Update on EP-AUG experiments and analysis

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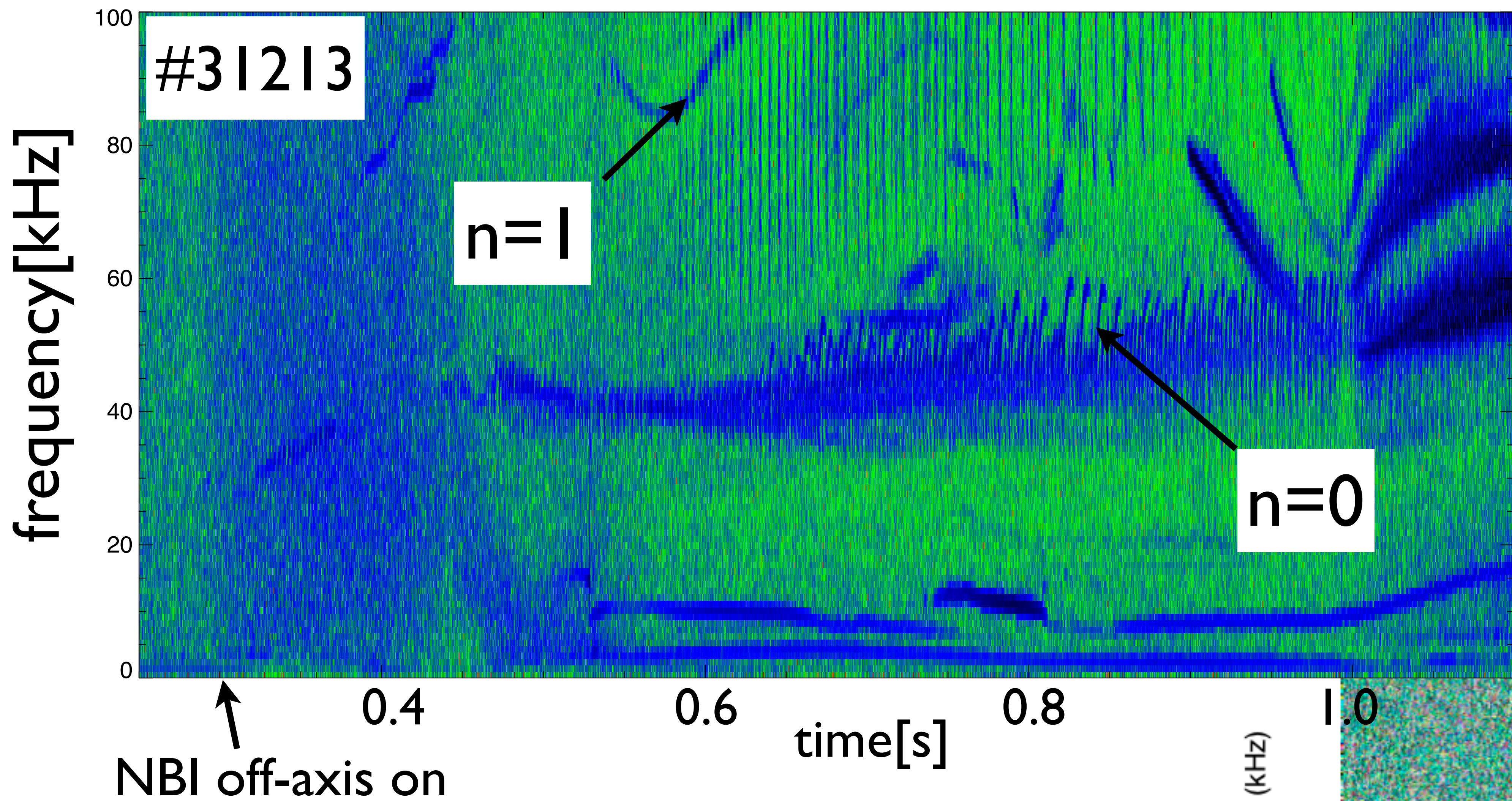
ITPA EP group
Confinement & Modelling Section, ITER: S.D. Pinches, M. Schneider
and ENR NLED/NAT/MET teams

background and motivation

- in order to predict the behaviour of energetic particle (EP) transport in a future burning plasma, models have to go beyond the regimes where present-day experimental data is available for verification: different distribution function, different unstable mode number spectrum, redistribution instead of direct losses, assess effects on transport time scales (self-organisation)
- similarly to hierarchical models for linear and non-linear EP physics (NLED/NAT) also various (hierarchical) models for EP transport are needed (MET)
- various useful but - under many conditions - insufficient models are validated with present day experiments or used in an interpretative way: critical gradient w/o upshift, quasi-linear, resonance broadening QL model, kick-model,…
- for comparison: non-linear multi-mode runs for hybrid models are available: HAGIS/LIGKA, HAGIS/Castor-K, CKA-Euterpe,NOVA/ORBIT, (X)HMGC,HYMAGYC,…
- within MET: provide set of (partially experimental) reference cases to address different aspects of EP transport that will be needed for developing reliable predictive tools
- this talk will address mainly1.AUG; 2.JT-60SA 3.ITER

reminder: ASDEX Upgrade: early off-axis NBI drive [93keV]:



[July 2014]

