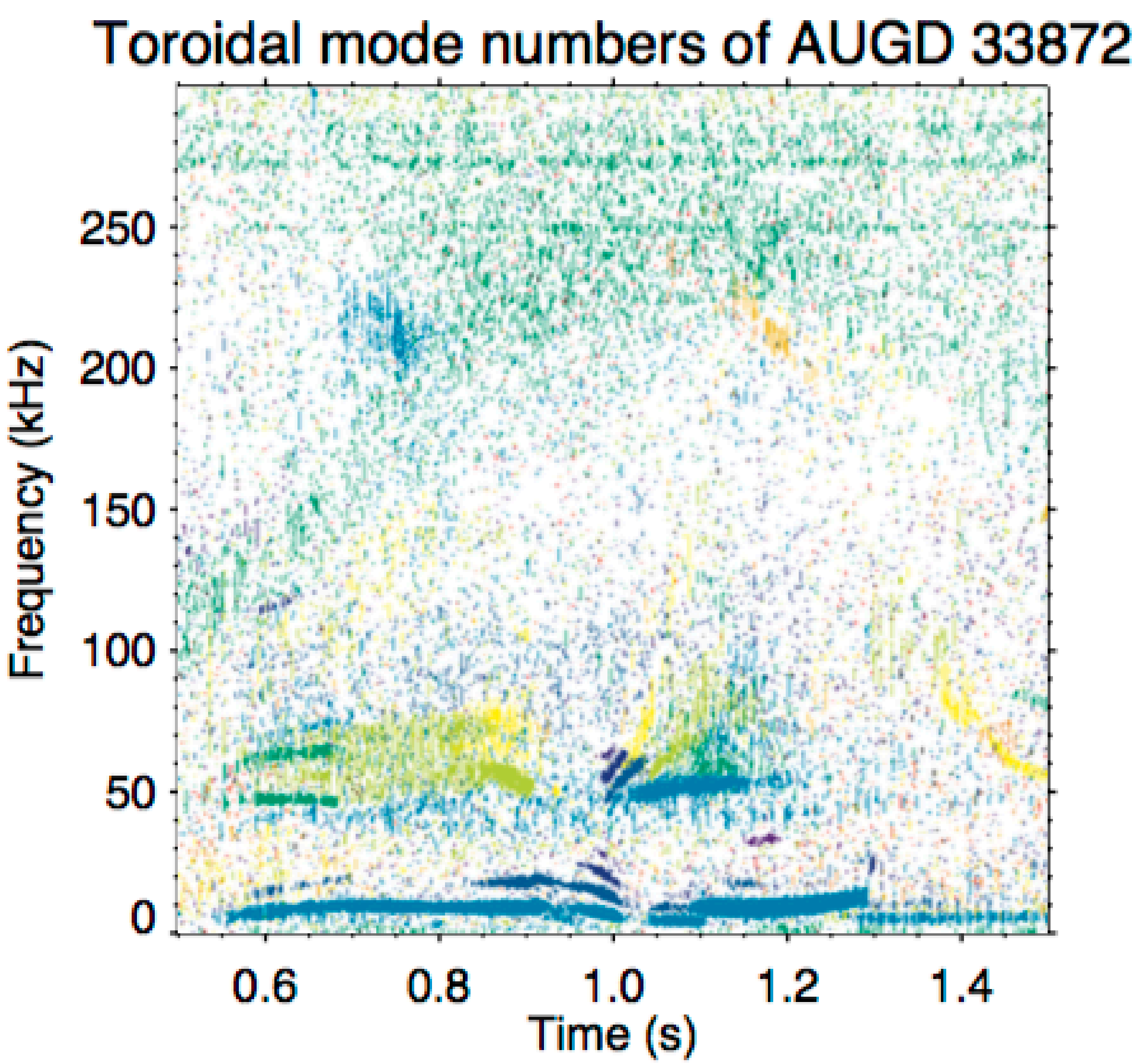
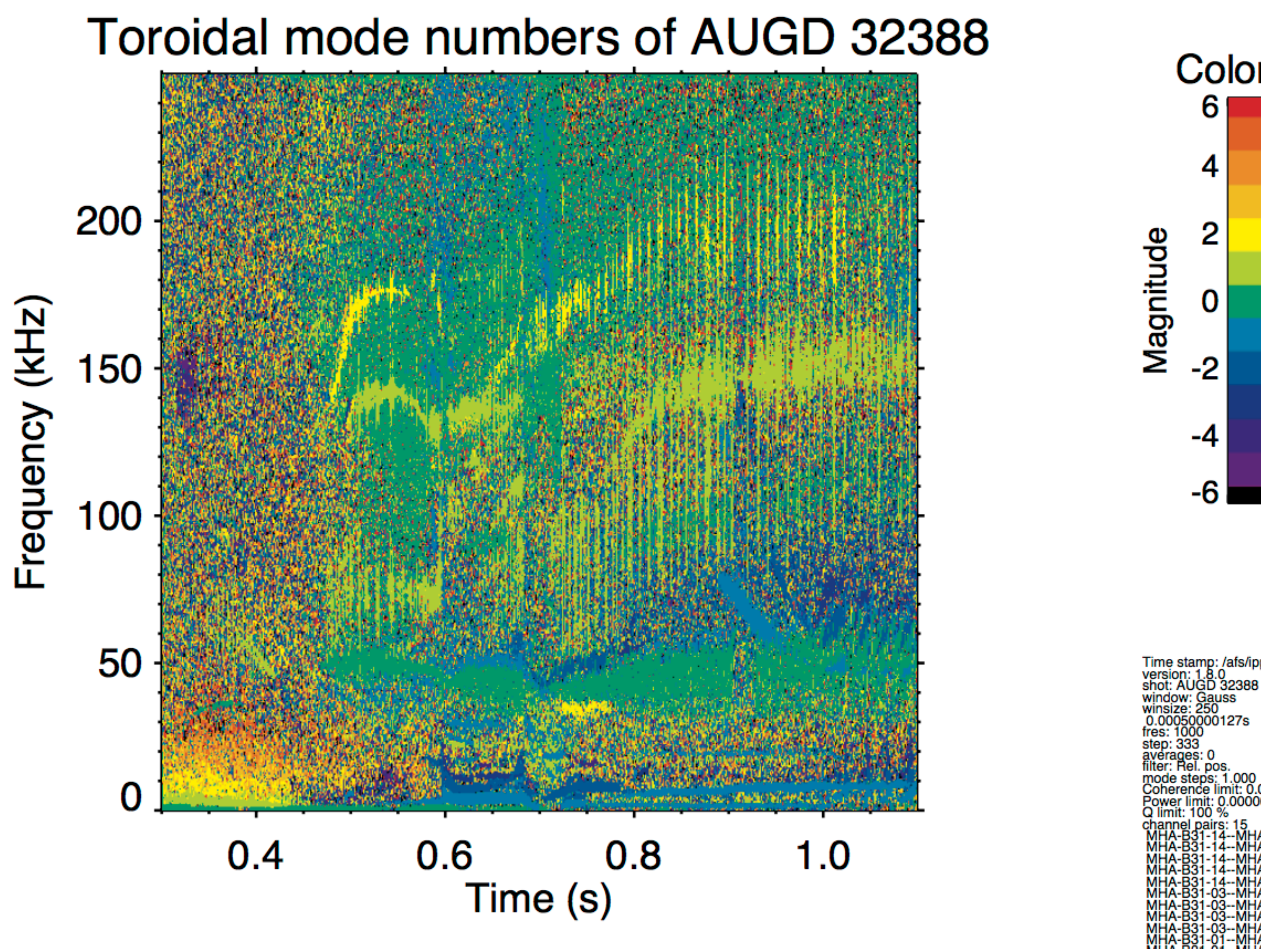




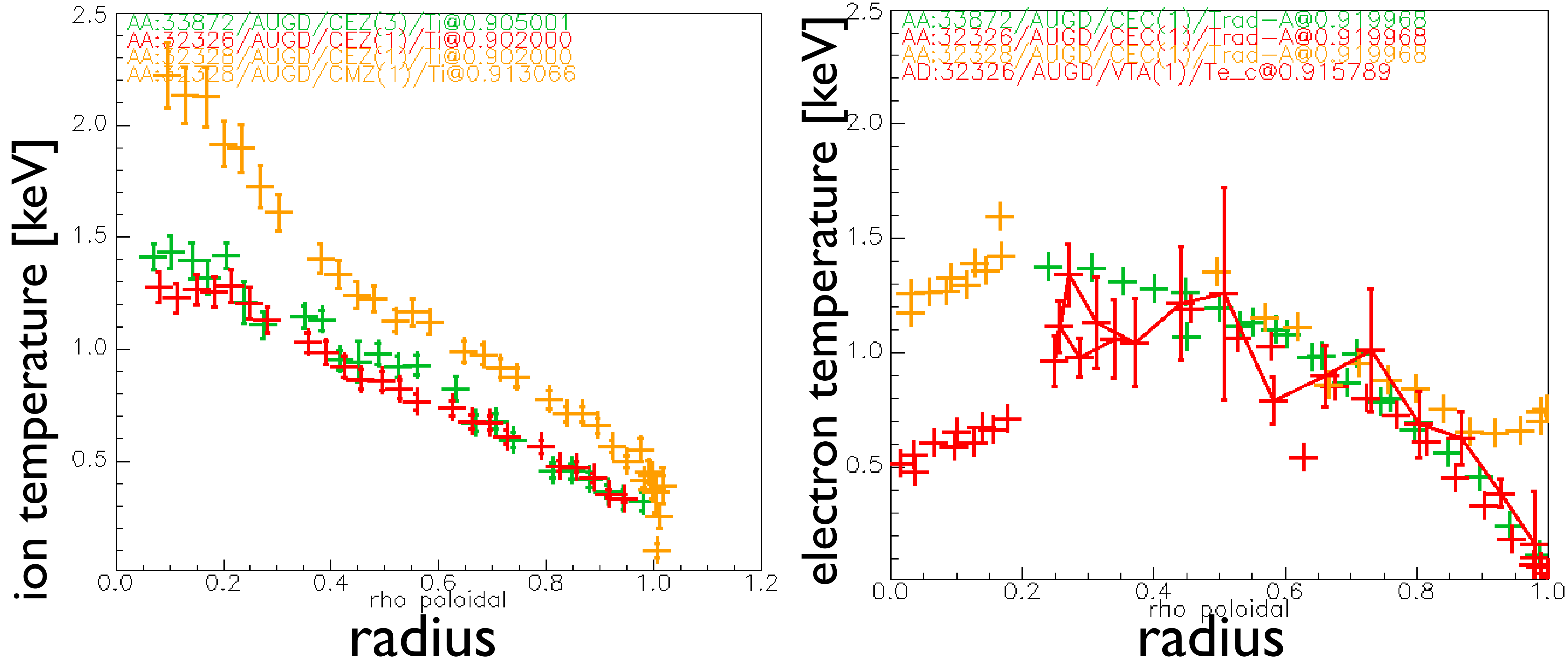
q-profile evolution similar: timing and slope of RSAEs similar

instability threshold for EGAM: Ti, Te profiles

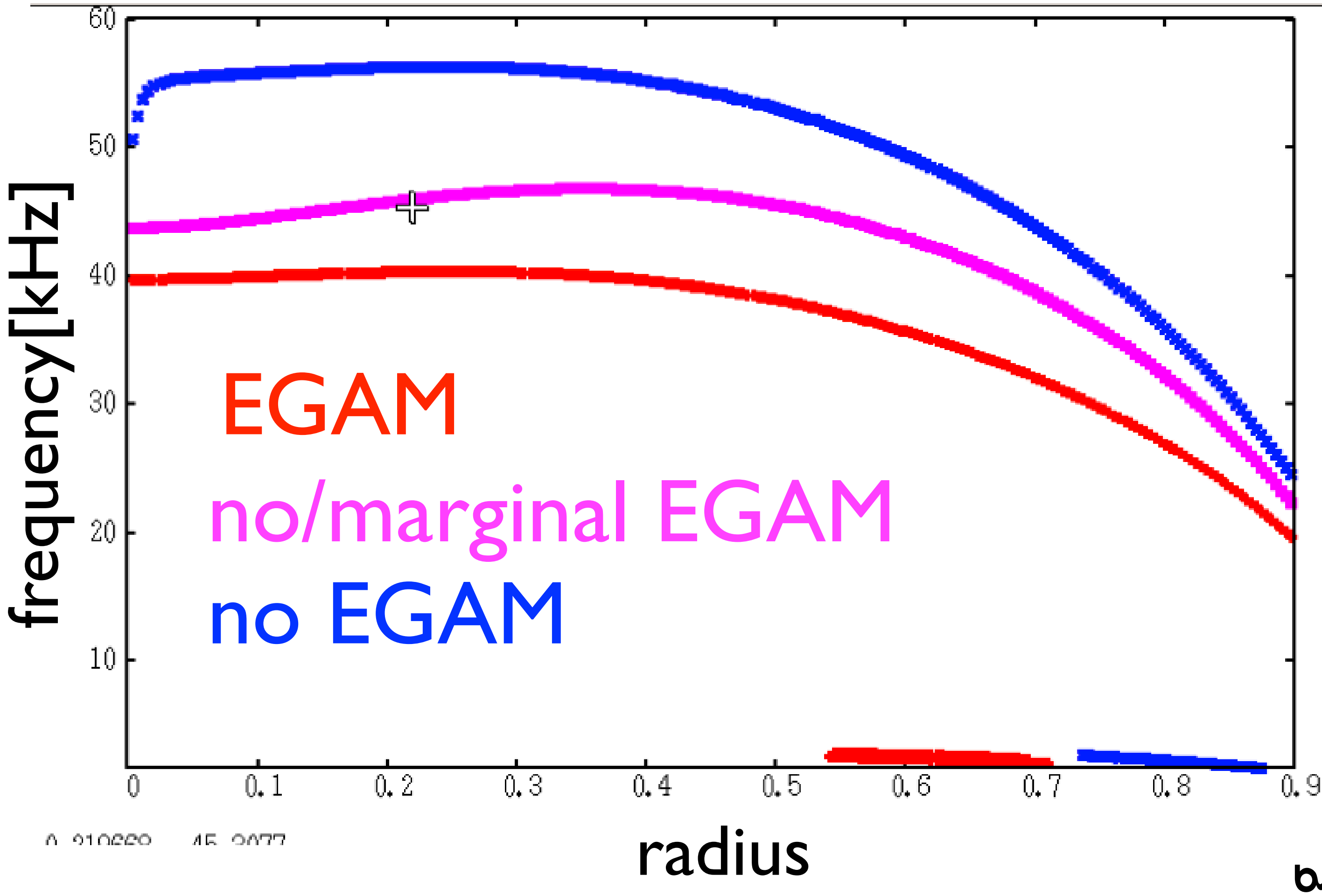
discharge with EGAM

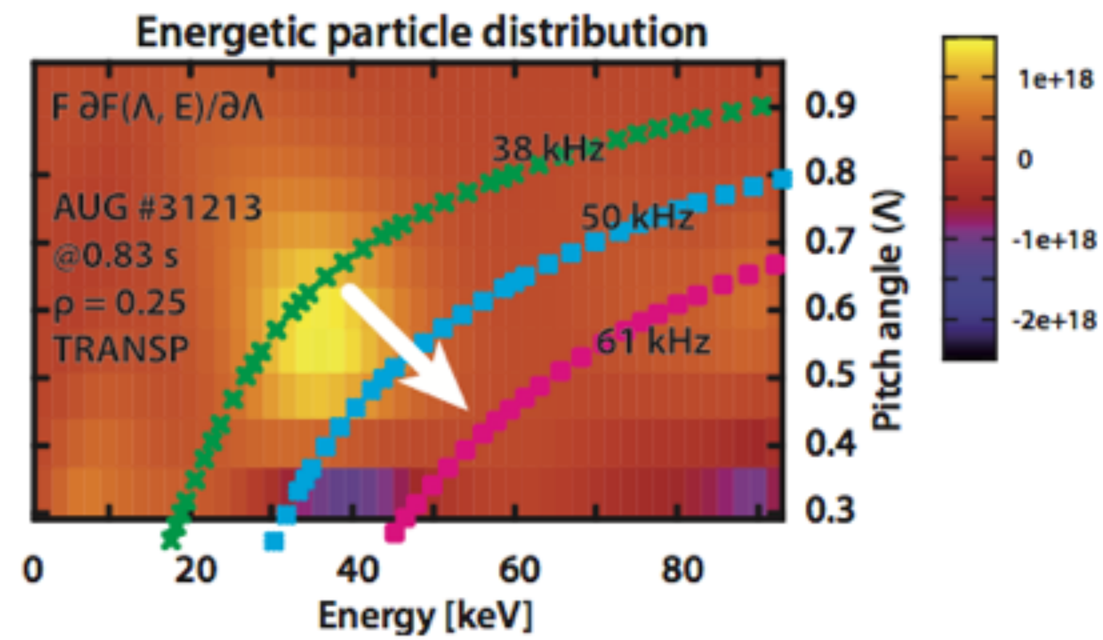
discharge without EGAM

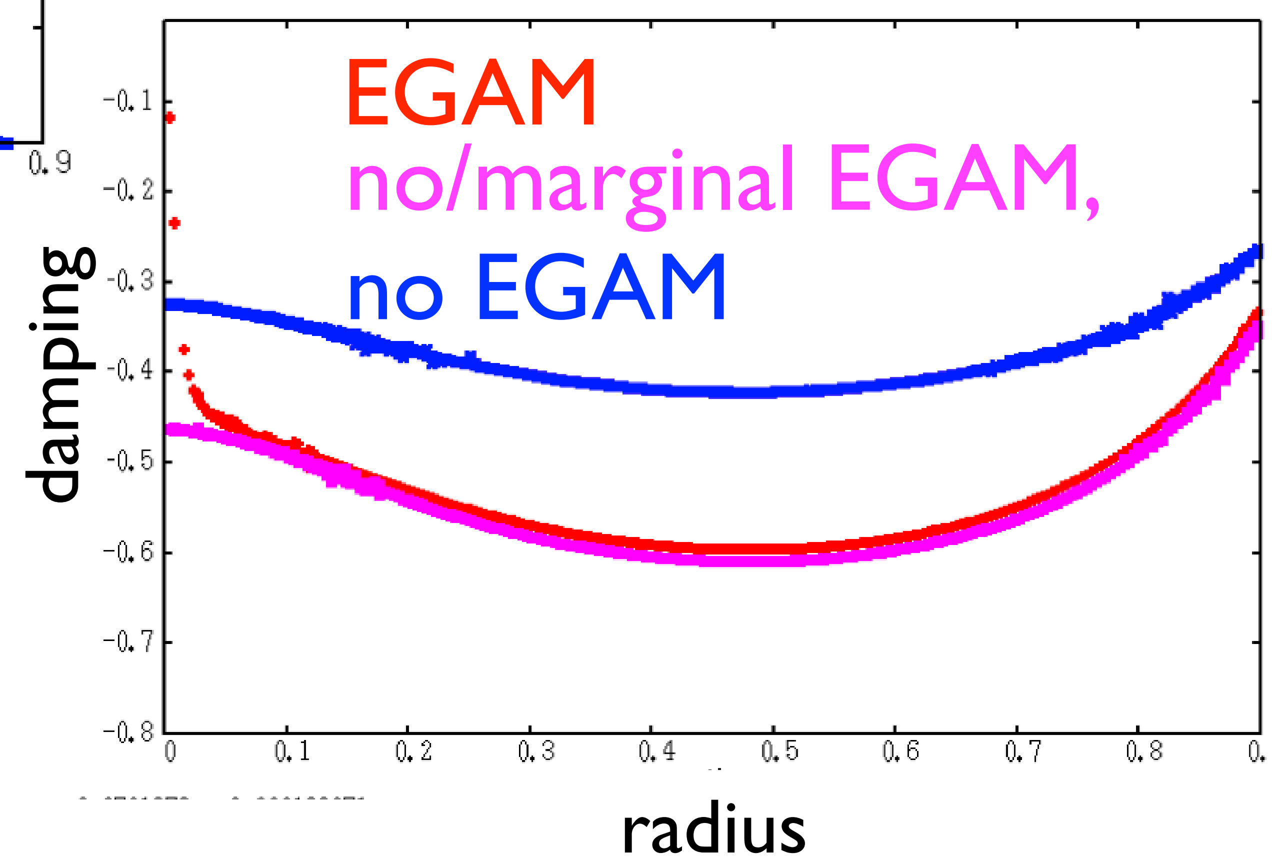
discharge at marginal stability of EGAM



LIGKA analysis: GAM continuum (ZOW/ZLR)

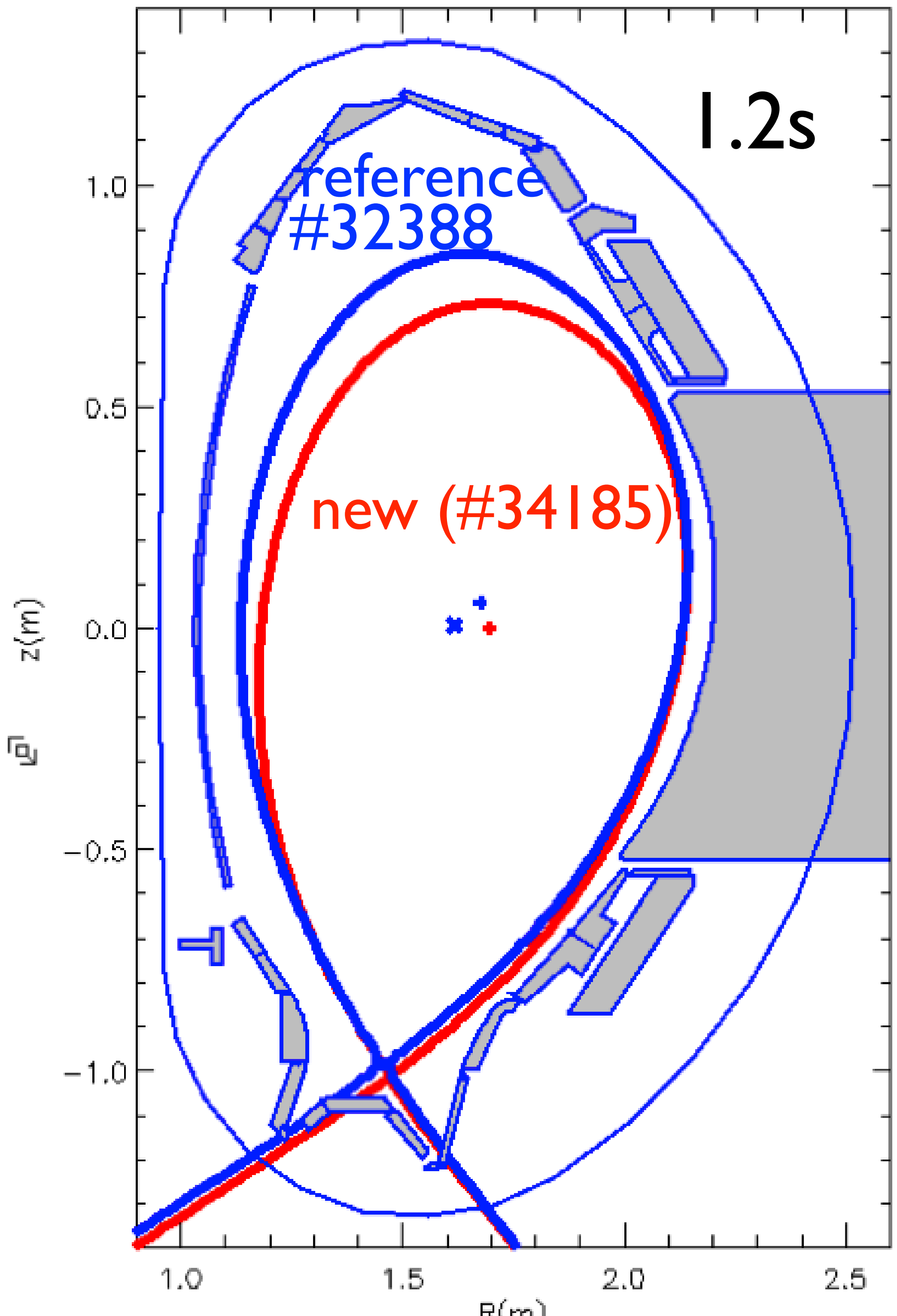




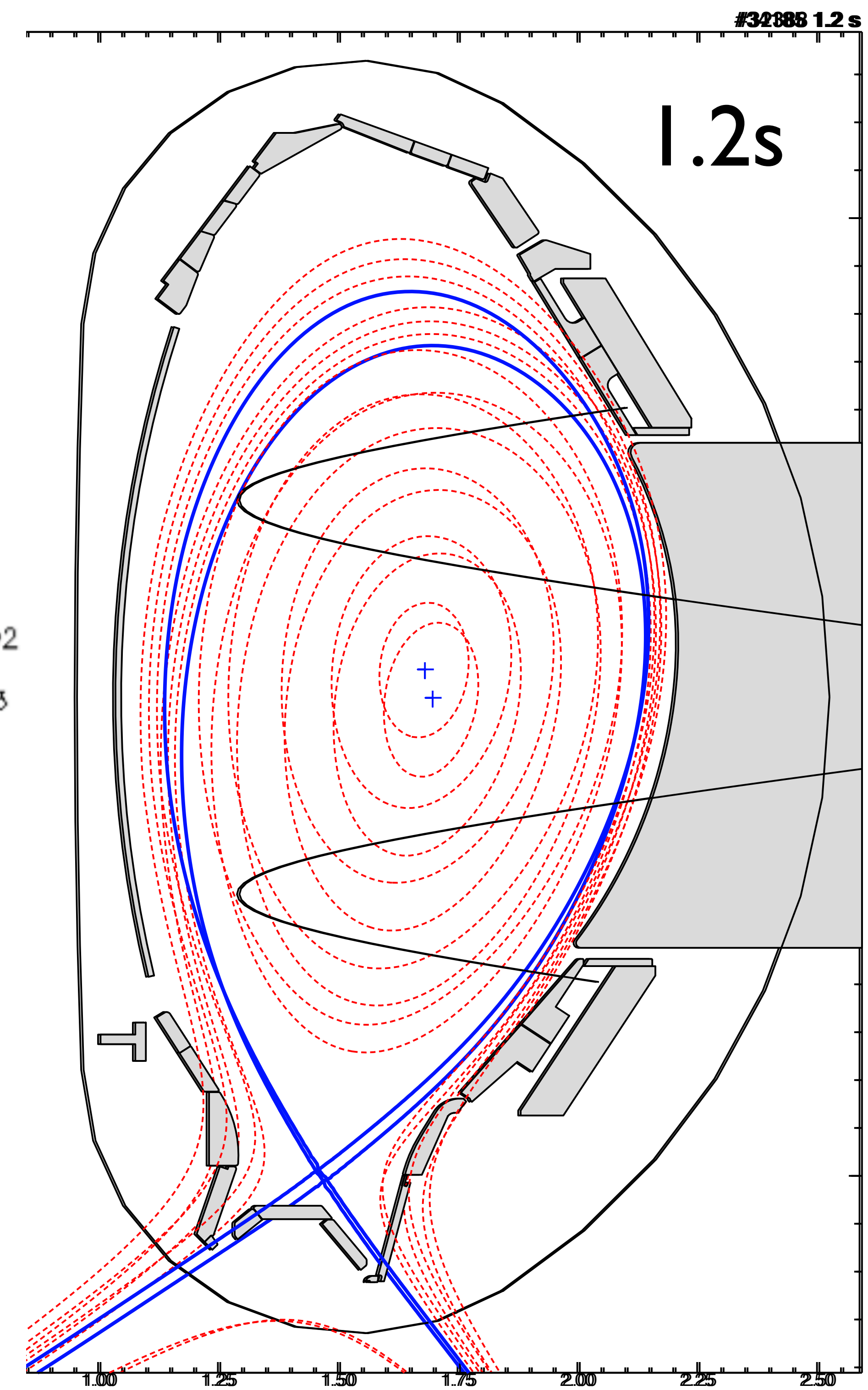


- both Ti and Te important for mode stability;
- strongest anisotropy has to match GAM continuum
- other effects important? propagation?

modification of plasma position and shape after t>0.8s: mainly different NB deposition position



AUG Flux: ρ_{pol}	AUG Flux: Ψ_{pol}
AUGD/EQI(1)	AUGD/EQI(1)
AUGD/EQI(1)	
Shot: 32388	Shot: 34185
Time: 1.200	Time: 1.200
From GQI	From GQI
I_p : 1.02MA	I_p : 1.01MA
β_p : 0.21	β_p : 0.23
l_i : 0.91	l_i : 0.84
ma: 1.677 : 0.05	ma: 1.698 :−0.002
cc: 1.619 : 0.007	cc: 1.640 :−0.063
δ_o : −0.022	δ_o : −0.082
δ_u : 0.361	δ_u : 0.389
κ : 1.742	κ : 1.728
a_{hor} : 0.497m	a_{hor} : 0.478m
q_{95}: −3.88	q_{95}: −3.52
R_{aus} : 2.144m	R_{aus} : 2.142m
vol : 13.45m³	vol : 12.44m³
Δ_s : 0.058m	Δ_s : 0.058m
z_{gi} : −1.116m	z_{gi} : −1.150m
z_{ga} : −1.346m	z_{ga} : −0.801m



results in different inductance, q-profile, elongation [thanks to Th Pütterich]

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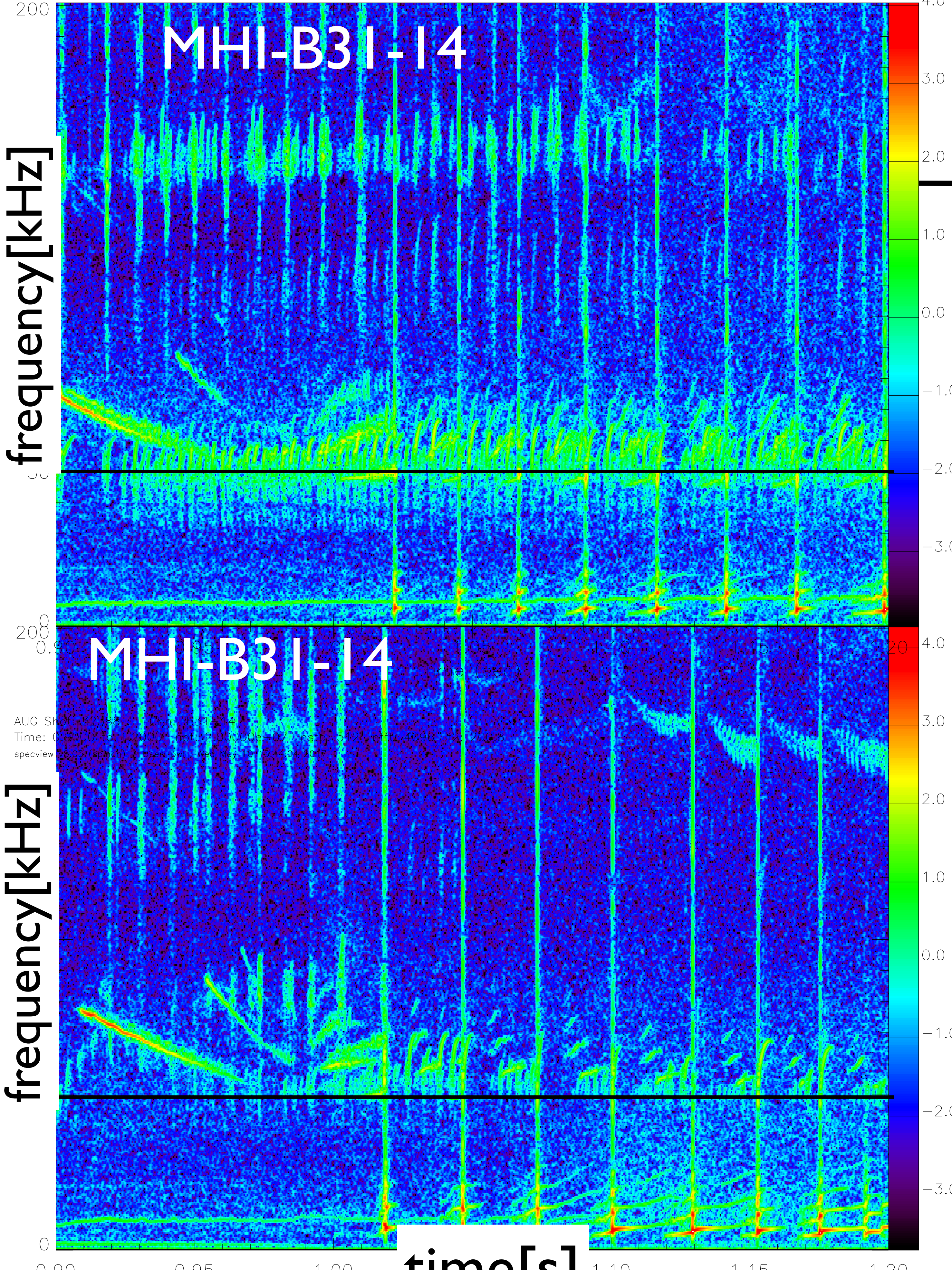
scenario developed further (II)

reference (#32388)

new shape (#34185)