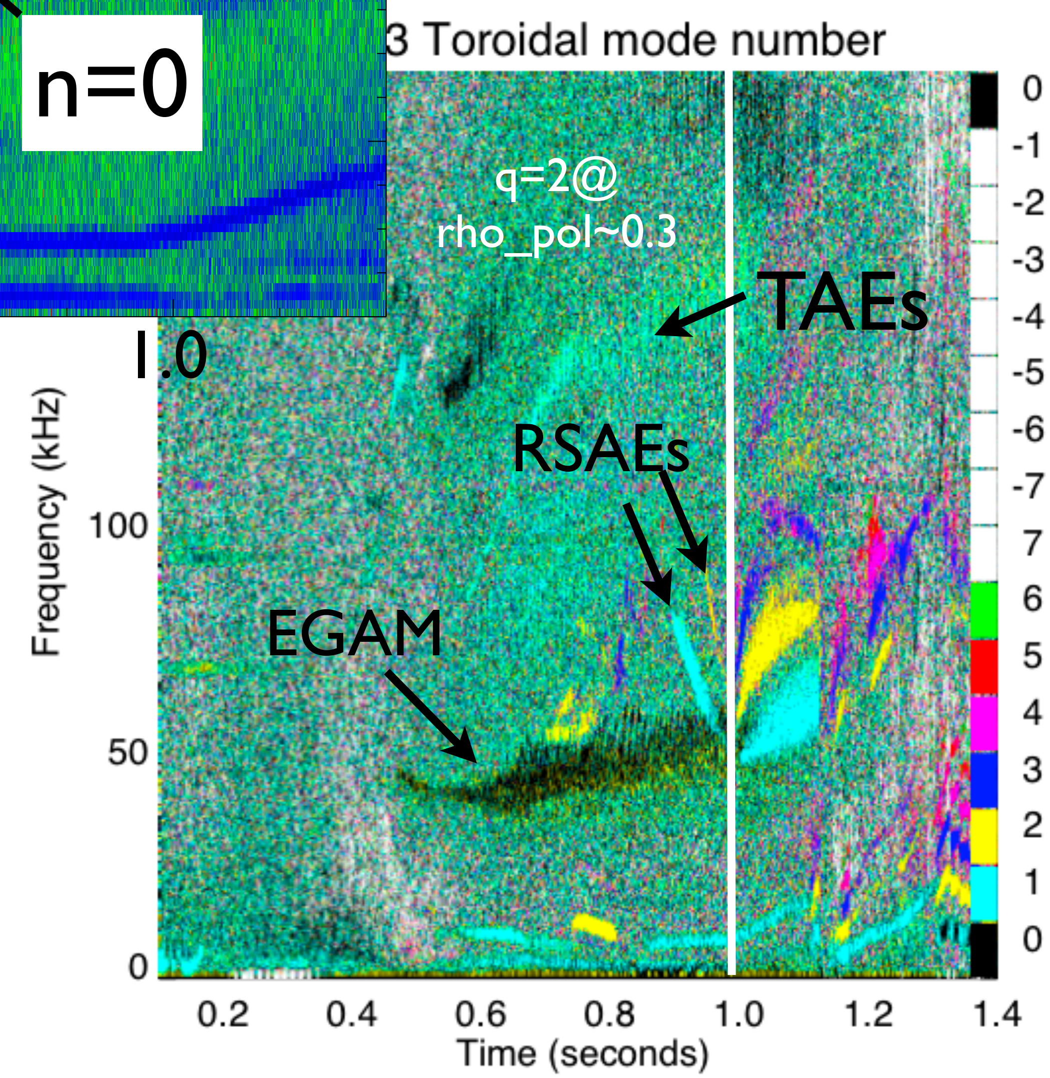
B0=2.2T

I=0.6-1.0MA

P_{beam}=2.5MW

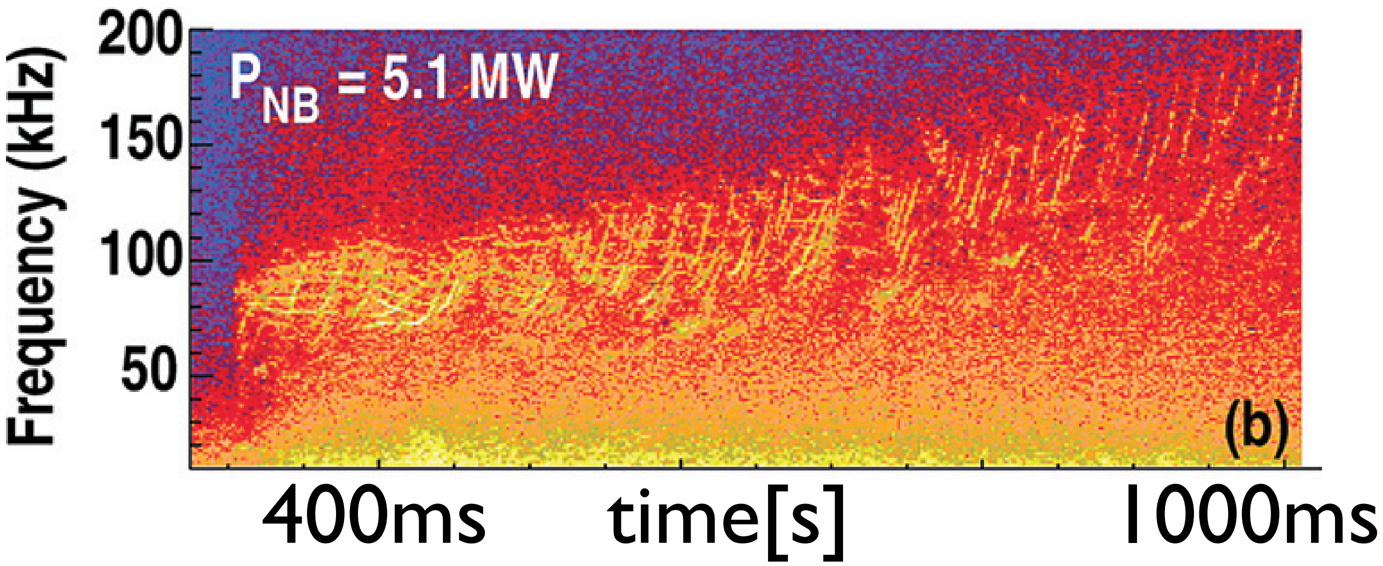
- very reproducible scenario - ramp-up phase
- no 'sea' of Alfvenic modes (RSAEs)
- but strongly chirping n=0 modes and n=1 'bursts'
- bursting modes at DIII-D very rarely observed ('15 shots out of thousand')