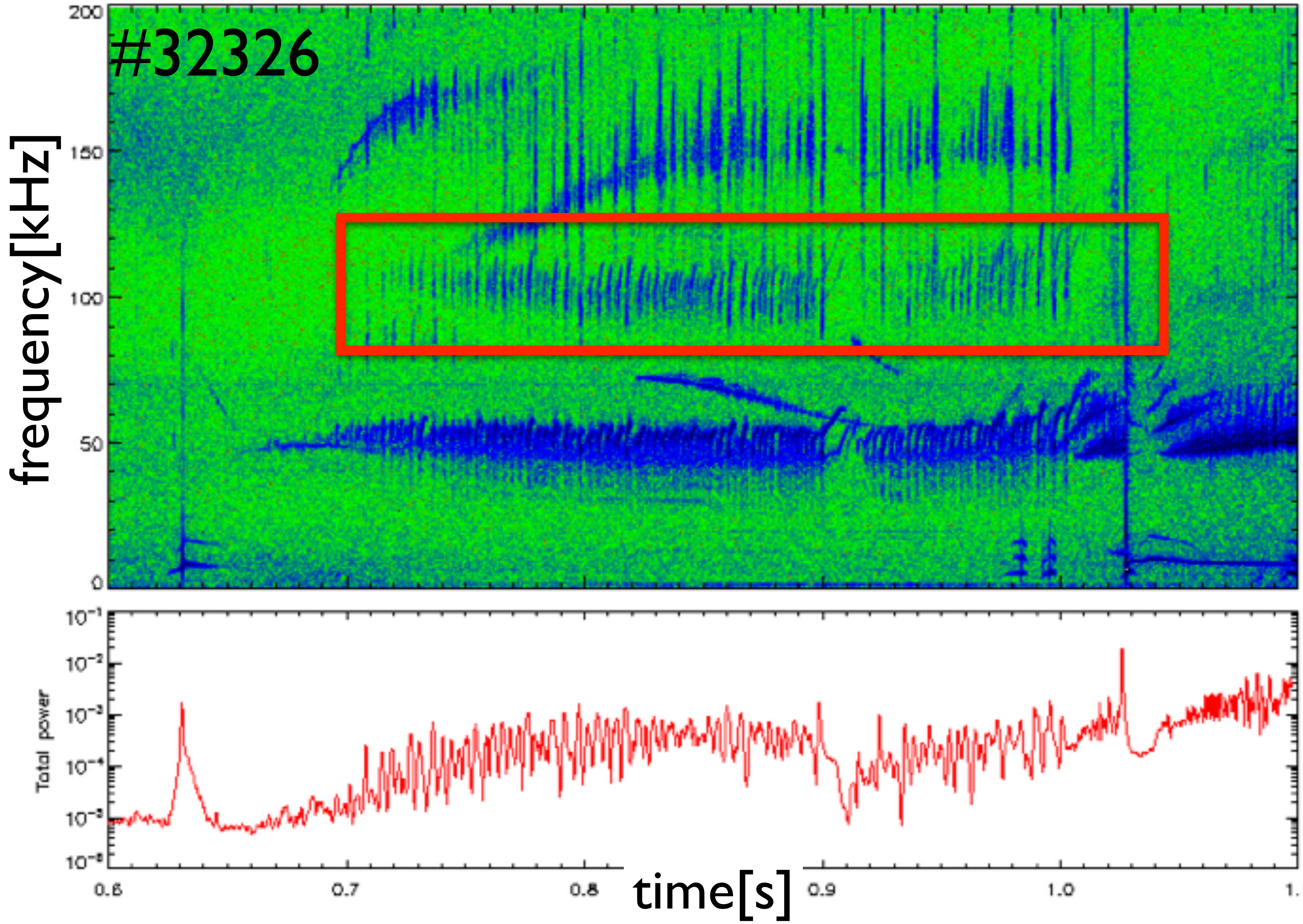


different dynamics for:

- TAEs
- EGAMs
- TAE/EGAM coupling
- q=2 crashes

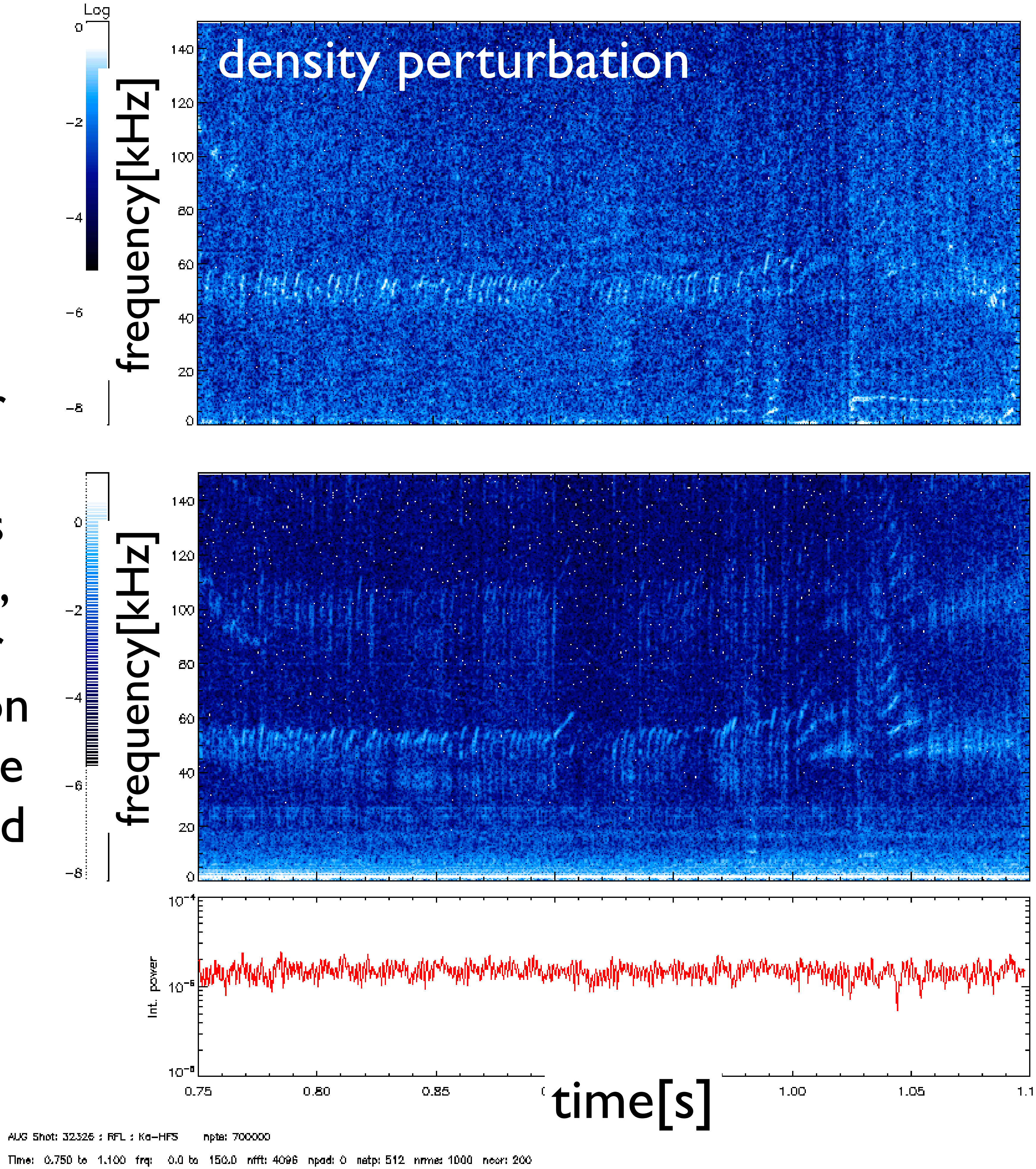
almost no difference in profiles; details of NB distribution function seem to be responsible

scenario developed further (III)



2nd order EGAM excitation: signature of density perturbation

DIII-D,Fu [2011]: 2nd order outboard midplane density perturbation is comparable to first-order perturbation at AUG: first order EGAM harmonics dominates, 2nd order perturbation more visible on high field side



reflectometry: low field side

reflectometry high field side

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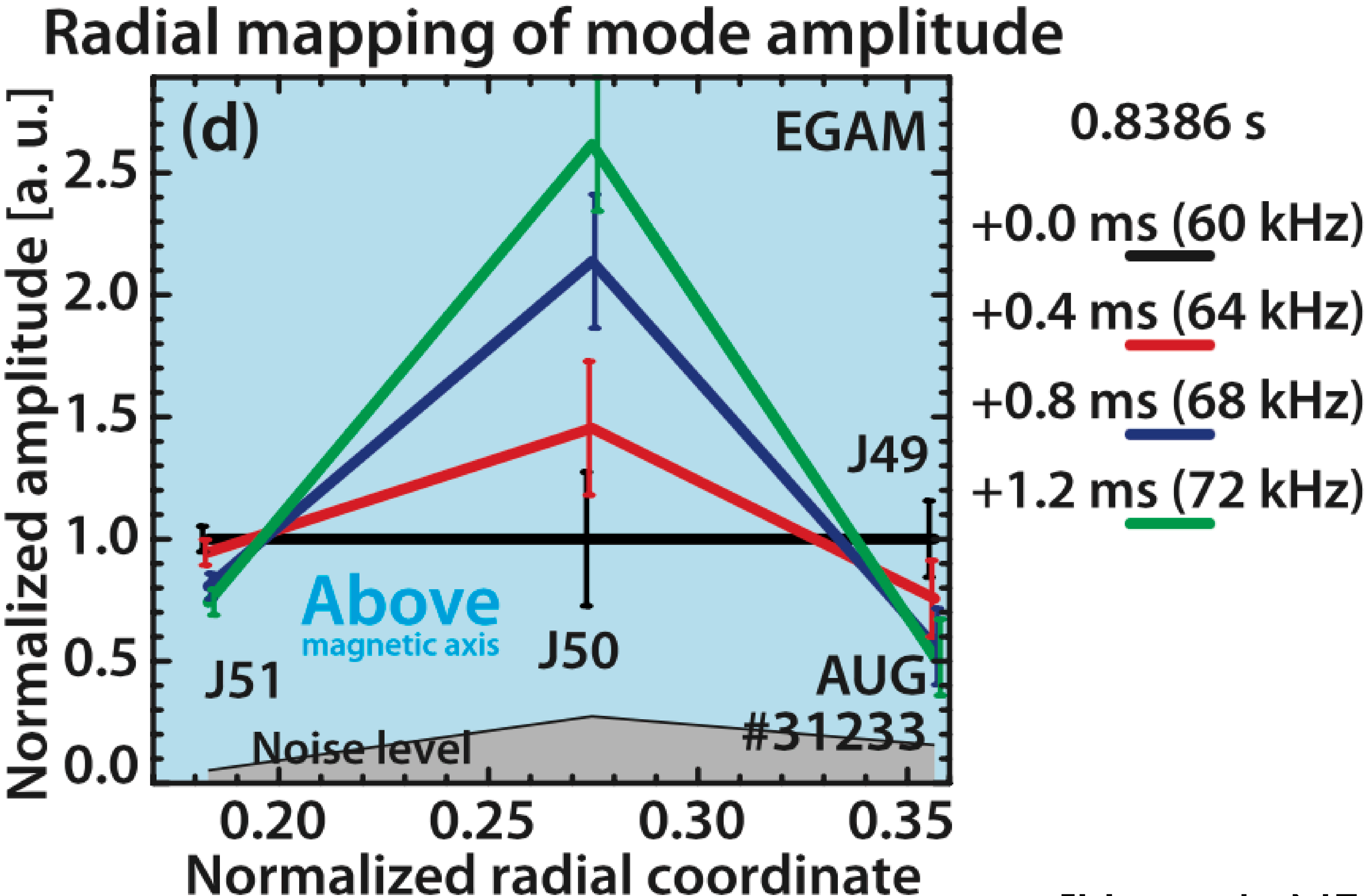
mode localisation: SXR data



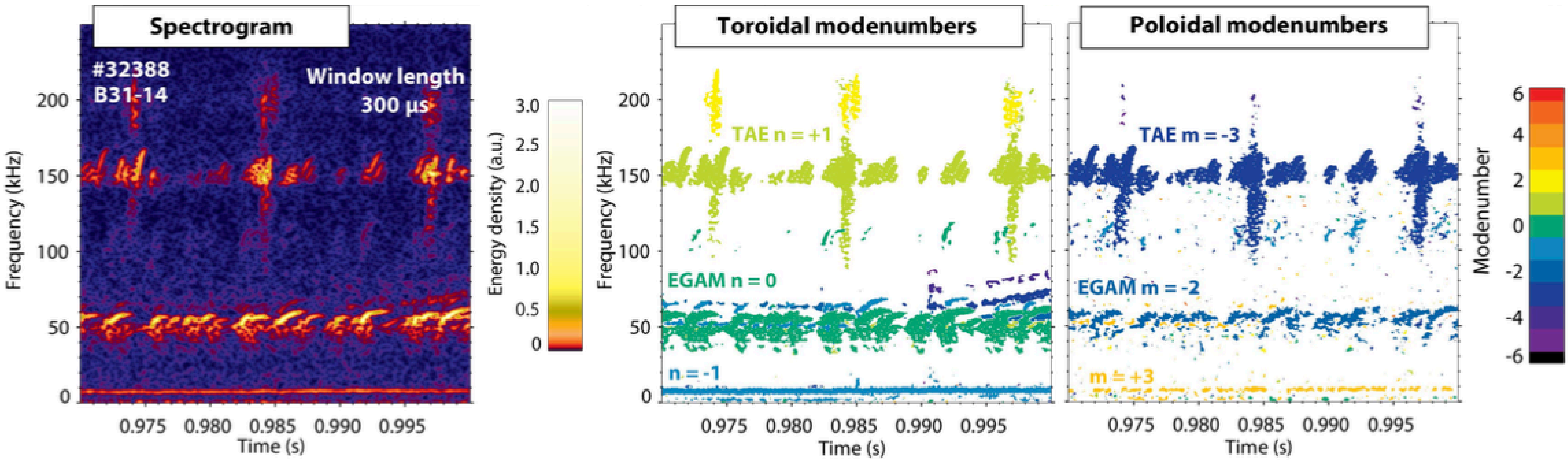
[Horvath, NF 2016]

radial position agrees with reflectometry data, interferometer

advanced bicoherence analysis [P Poloskei et al IAEA TCM 2017]

- Chirping **EGAMs at ~50 kHz** with **(-2,0)** (propagating in electron diamagnetic direction)
- Chriping/bursting **TAEs at ~150 kHz** with **(-3,+1)**

AUG #32388

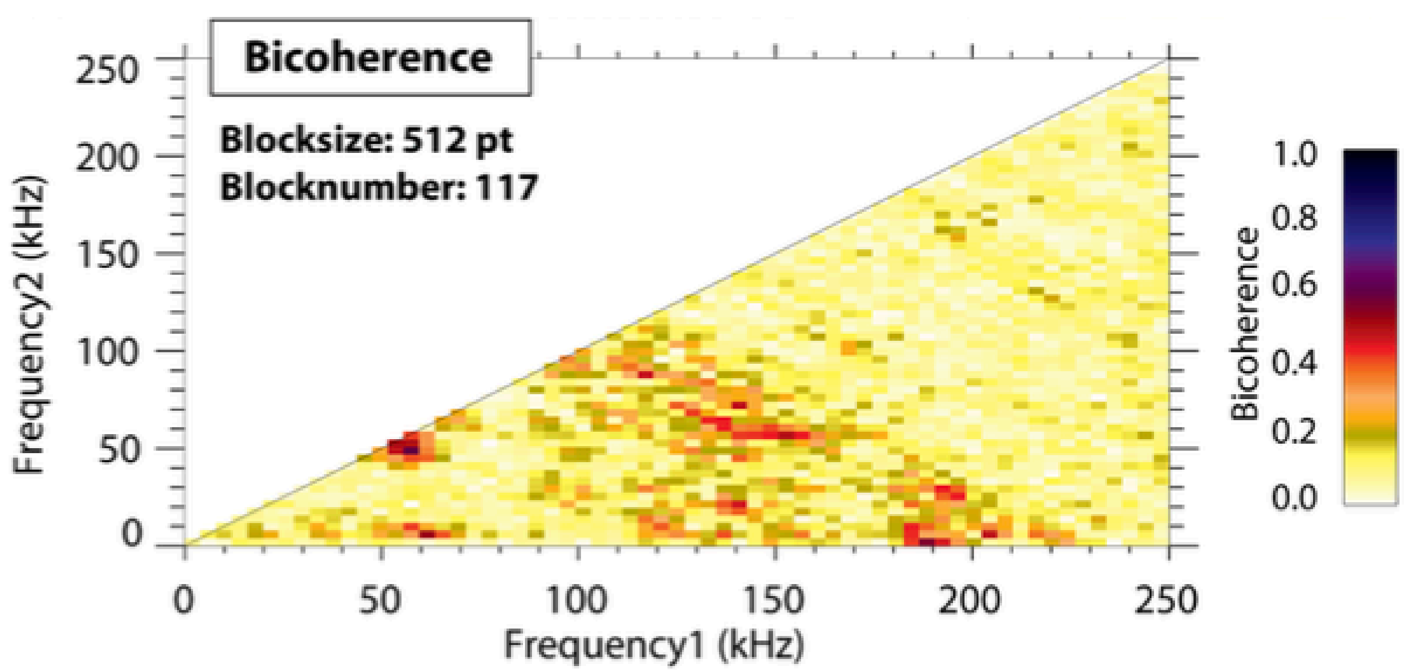


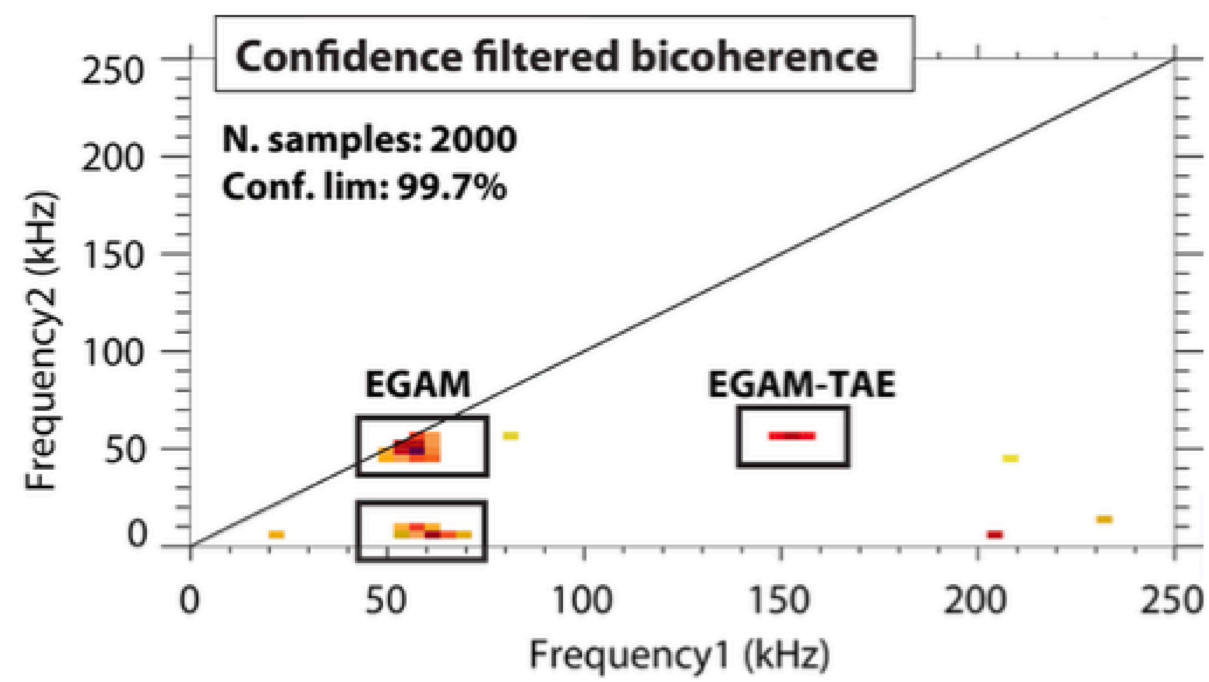
signals with rapid chirping (amplitudes, frequency) may cause 'spurious' bicoherence

phase randomized bicoherence probability density function calculation

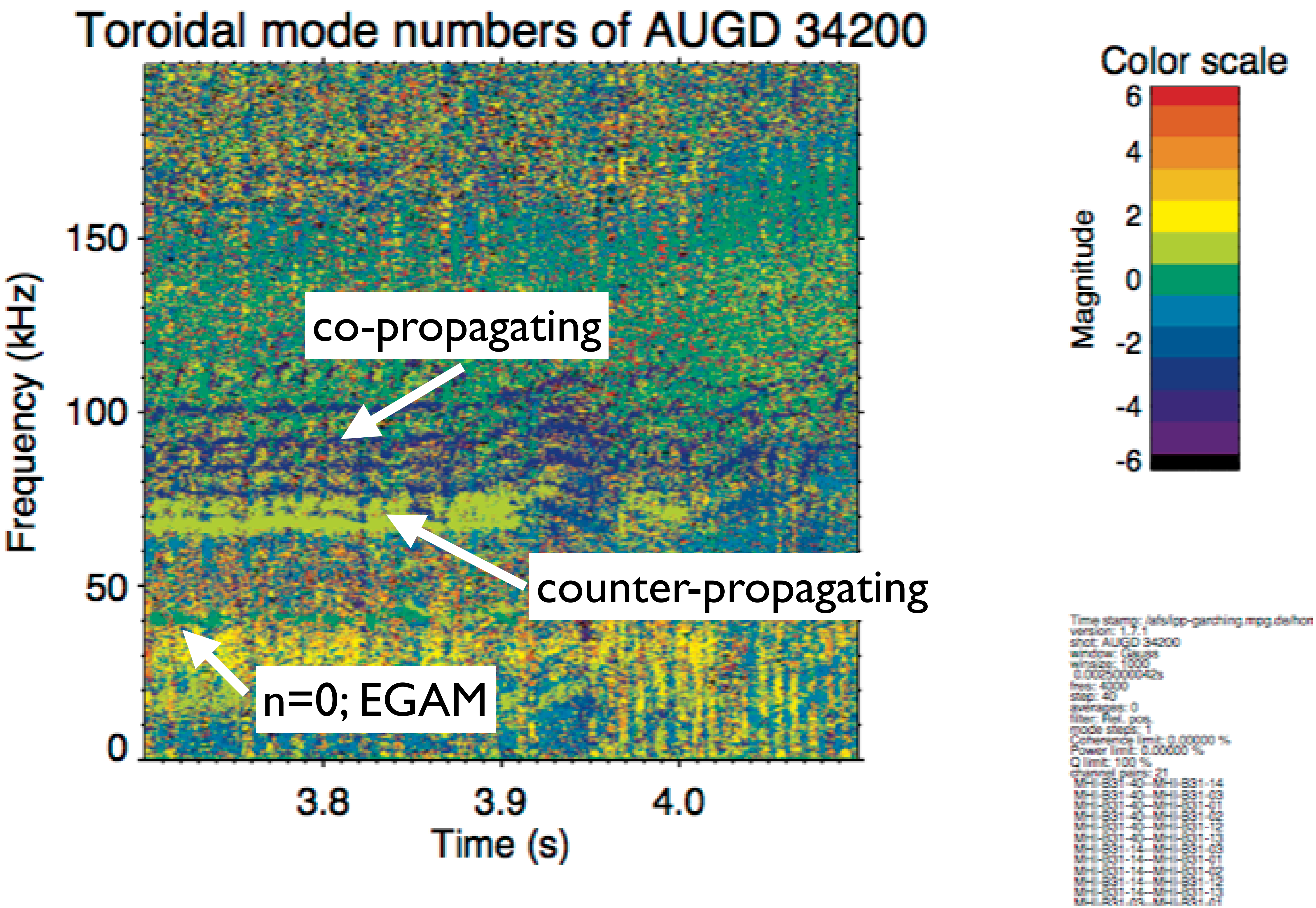
- High bicoherence around at (55, 55) kHz indicates **strongly nonlinear EGAMs.** (see spectrogram at ~110 kHz)
- **Without filtering interaction with TAEs is not clear**

- Filtering shows high, significant bicoherence around (155, 55) kHz
- Indicates the **nonlinear interaction between EGAMs and TAEs**





consistent observation: similar EP dynamics found in 600kA discharges with off-axis NBI only [B. Geiger]



modeling efforts

AUG data inspired wide-spread theory efforts:

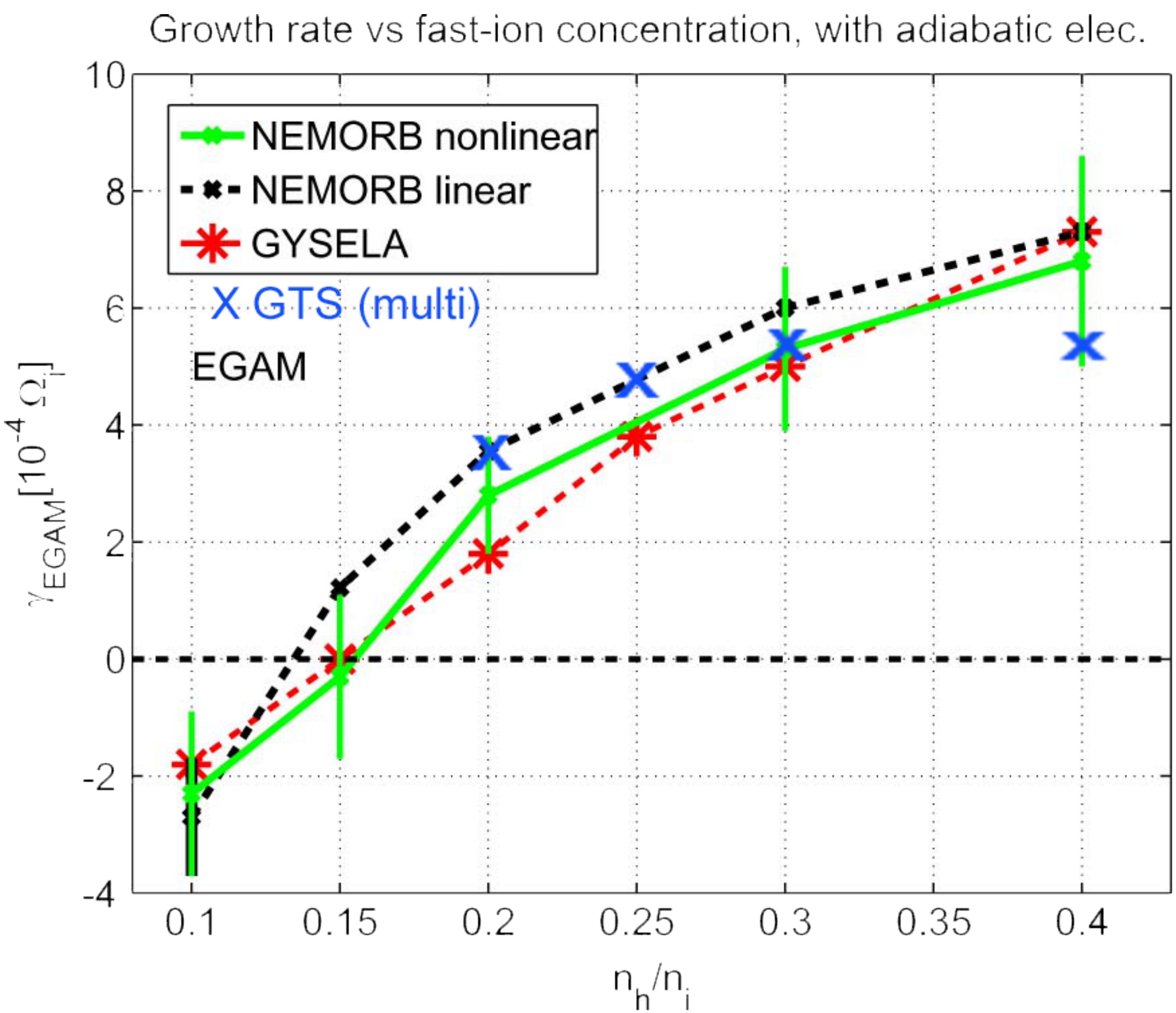
- ENR NLED (Zonca);
- ENR NAT(Lauber) ;

} Biancalani:ORB5; X. Wang: XHMGC; A. Mishchenko: Euterpe, Lauber: LIGKA

- MPPC: M. Schneller, (GTS), I. Chavdarovski
- QST, Japan: H. Wang (MEGA), A Bierwage(LIGKA)

- linear drive
- radial propagation
- non-linear interaction: wave-wave
- non-linear interaction: wave-particle

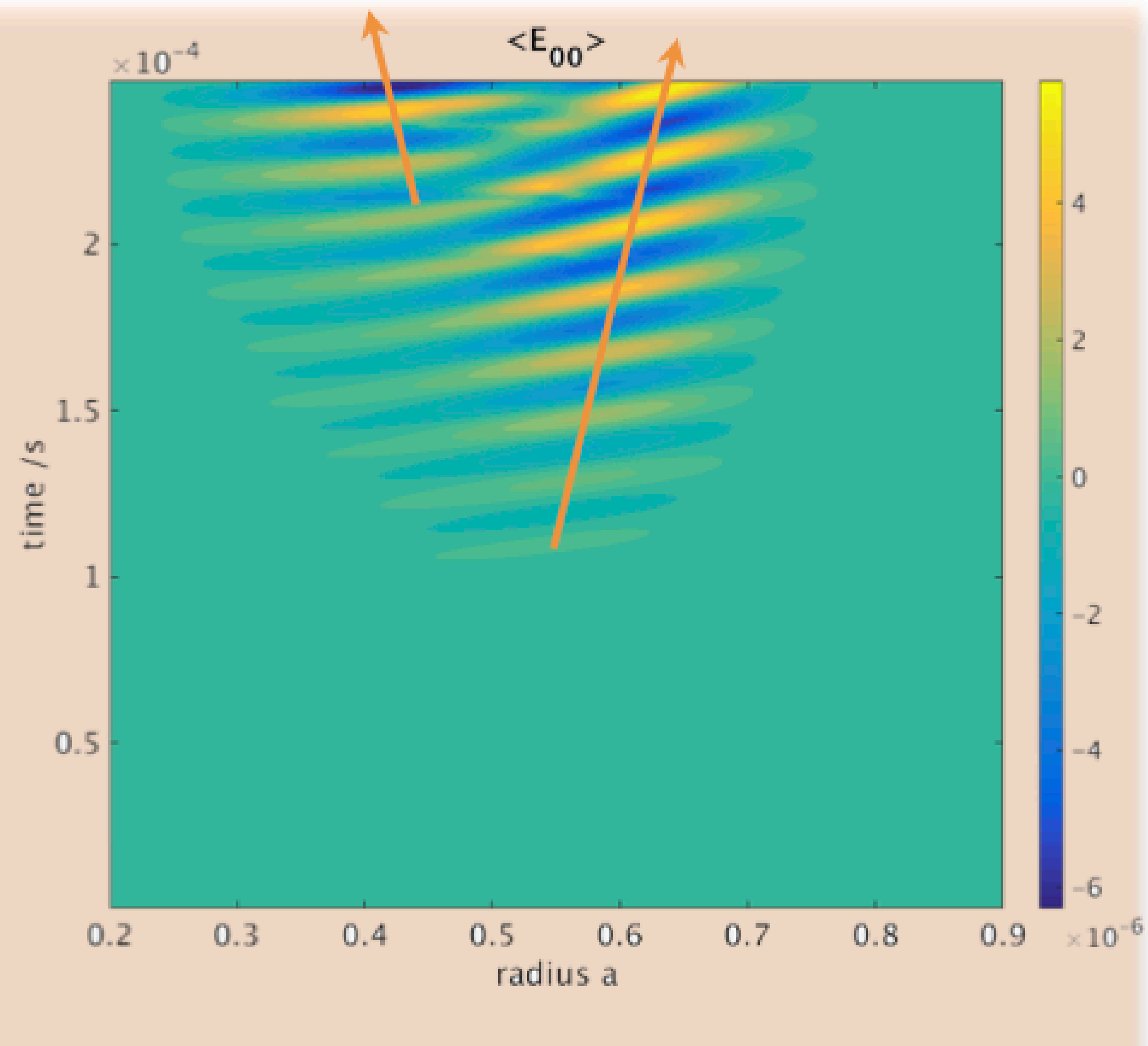
linear EGAM physics: codes agree rather well



importance of radial propagation

- analytical/numerical models point out importance of radial GAM/EGAM propagation [Zonca 2008, Qiu, 2009,Smolyakov 2009, Sasaki, Miki&Idomura 2015, Palermo 2017, etc..]

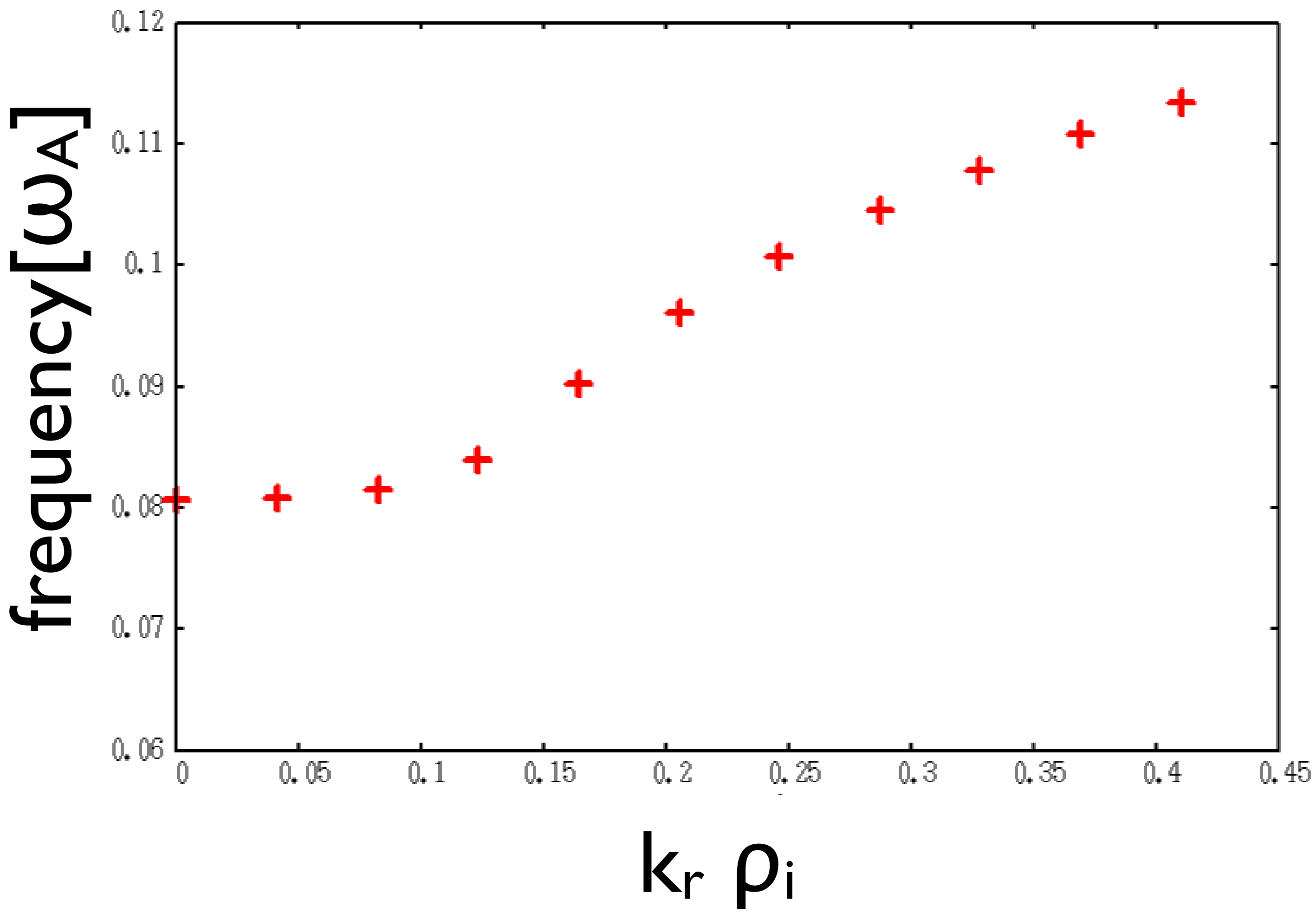
- nonlinear simulations GYSELA, GTS [Zarzoso, Schneller] and nl-analytical models [Sasaki] emphasise the role of radial GAM/EGAM propagation for turbulence spreading