this is NLED-NAT AUG base case

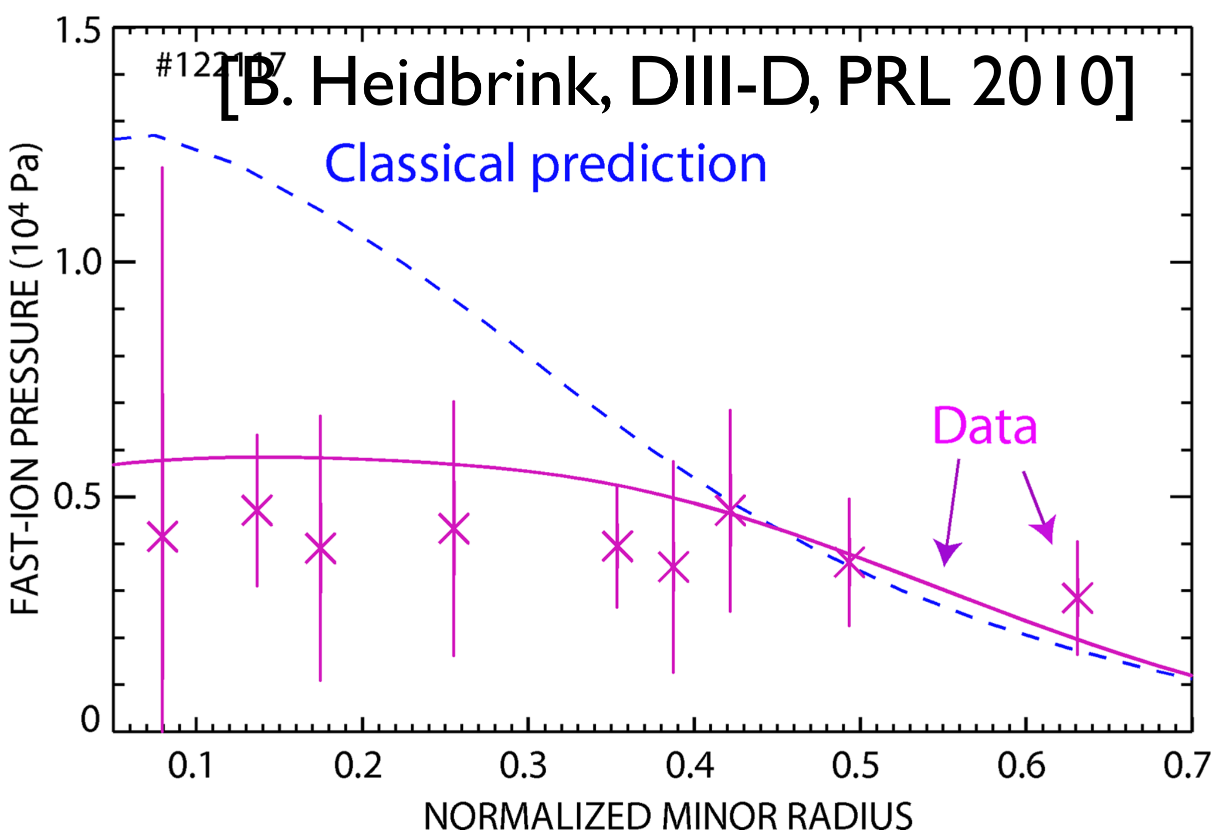


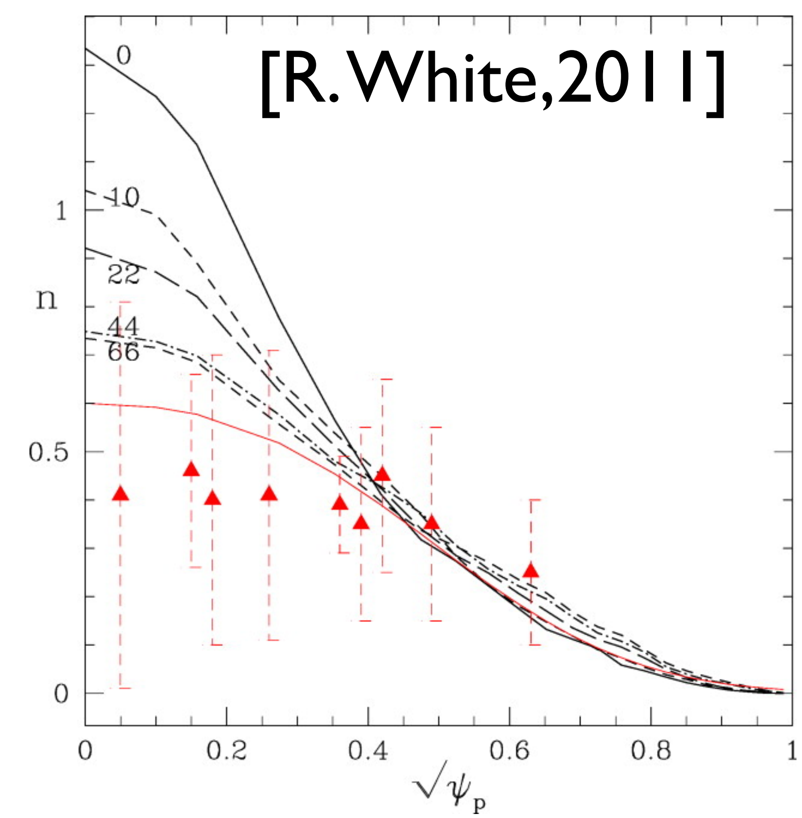
in contrast: DIII-D: multi mode experiments & modeling (#142111)

[VanZeeland et al Phys. Plasmas 18, 056114 (2011)]



successful comparison to quasi-linear hybrid models (amplitudes given by the experiments) and critical gradient models [White et al, Ganthous, Gorelenkov et al, Waltz et al]



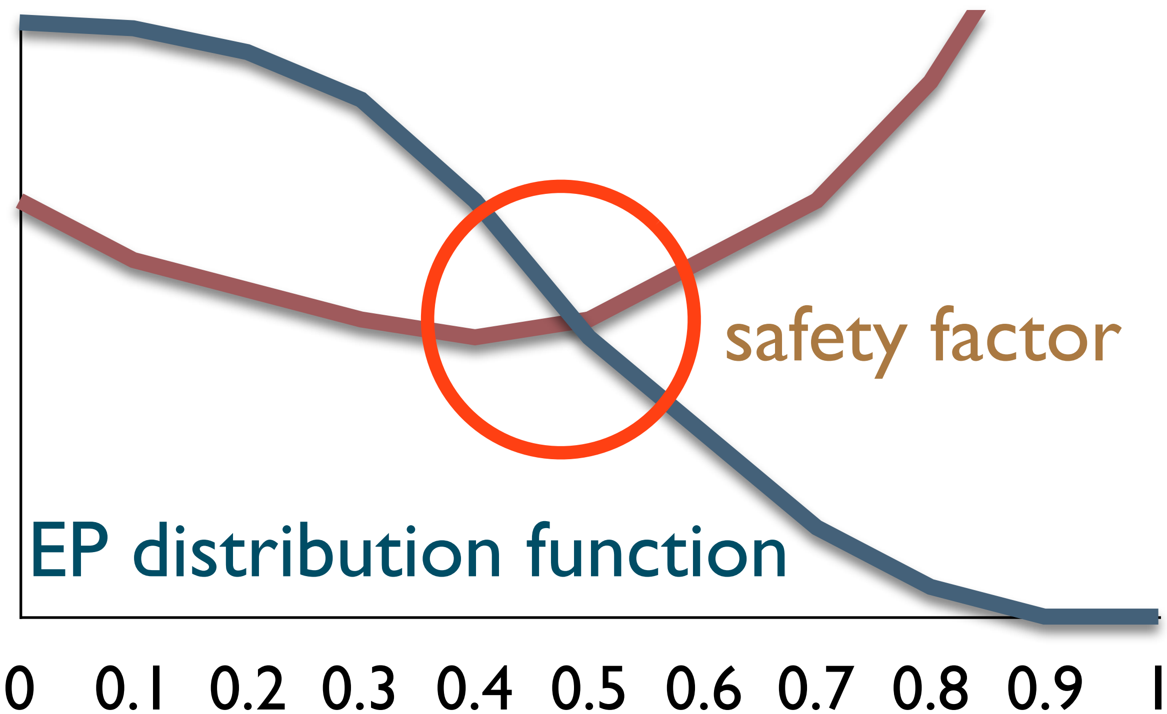


also later (2017-2019) flat top experiments on DIII-D show 'steady state' gap-AEs

off-axis NB drive

in order to drive a sufficient amount of off-axis current, the NBI drive (+ECCD,LH,..) has to be off-axis (JT-60SA, ITER,…)