[Schneller, 2017 MPPC meeting; modified AUG]

newly developed FLR/FOW analytical LIGKA allows for radial propagation studies: $\omega(k_r)$

vg= ∂ω/∂kr can be determined from this:



outward propagation for q=2.1

stable, global kGAM solutions emphasize importance of GAM continuum[LIGKA], exp. f_{EGAM} close to f_{GAM}

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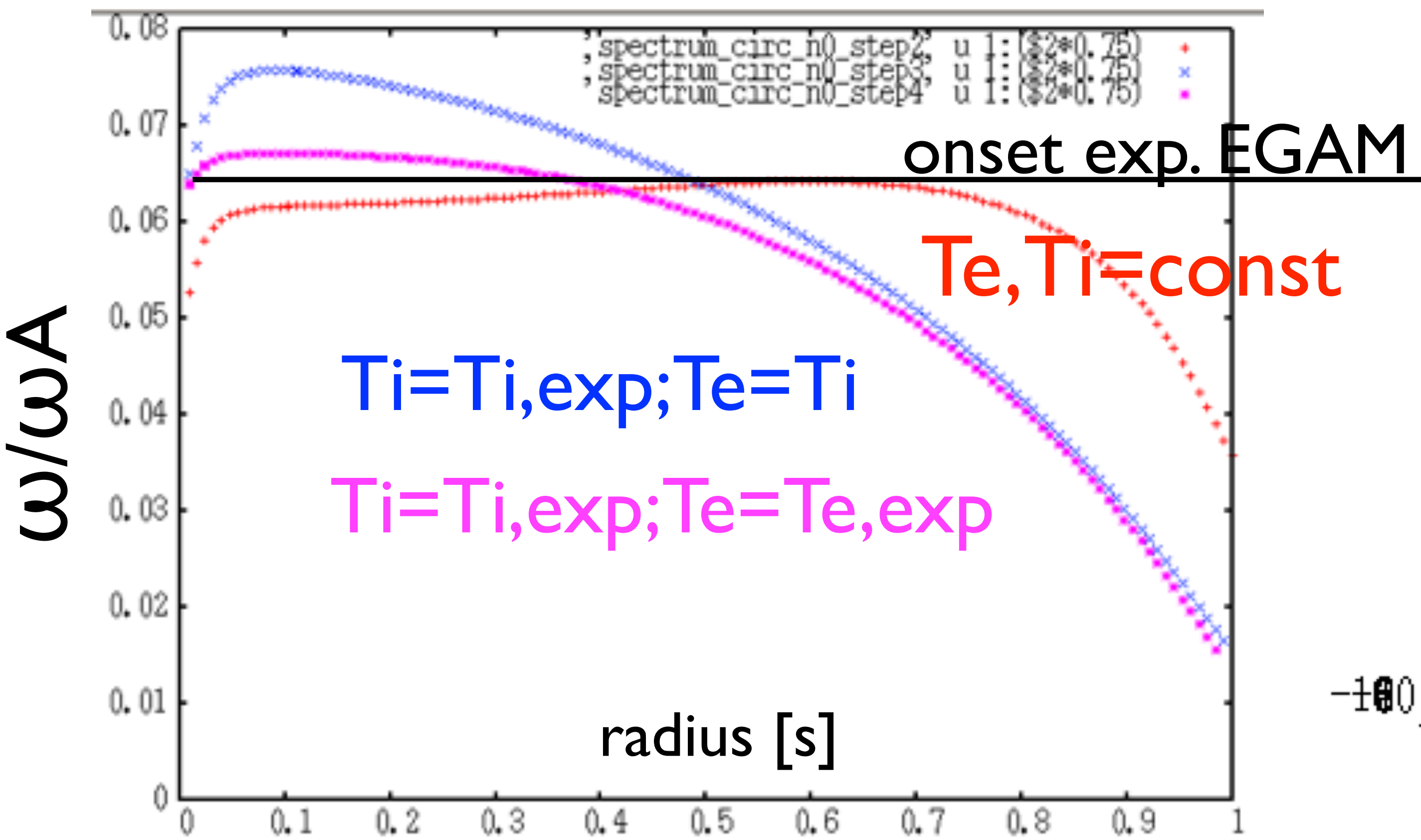
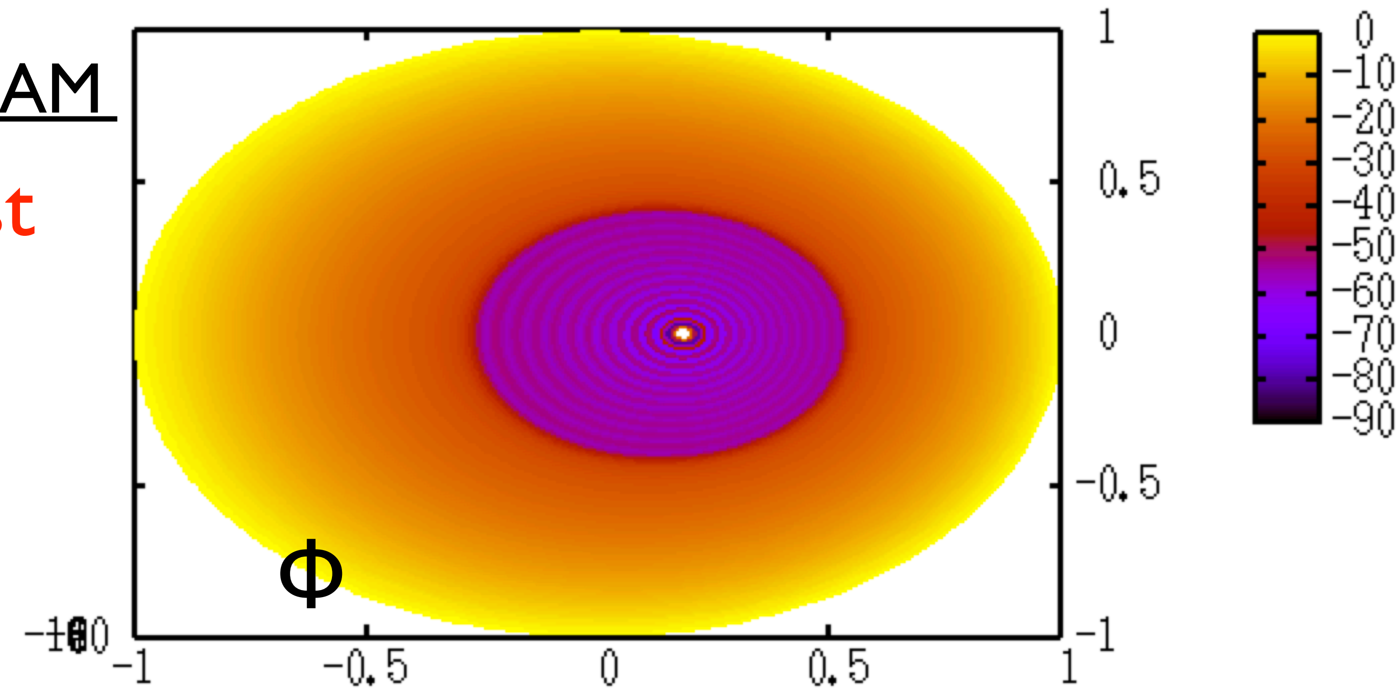
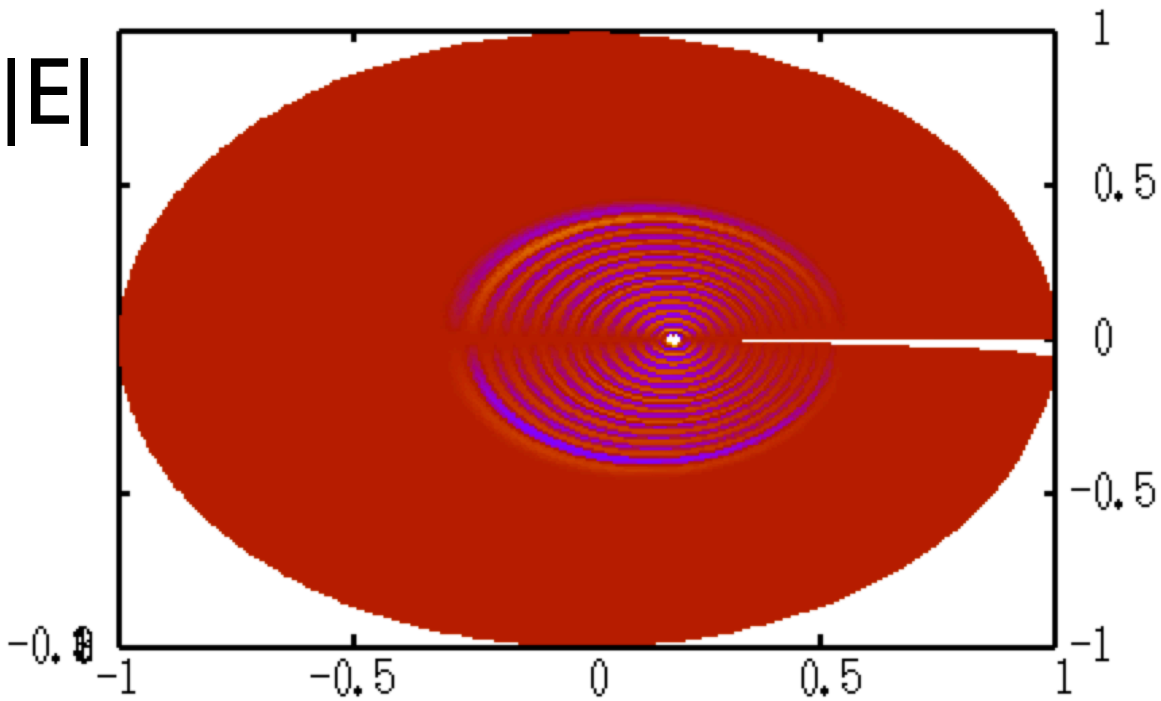
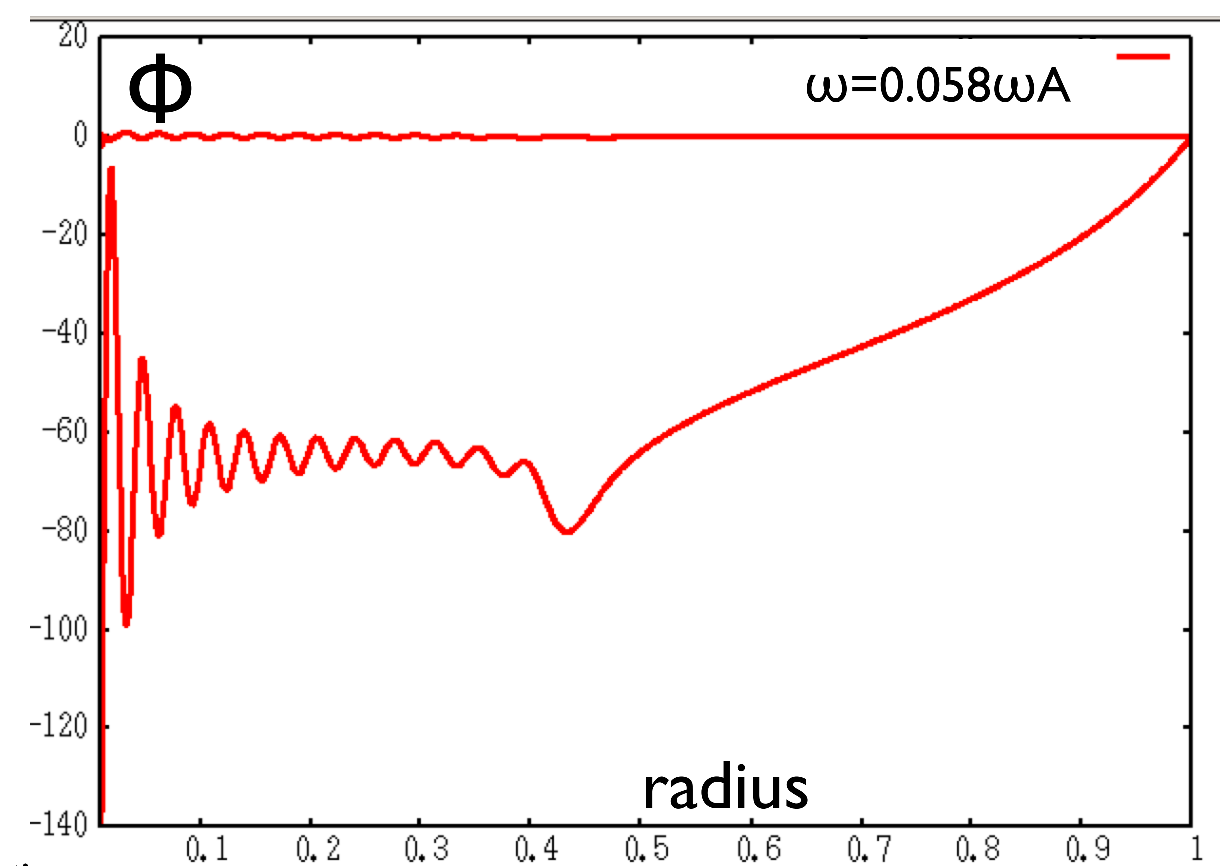








Effects of velocity anisotropy on the excitation of EGAMs;

Work in progress; To be submitted to Nuclear Fusion: Conf. series ,

I Chavdarovski, M Schneller, Z Qiu, A Biancalani;

- The local dispersion relation of energetic -particle-induced Geodesic acoustic mode (EGAMs) is derived for both circulating and trapped particle beam with single pitch angle slowing down and Maxwellian distribution.
- Solutions of the local dispersion relation for each case give the spectrum, the growth rate and the threshold of excitation as function of the slowing down critical energy (for the trapped) and the pitch angle (for circulating).
- Sample result: dispersion relation for trapped EP with slowing down distribution, as function of the bounce frequency and Λ. The logarithmic term gives the drive.

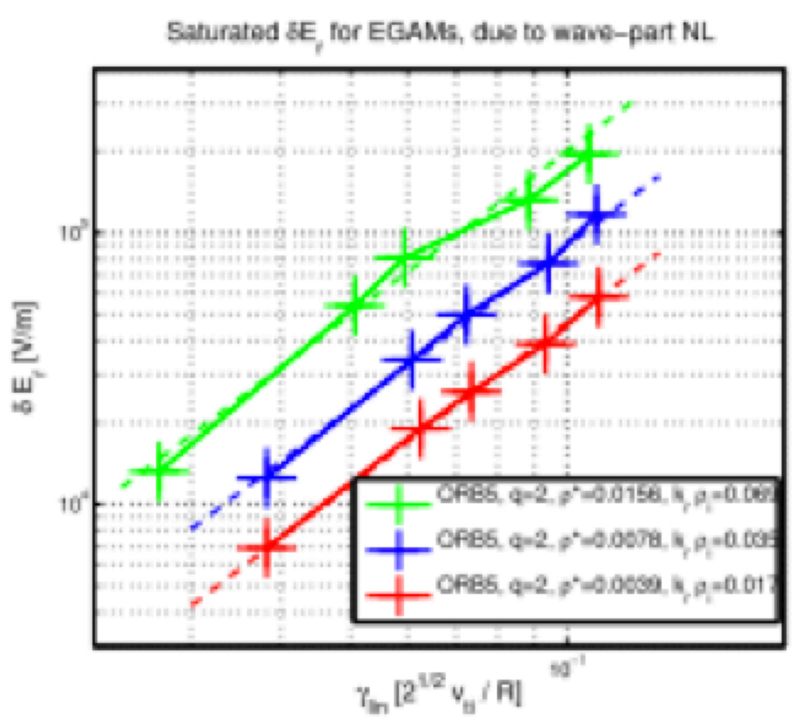
$$0 = -1+\frac{\omega_G^2}{\omega^2}+\frac{\pi}{8}N_b\frac{1}{\epsilon\Lambda_0 B_0}\left[\frac{3-2\Lambda_0 B_0(1-\epsilon)}{2(1-\Lambda_0 B_0(1-\epsilon)^{3/2})}\log\left(1-\frac{\omega_b^2}{\omega^2}\right)+\frac{1}{1-\Lambda_0 B_0(1-\epsilon)^{1/2}}\cdot\frac{\omega_b^2/\omega^2}{1-\omega_b^2/\omega^2}\right]$$

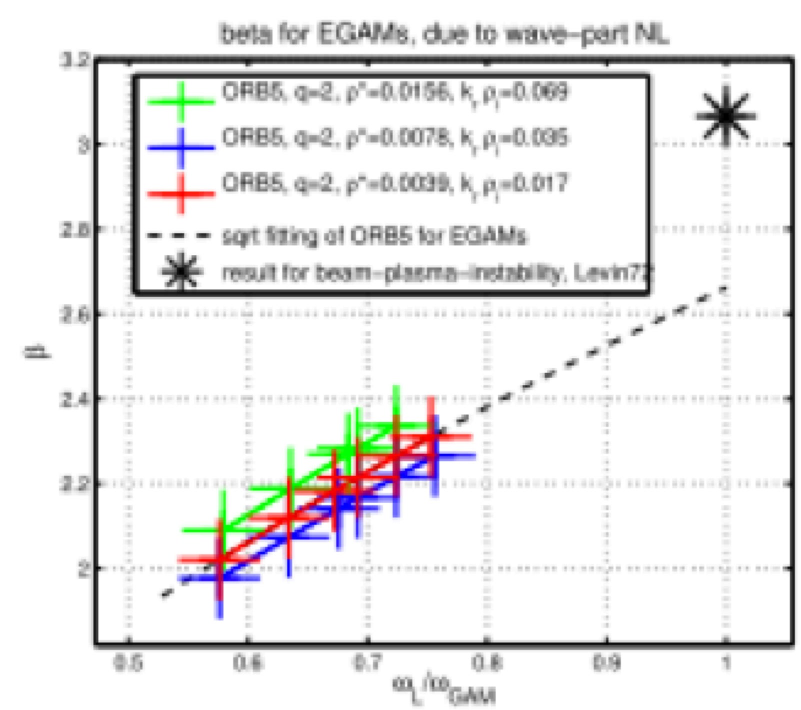
to be implemented together with anisotropic shifted Maxwellian into LIGKA

Saturation of EGAMs due to wave-particle nonlinearity

Work by A Biancalani, I Chavdarovski and Z Qiu. Currently on IPP pinboard.

- Only wave-particle nonlinearities are considered.
- The EGAM saturates mostly due to flattening of the EP profile in velocity space.
- Quadratic scaling of the saturated electric field with the linear growth rate is found, similarly to the beam-plasma instability: $\delta \bar{E}_r = \alpha_2 \gamma_L^2$





Non-linear generation of Zonal Flow and EGAMs second harmonic;

Published work Z Qiu , I Chavdarovski, A Biancalani and J Cao,

Physics of Plasmas 24, 072509 (2017);

- Both second harmonic and ZFZFs can be driven by EGAMs, with the finite orbit width (FOW) effects playing a dominant role in the nonlinear couplings, contrary to the thermal where toroidicity dominates
- The contribution of resonant EPs to the cross-section of the nonlinear couplings dominates that of the thermal plasma.
- The generated ZFZF has a radial scale length half of the pump EGAM and growth rate double the size.
- For GAMs perpendicular and parallel non-linearities cancel out , but present EP will dominate (Fu 2011). Second harmonic is generated with *l=1,2* resonances and radial scale half of the primary EGAM.

$$b_S \hat{\mathcal{E}}_{EGAM}(\omega_S)\hat{\Phi}_S = -\frac{ik_r T_i}{n_0 m \Omega}\left\langle \frac{\partial F_{0h}}{\partial E}\frac{3\omega\hat{\omega}_d^2}{(\omega^2-\omega_{tr}^2)(\omega_S^2-\omega_{tr}^2)}\right\rangle \times \frac{\hat{\Phi}_G\hat{\Phi}_G}{r}$$

$$\hat{\mathcal{E}}_{EGAM}(\omega_S) \equiv -1 + \frac{\omega_G^2}{\omega_S^2} + \frac{T_i}{n_0 m_i b_S}\left\langle \frac{\partial F_{0h}}{\partial E}\sum_{l=\pm1,\pm2}\frac{J_l^2(\hat{\Lambda}_S)\omega_S}{\omega_S - l\omega_{tr}}\right\rangle$$

5. Study Case for EGAM & Turbulence Investigation

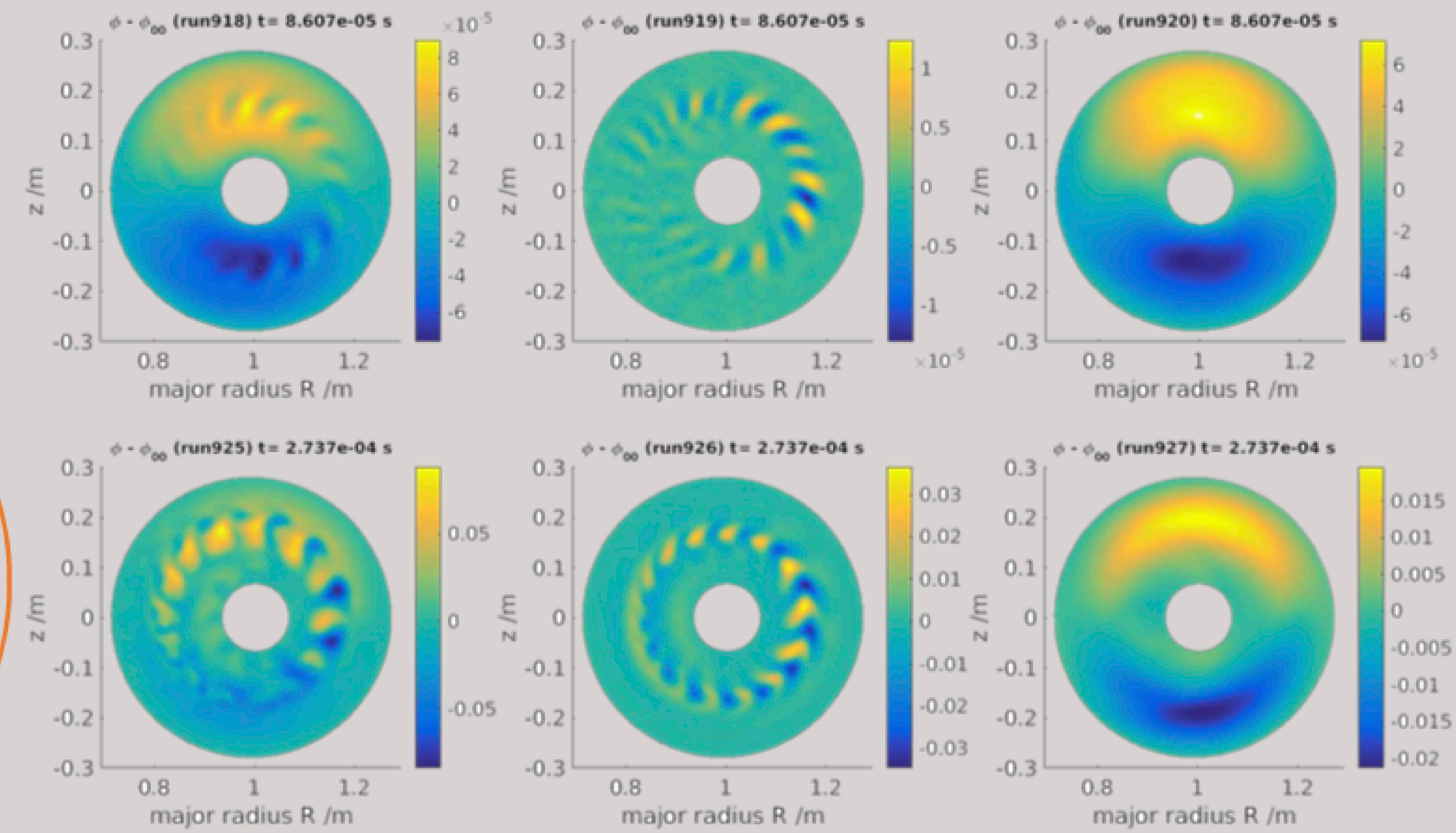
3 simulations:

EGAM + turbulence | only turbulence | only EGAM

2 cases:

EGAM grows faster than turbulence

turbulence grows faster than EGAM



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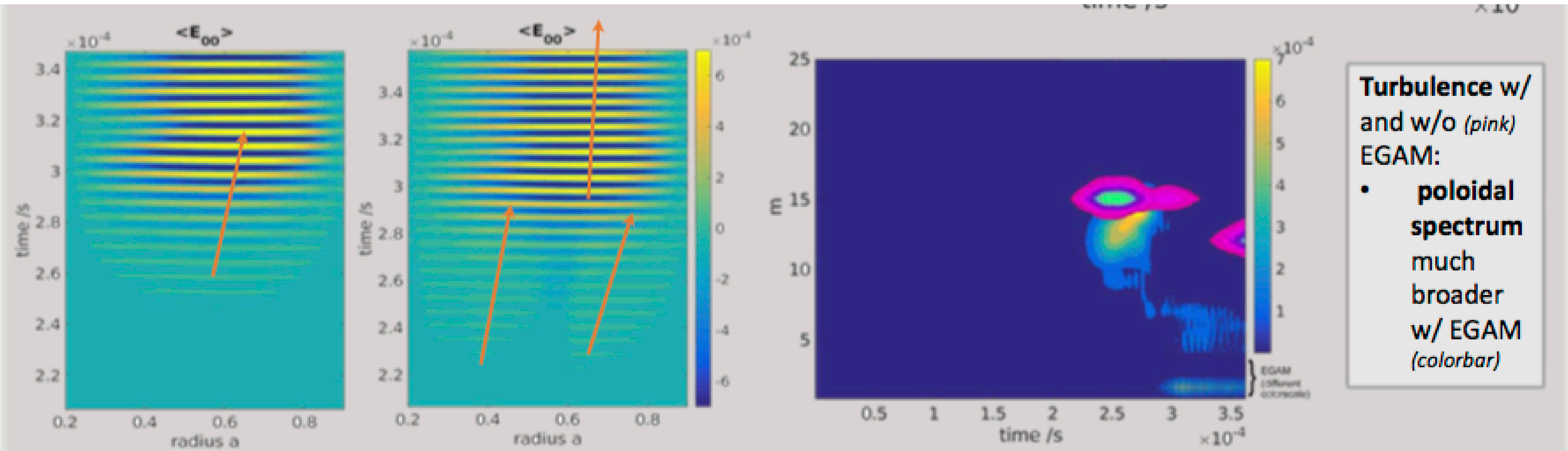
preliminary results:

radial propagation and mode localisation changes in EGAM+turbulence case, more complex than in Zarzoso[2015], Sasaki[2017]



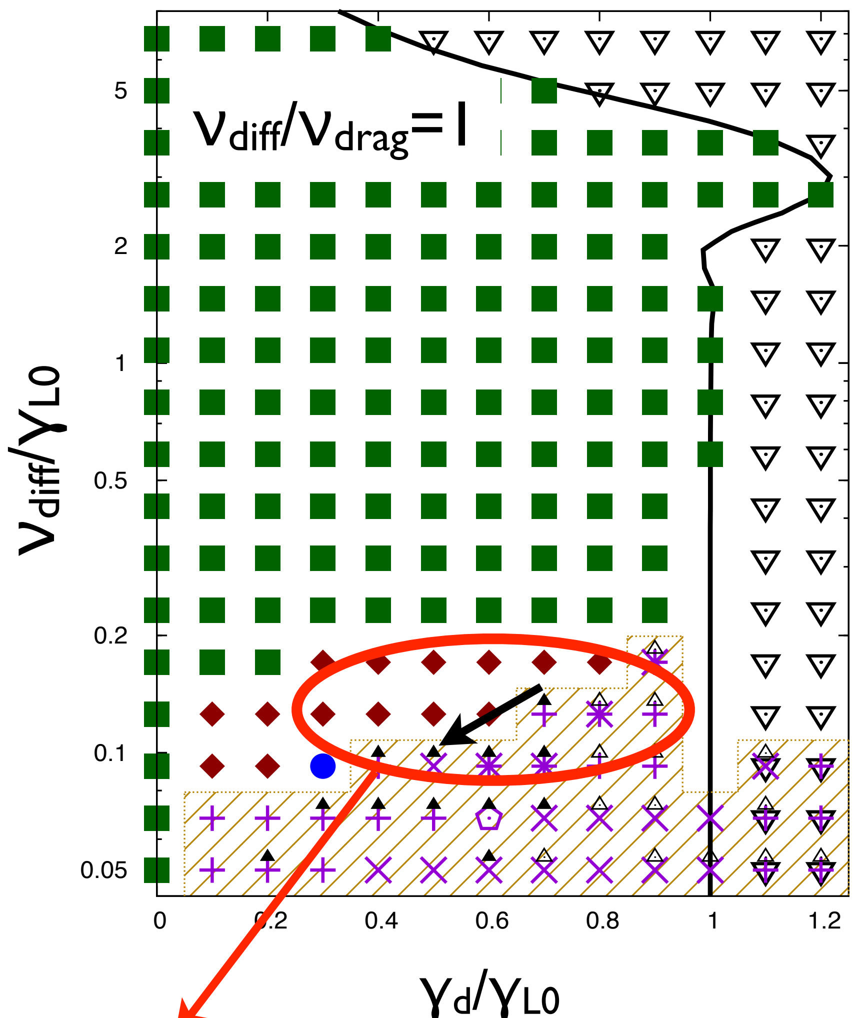
outlook:

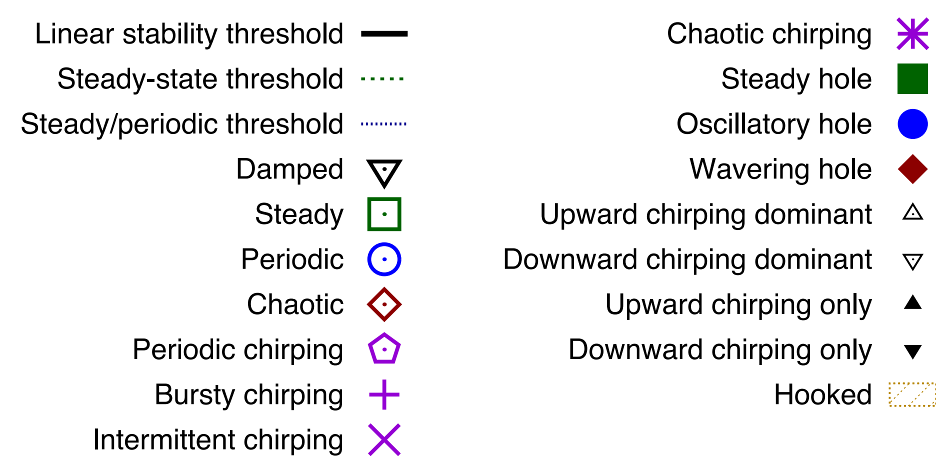
modelling to be continued step by step
comparison of analytical theory, linear and non-linear simulations with experiments ongoing

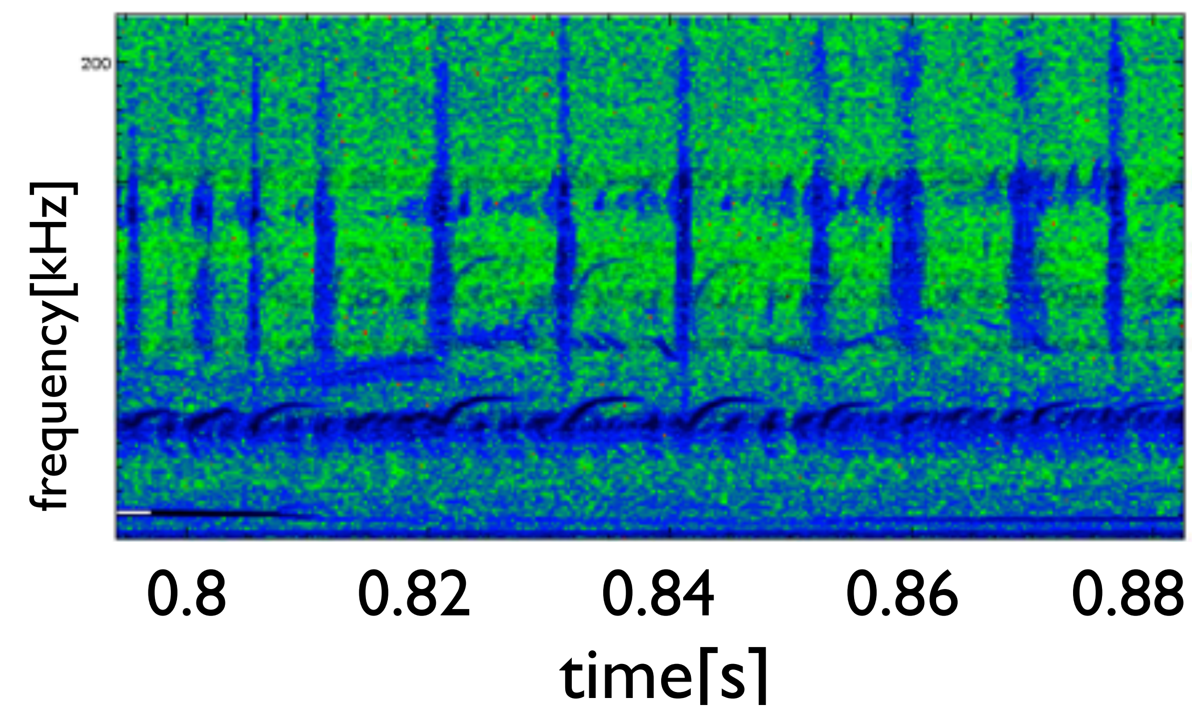
new discharge proposals (~#8-10):

- slighty reduce current to prolong stable q~2 phase: determine importance of AEs/EGAM and q=2 crashes with respect to EP transport (maybe also ECCD necessary)
- attempt elongation scan in flat top
- add ECRH for threshold studies
- add ICRF for impact of drag/diffusion chirping

[M. Lesur,,2013]