$r(q_{min})=r(\max \nabla n_{EP})$



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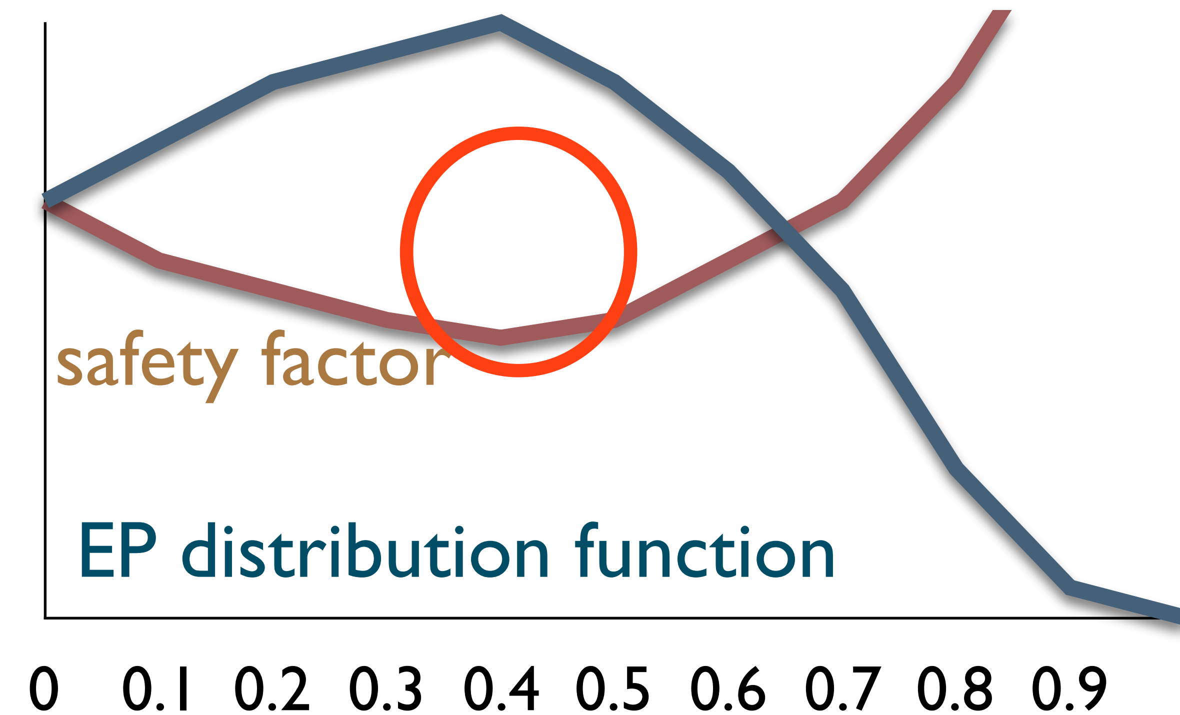


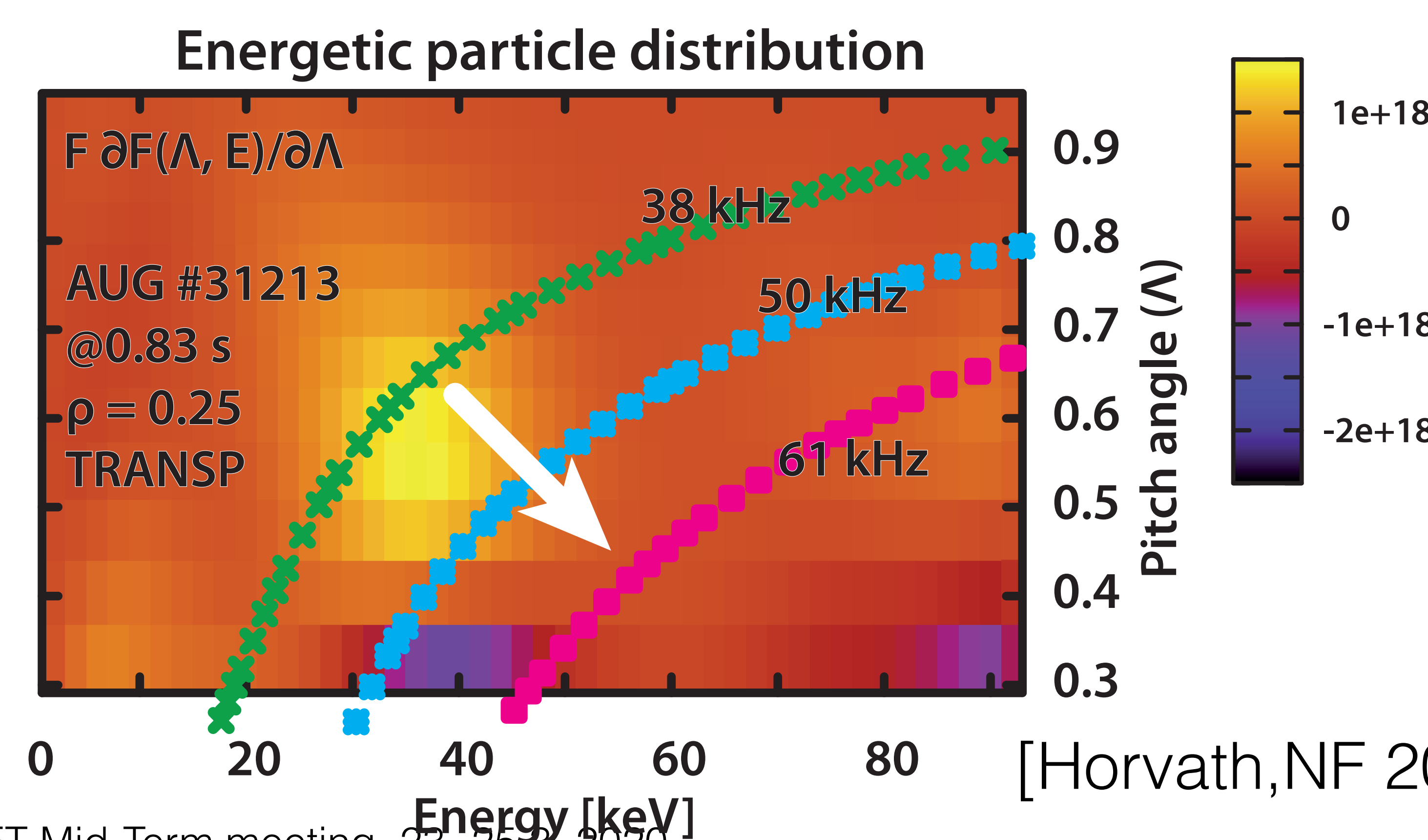
off-axis NBI scenarios relevant when current profile modifications or advanced/ hybrid scenarios are under investigation

step ladder: AUG - JET/JT-60SA/DDT - ITER

note: the 2 ITER beams can be moved from on to off-axis deposition due to mechanical stresses only possible ~ 100 times: reliable modelling needed

reminder: systematic scans at ramp-up reveal existence conditions for AEs and EGAMs

- power/beam voltage scan (2.5MW/93kV; 2.0MW/82kV; 1.25MW/65kV; 2.5MW/2*65kV) → verify theoretical onset condition, i.e. onset frequency and damping (Ti) vs. drive (dF/dΛ) of EGAMs
- substituting 2.0MW/82kV + 0.5MW ECRH suppresses all mode activity → higher Ti, no W → high Landau damping
- EGAMs can be driven also with half power/65kV off axis beams → confirmation of drive mechanism and resonance condition
- bursting TAEs disappear for 65kV → main resonance drive is missing