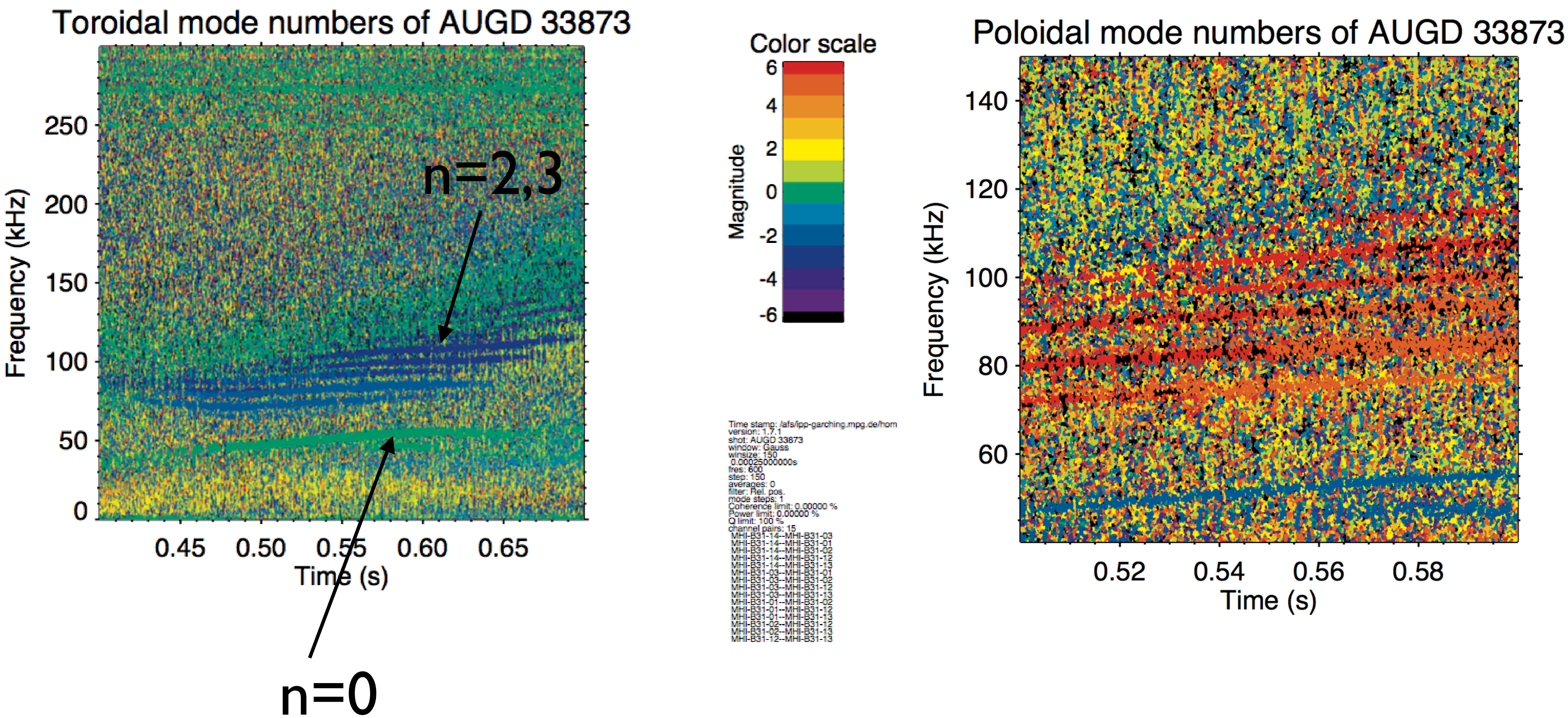




AUG? increased linear growth rate would explain transition from ‘wavering hole’ to hooked up-chirping

or low level of turbulence?

for higher B: multiple TAEs with the same n and m!

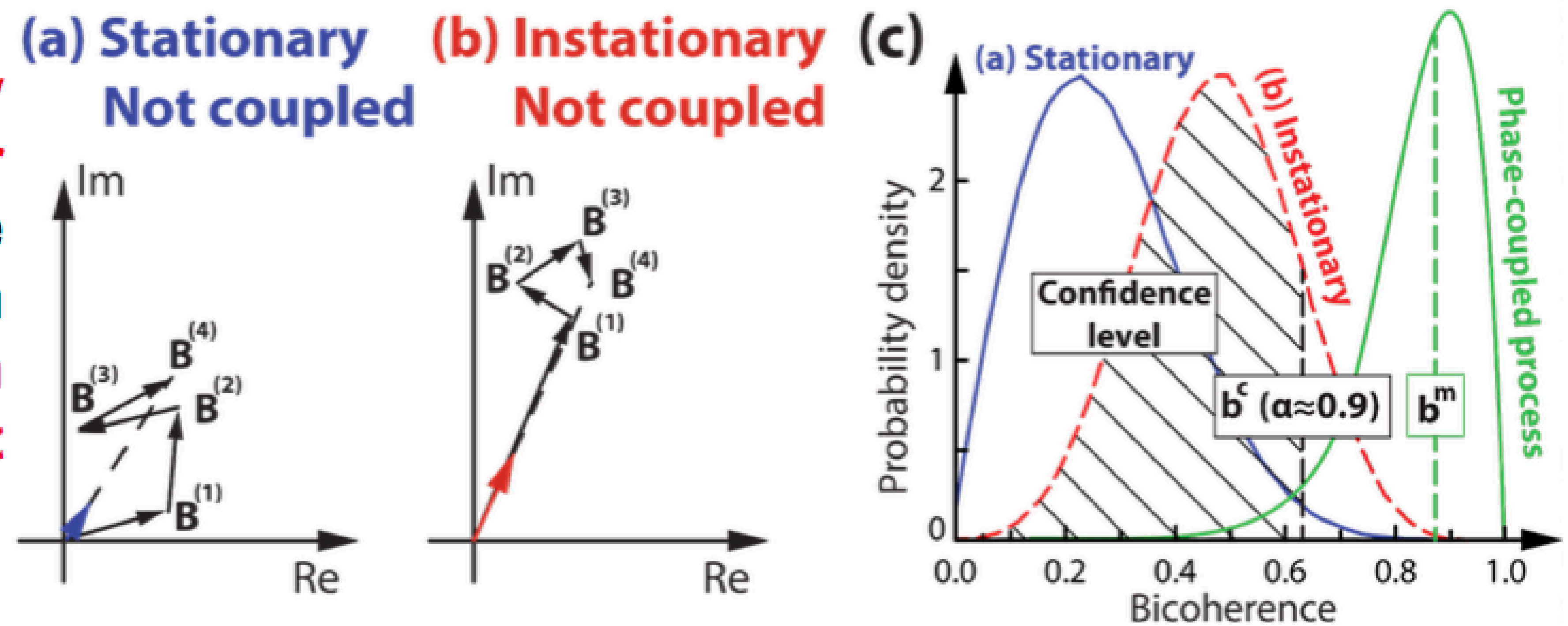


instability threshold for EGAM clearly observed,
no chirping

- **Bicoherence analysis** is a widely applied method for identifying quadratic nonlinear interactions of **stationary processes [1]**

$$b^2(f_1,f_2) = \frac{|\mathbf{A}[X(f_1)X(f_2)X^*(f_1+f_2)]|^2}{\mathbf{A}[|X(f_1)X(f_2)|^2]\mathbf{A}[|X^*(f_1+f_2)|^2]}, \text{ with } \mathbf{A}[Y] := \lim_{N\to\infty}\frac{1}{N}\sum_{i=1}^{N} Y_i,$$

- Signals exhibiting **rapidly changing amplitudes or frequencies** (typical in the case of strongly driven EPMs) may cause **high bicoherence even without phase coupling**



- **Phase randomized bicoherence probability density function** calculation for each (f_1,f_2) point, which will **describe** a random **process without** any **phase coupling.**

- We can set an **α confidence level**, which will define a **b_c critical bicoherence value** (at each (f_1,f_2) point)

$$\alpha = \int_0^{b^c} \rho(b)\mathrm{d}b$$

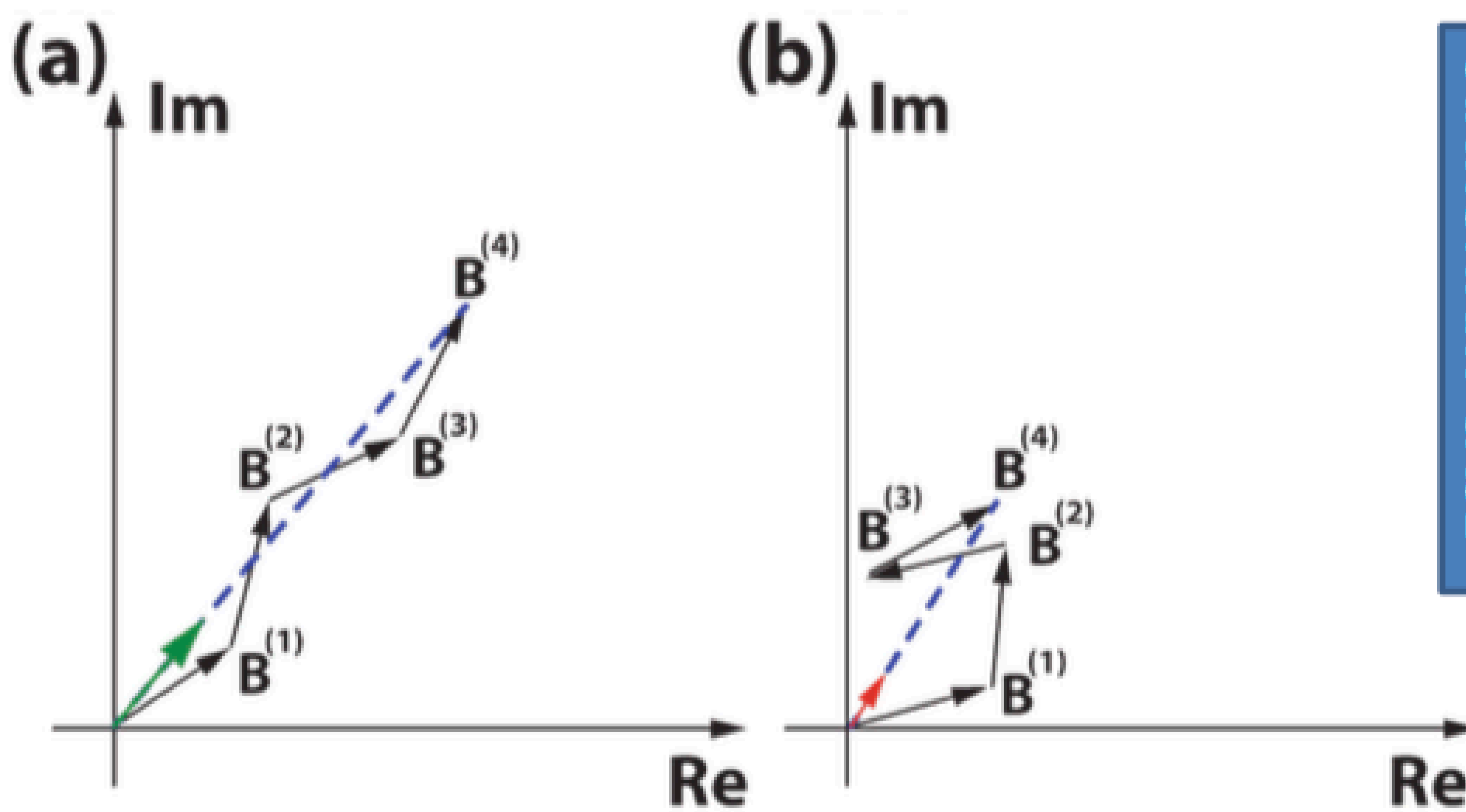
- **Bicoherence values higher than b_c** are from **non-phase coupled** process with **1-α probability**. **Confidence level** can be used as a **filtering parameter**, by only plotting bicoherence values higher than b_c, thus **eliminating probable false positives**