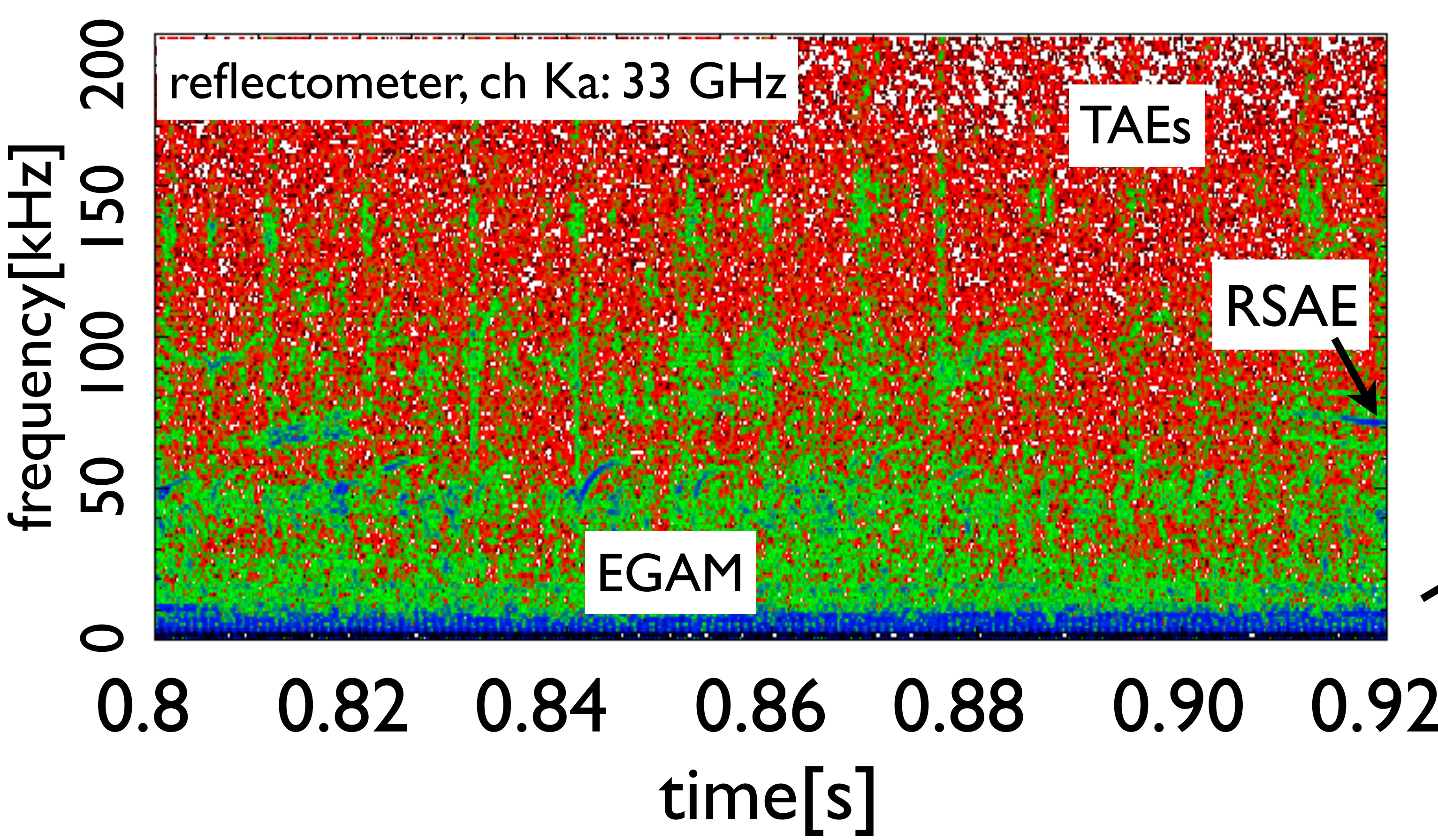


[Horvath,NF 2016]

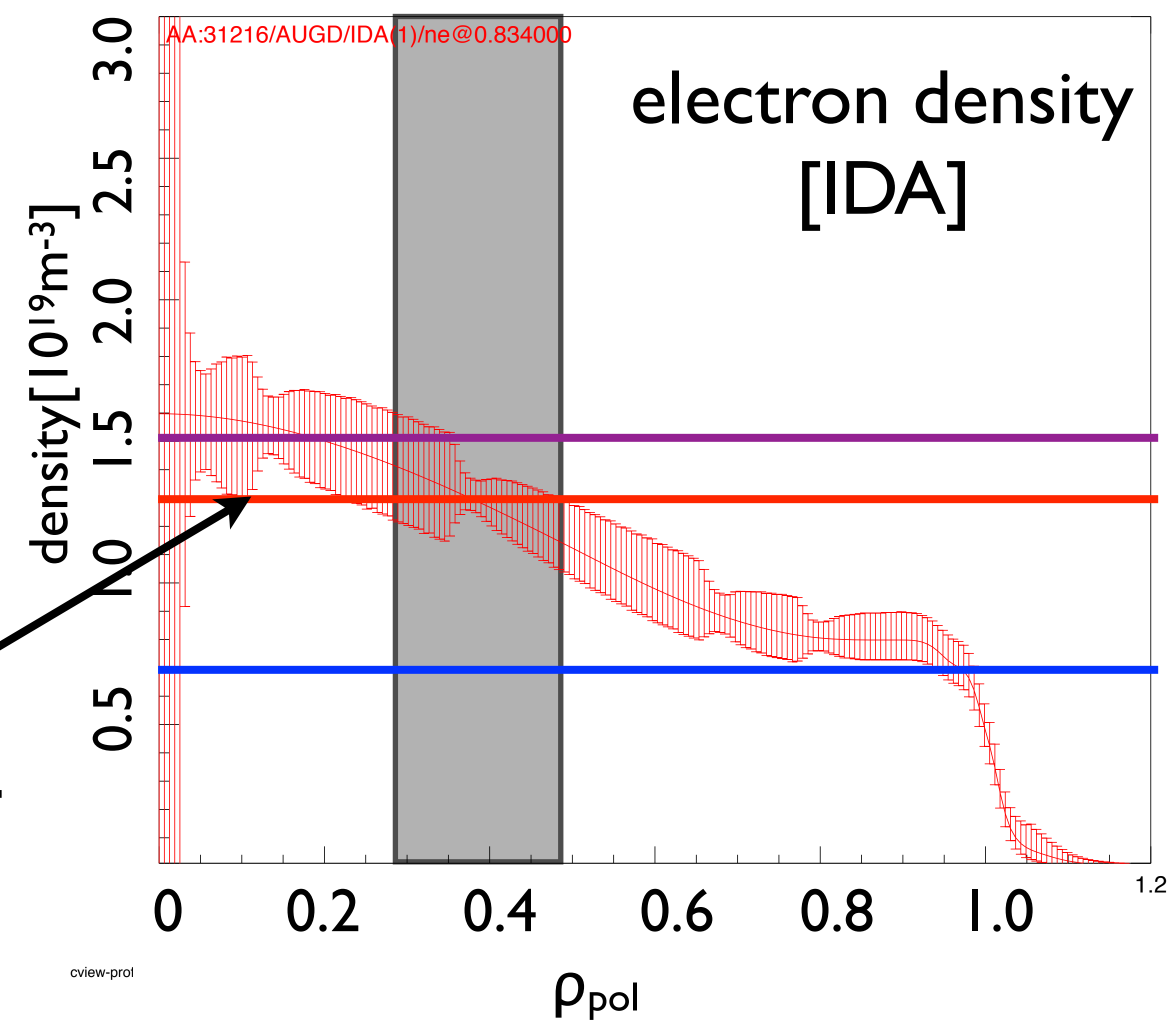
radial mode localisation

from reflectometry (hopping frequency) and soft-X-ray measurements: EGAMs, TAEs RSAEs and intermediate frequency modes are visible in the same channels ⇒ similar radial location at ρ_{pol} ~0.2-0.4,

EGAMs more core localised (0.1-0.4), TAEs more outside (0.2-0.6)



[V. Nikolaeva, L Guimares]



IPP

reason to carry out more experiments:

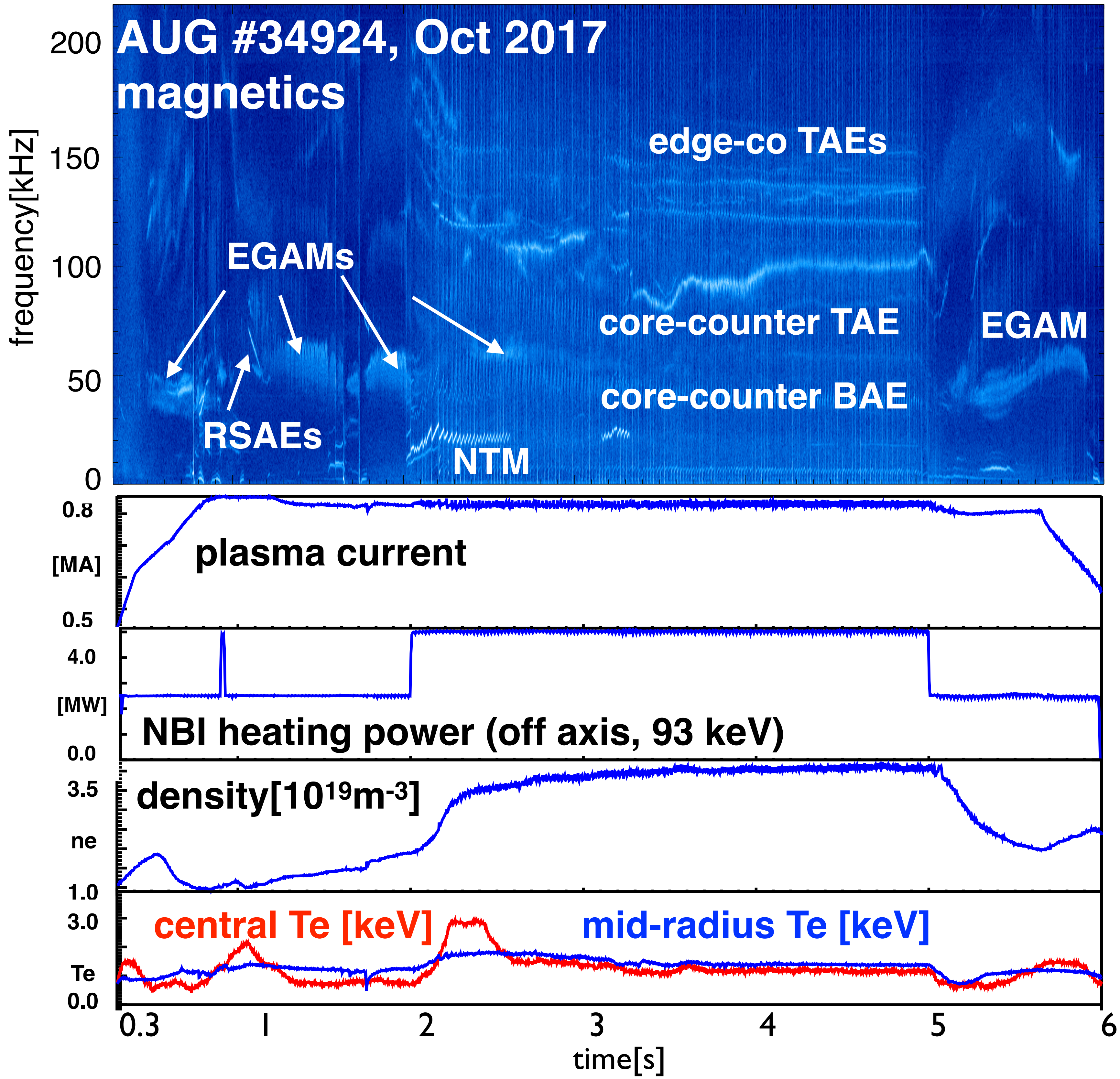
ASDEX Upgrade

- unique data for code validation: vary exp. parameters and heating mix
    - linear drive
    - beam anisotropy as exclusive mode drive - EGAMs
    - non-linear saturation
    - non-linear multi-mode interaction: bi-coherence observed

- improve diagnostics setup: radial location (reflectometry), gain factors (SXR), FILD setup, optimised beam blips for Ti measurements

- develop scenarios that show similar mode dynamics in flat top: this would allows us to measure EP transport and effects on background plasma - ENR MET mission