Bicoherence for stationary processes

- Used for detecting quadratic nonlinearities

$$B(f_1,f_2) = \mathbb{E}\left[X(f_1)X(f_2)X^*(f_1+f_2)\right]$$

- Bispectrum calculation as random walk on the complex plane

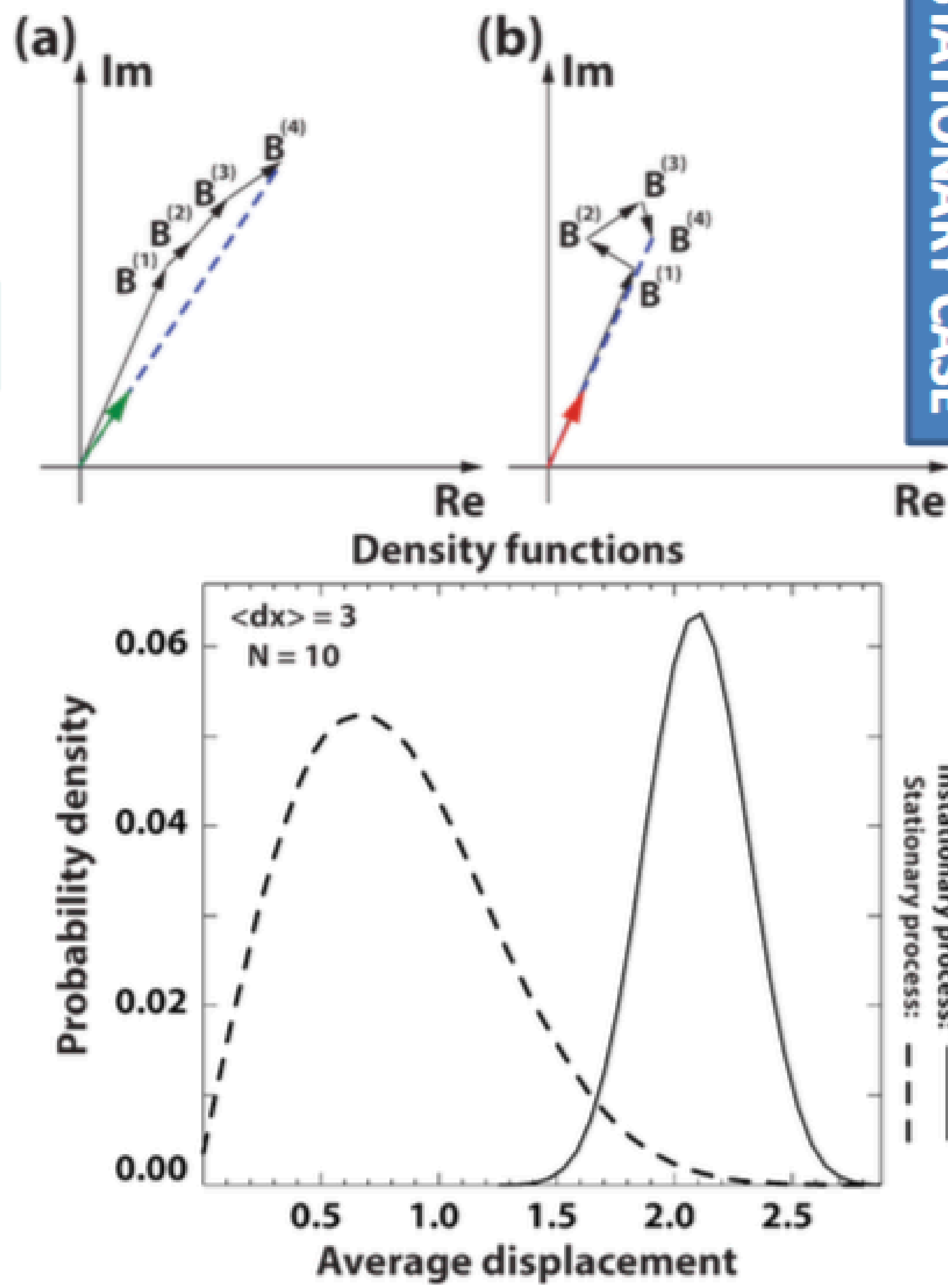


STATIONARY CASE

Bicoherence for instationary case

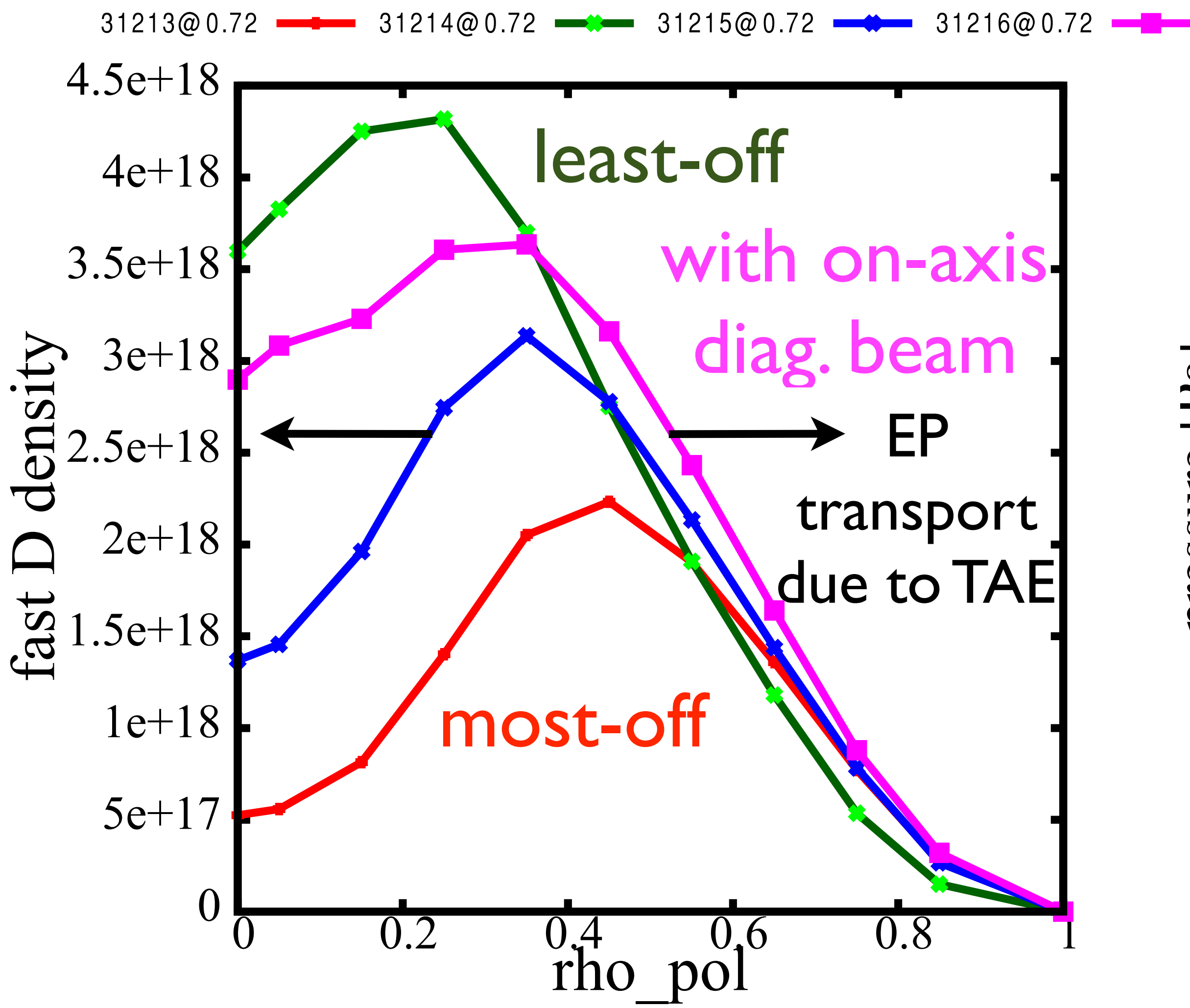
INSTATIONARY CASE

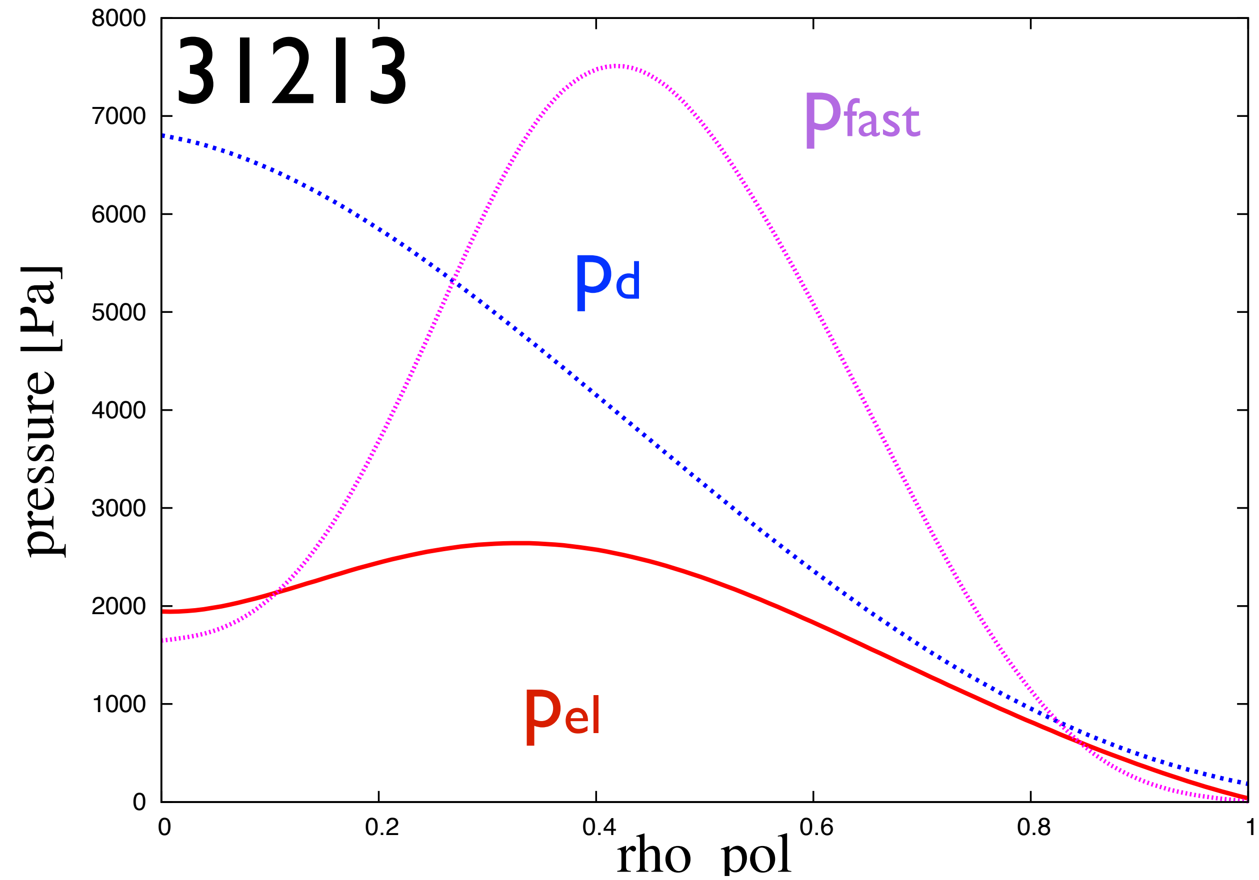
- Due to instationarity
  „false high” bicoherence
- Random walk with same total length, but different step length
- Significant differences in the probability density functions of bispectrum



#	EGAM/BAE/	NBI	angle	behav	later heating		I	B
27923	y/y/y/n	2:0.35-0.5;3:0.38-0.59;80.59-0.63;5:0.63-0.76;7:0.76	6,65					
28880	n/y/y/n	2:0.35-0.5;3:0.5-0.6;7:0.6	6,65				1	2,4
28881	y/y/y/n	2:0.35-0.5;3:0.5-0.6;7:0.6	6,65				1	2,4
28883	n/y/n/n	2:0.35-0.5;3:0.5-0.6;7:0.6	6,65					2,4
28884	y/y/y/n	3:0.5-0.6;7:0.6	6,65				1	2,4
28885	y/y/y/n	2:0.35-0.5;3:0.5-0.6;7:0.6	6,65				1	2,4
30383	y/y/y/n	7: 0.26-0.75	6,65	Hmode		FILD FHA FIPM 09	1	2,6
30945	n/y/n/n	2:0.28-0.376;6:0.382-0.697	6,65	dis@4s			1	2,2
30946	y/y/n/y	2:0.28-0.445;6:0.451-0.928	6,65	Lmode	no heating!	later TAE???	1	2,2
30947	y/n/n/y	2:0.28-0.478;6:0.482-0.928	6,65	dis@4s	H mode	EGAM @1s 100kHz	1	2,2
30948	n/y/y/n	2:0.28-0.491;3:0.497-0.789	6,65	dis@1.2s	Q6@0.789		1	2,2
30949	y/y/n/n	2:0.35-0.5;3:0.38-0.79;6:0.79;7:1.0;8:1.2	6,65	dis@1.5		late EGAMs	1	2,2
30950	y/y/y/n	3:0.28-0.295;7:0.312-0.797	6,65	dis@1.5	3:0.8-0.92;6,8@0.9		1	2,2
30951	n/y/n/n	3:0.28-0.295;5:0.312-0.552,8	6,65	dis@1.7	8-0.84;3:-0.99		1	2,2
30952	y/y/y/n	3:0.28-0.295;7:0.312-0.797	6,65	dis@1.18	Q6@0.8		1	2,2
30953	y/y/n/n	3:0.28-0.295;6:0.312-0.753	6,65	dis@1.11	Q2@0.76++		1	2,2
31213	y/y/y/n	3:0.28-0.295;7:0.296-1.033	7,13	dis@1.7	Q6@1.0		1	2,2
31214	y/y/y/n	3:0.28-0.295;7:0.296-1.033	6,05	dis@1.0			1	2,2
31215	y/y/y/n	3:0.28-0.295;7:0.296-1.033	6,65	dis@1.0			1	2,2
31216	y/y/y/n	3:0.28-0.295;7:0.296-3.045+blips	6,65	Lmode		q=2 and qa>4!	1	2,2
31233	y/y/y/n	3:0.28-0.501;7:0.506-3.227	7,13	Hmode	Q6@1.0		1	2,2
31234	y/n/y/n	3:0.28-0.310;7:0.318-0.813	7,13	dis@ 0.8			1	2,2
32326	y/n/y/y	7: 0.28 +blips	7.13	EGAMS, TAEs			1	2.2
32327	y/n/y/n	7: 0.28 +blips: 82kV	7.13	transition			1	2.2
32328	n/n/n/n	7: 0.28 +blips +0.5 ECRH	7.13	only turbulence			1	2.2
32329	n/n/n/n	7: 0.28 + blips+0.5 ECRH	7.13	only Alfvenic turb			1	2.2
32384	y/n/y/n	7: 0.28 +blips 93kV	7.13	too high density			1	2.2
32386	y/n/n/n	7: 0.28 +blips: 65kV	7.13				1	2.2
32387	y/n/y/y	7+6: 0.28 +blips: 65kV	7.13				1	2.2
32388	y/y/y/y	7: 0.28 +blips + higher density 93kV	7.13				1	2.2
33872	y/y/y/y	7: 0.28 +blips + higher density 93kV	7.13		diff breakdown	no Te inversion		2.2
33873	y/y/y/y	7: 0.28 +blips + higher density 93kV	7.13		diff breakdown	no Te inversion		2.5
33874	y/y/y/y	7: 0.28 +blips + higher density 93kV	7.13	dis@1.0	std brkdwn	no Te inversion		2.0
33875	y/y/y/y	7: 0.28 +blips + higher density 93kV	7.13	dis@1.0s	std brkdwn	no Te inversion		2.2
34184	y/y/y/y	7: 0.28 +blips + higher density 93kV	7.13	shape scan t>0.8		Te inversion		2.2
34185	y/y/y/y	7: 0.28 +blips + higher density 93kV	7.13	shape scan t>0.8		Te inversion		2.2
34186	y/y/y/y	7: 0.28 +blips + higher density 93kV	7.13	std		Te inversion		2.2
34187	y/y/y/y	7: 0.28 +blips + higher density 93kV	6.65	std		Te inversion		2.2

fast ion distribution [Transp, B. Geiger]





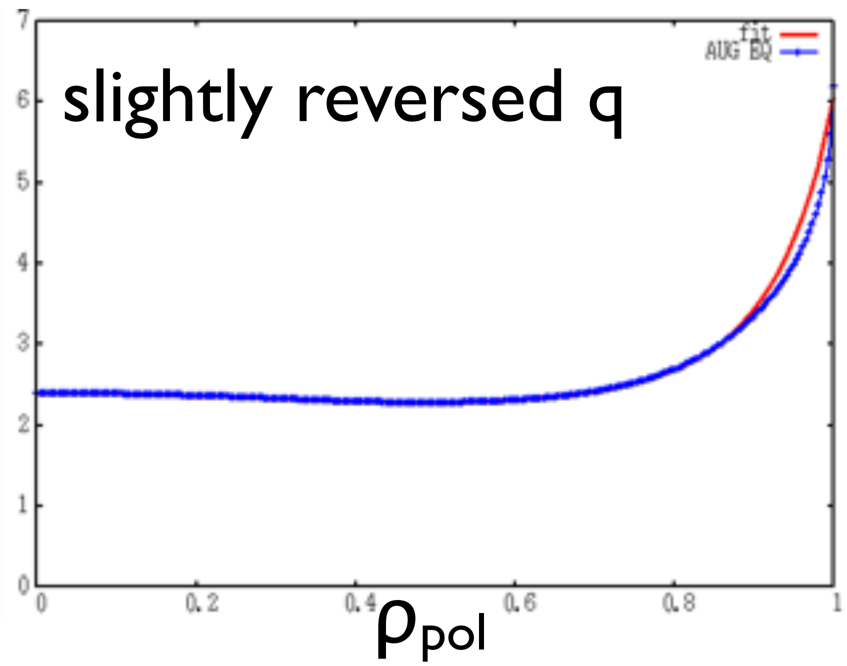
$p_{EP} \gtrsim p_e + p_d$

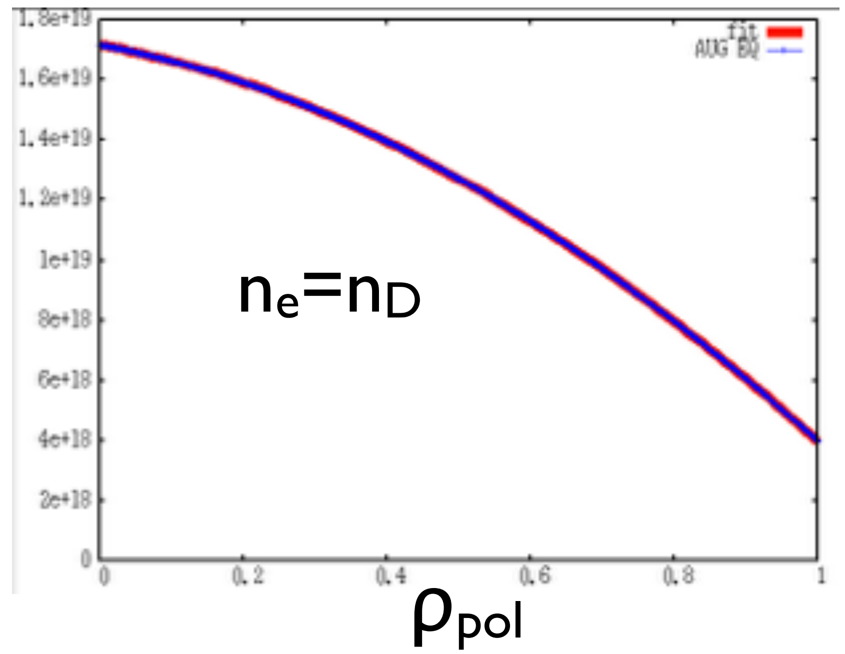
$\beta_{EP}/\beta_{th} > 1$; $T_f \sim 90\, T_i$

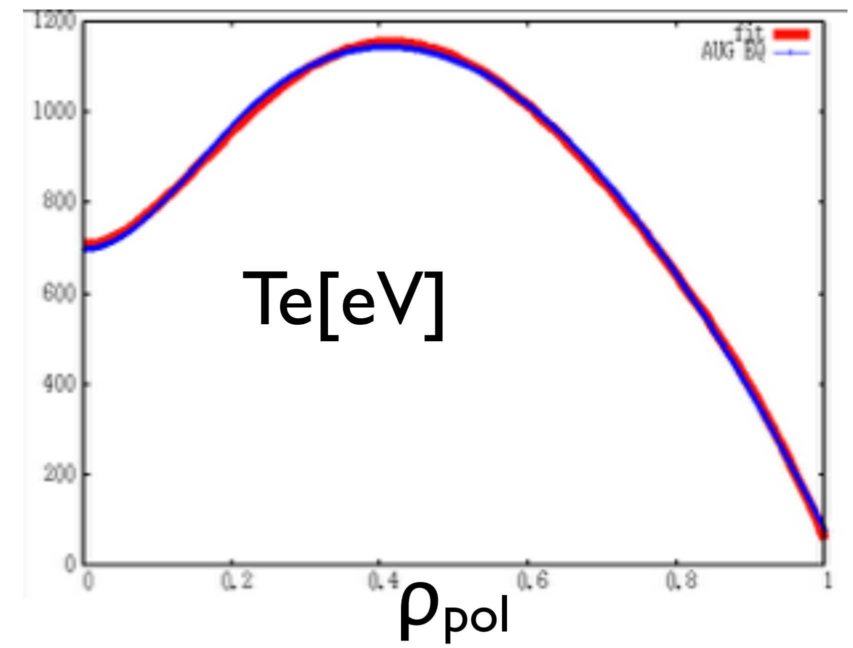
DEMO-like conditions for these two parameters

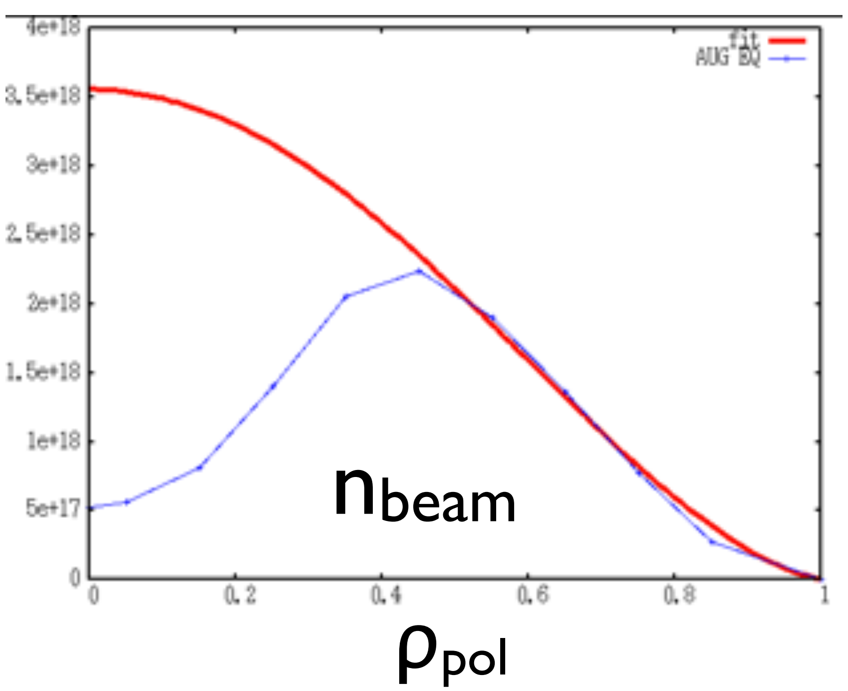
based on #31213@0.84s a reference case was created

http://www2.ipp.mpg.de/~pwl/NLED_AUG/data.html









benchmark
steps:

step 1: flat Te, Ti, ne
step 2: ne, flat Te, Ti
step 3: ne, Te=Ti
step 4: ne, Te≠Ti