first successful experiments in 2017

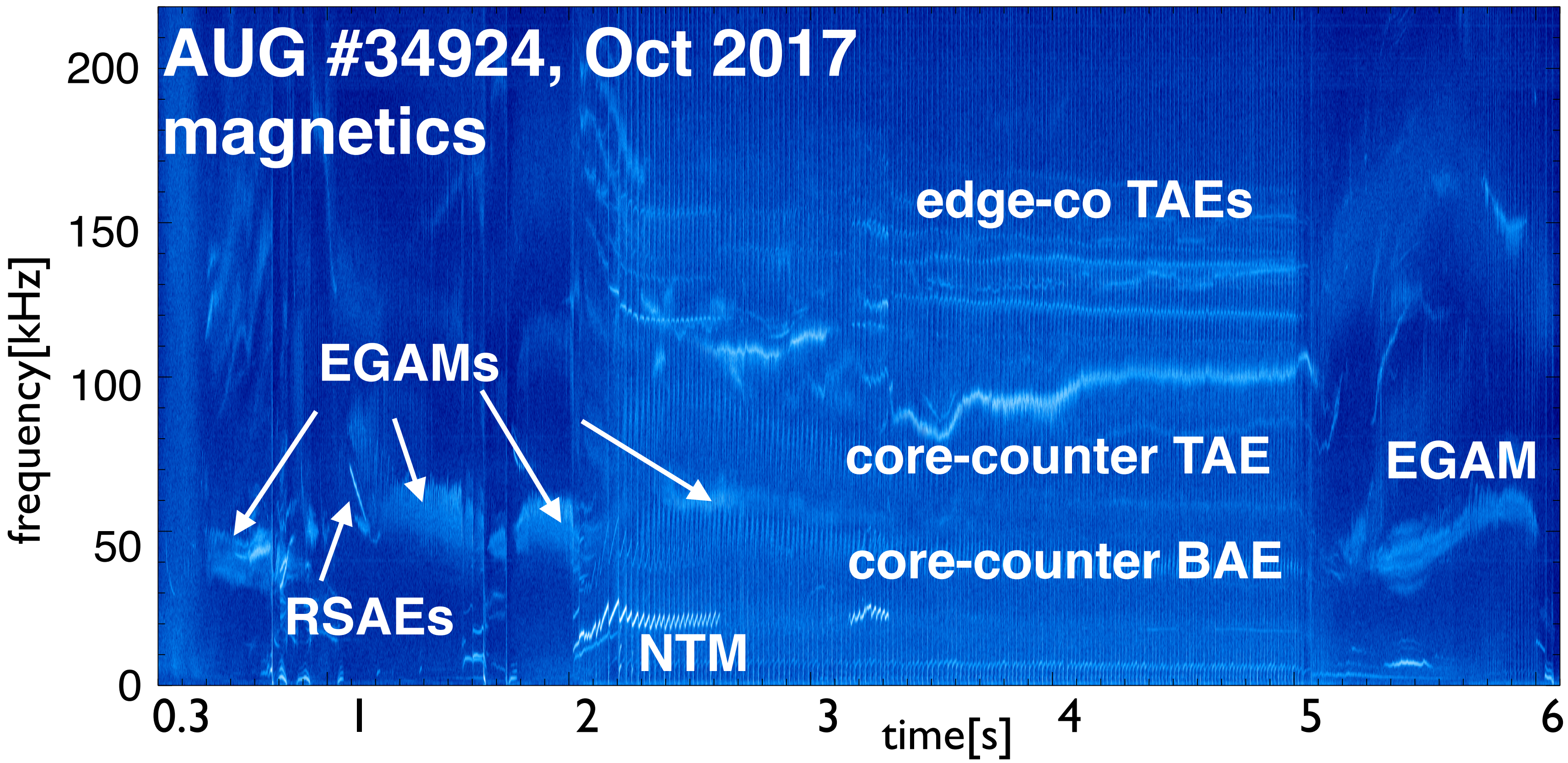


I=800kA
B=-2.5T

q≥2
slightly
reversed

[Lauber, IAEA 2018]

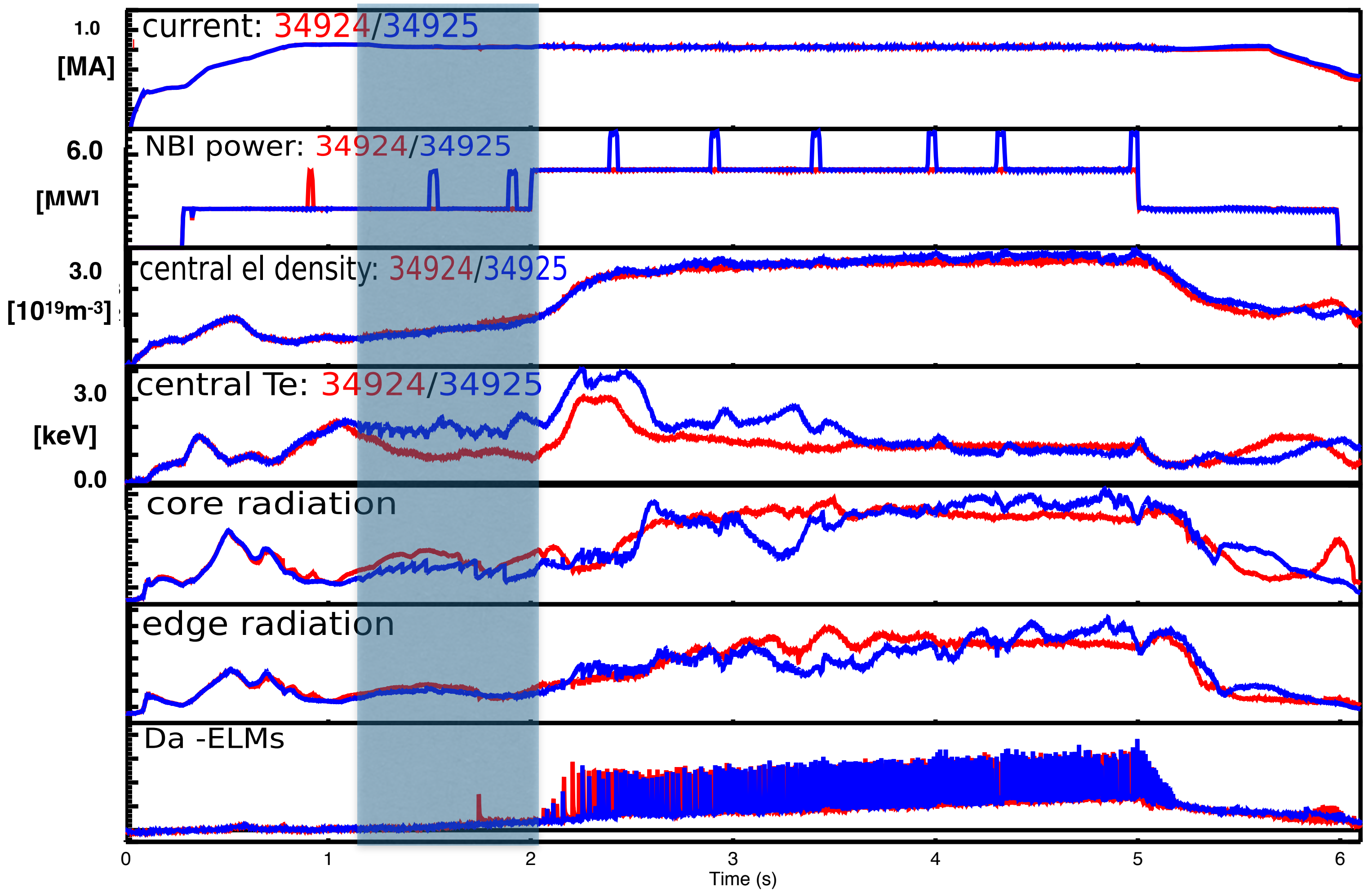
new scenario with strong mode activity induced by energetic particles (EPs) was established at ASDEX Upgrade

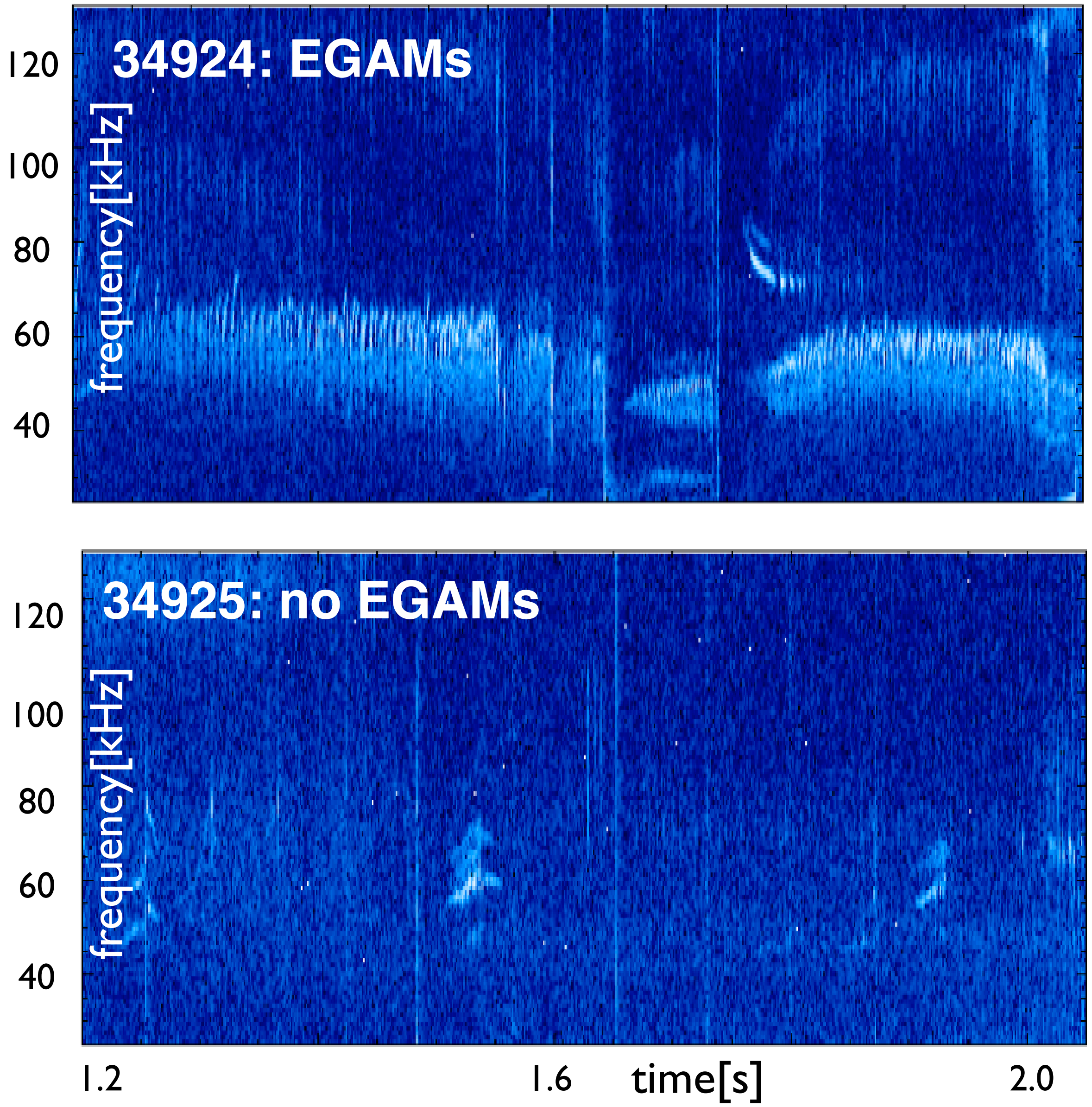


investigation of strongly non-linear EP dynamics at ASDEX Upgrade is now possible:

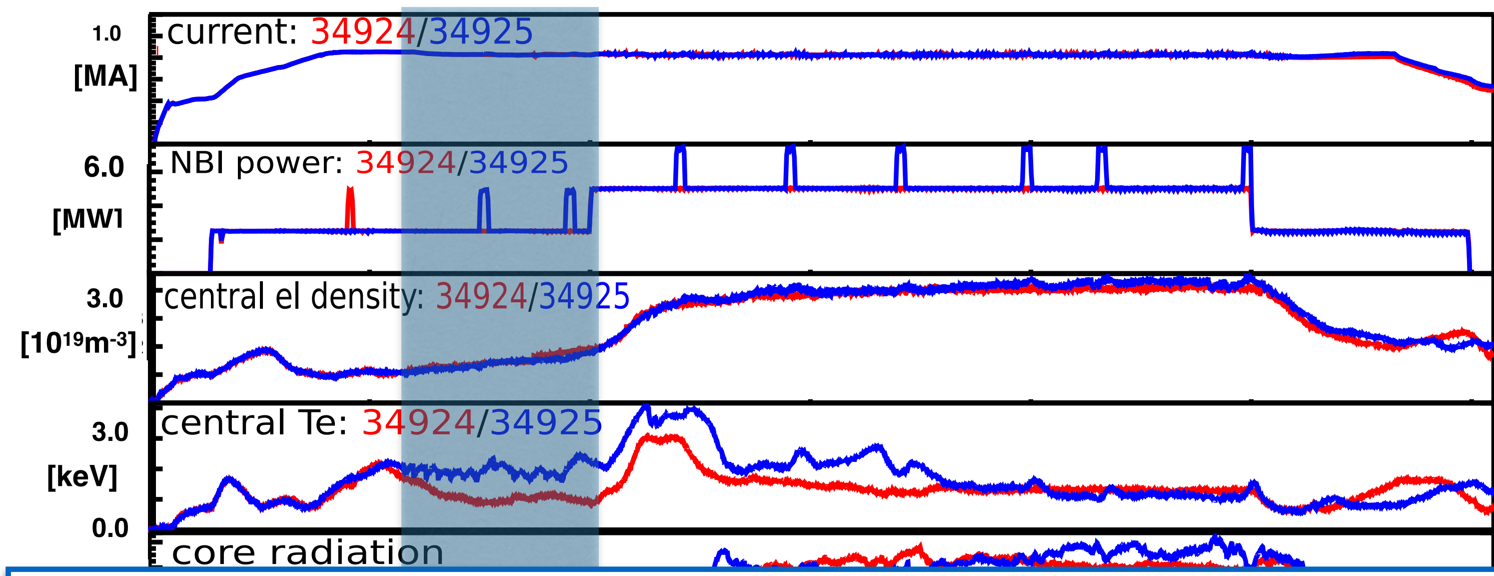
- with sub-Alfvénic beams (2.5-5MW)
- in current flat top with stationary plasma conditions
- compatible with tungsten wall
- for EP physics (at ITER) relevant parameters: $\beta_{EP}/\beta_{thermal} \sim 1$, $E_{NBI}/T_{i,e} \approx 100$

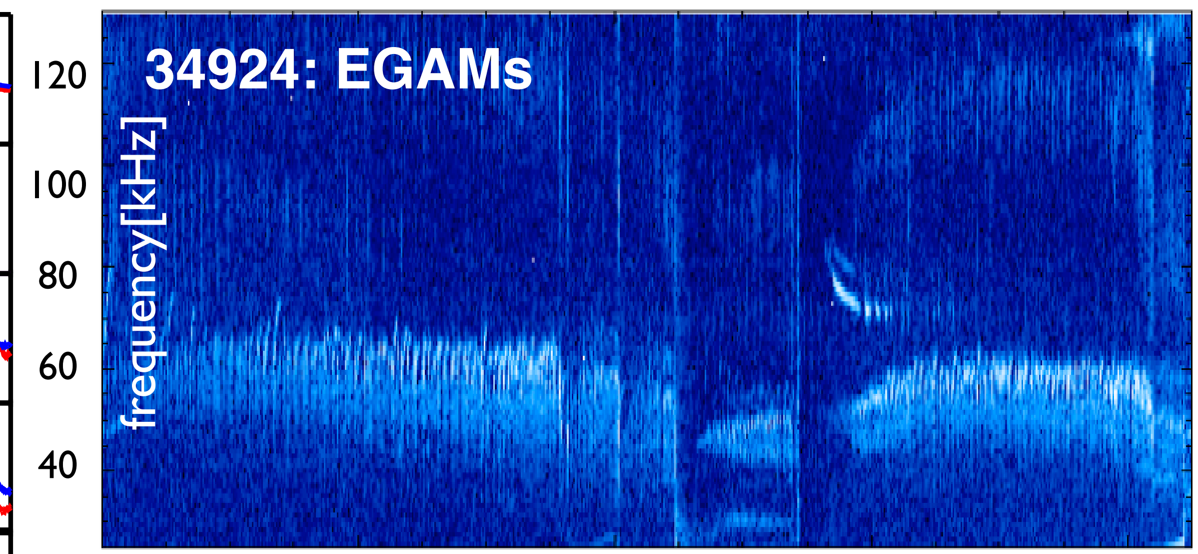
EGAM/AE excitation conditions: comparison of discharges w/o EGAMs/AEs

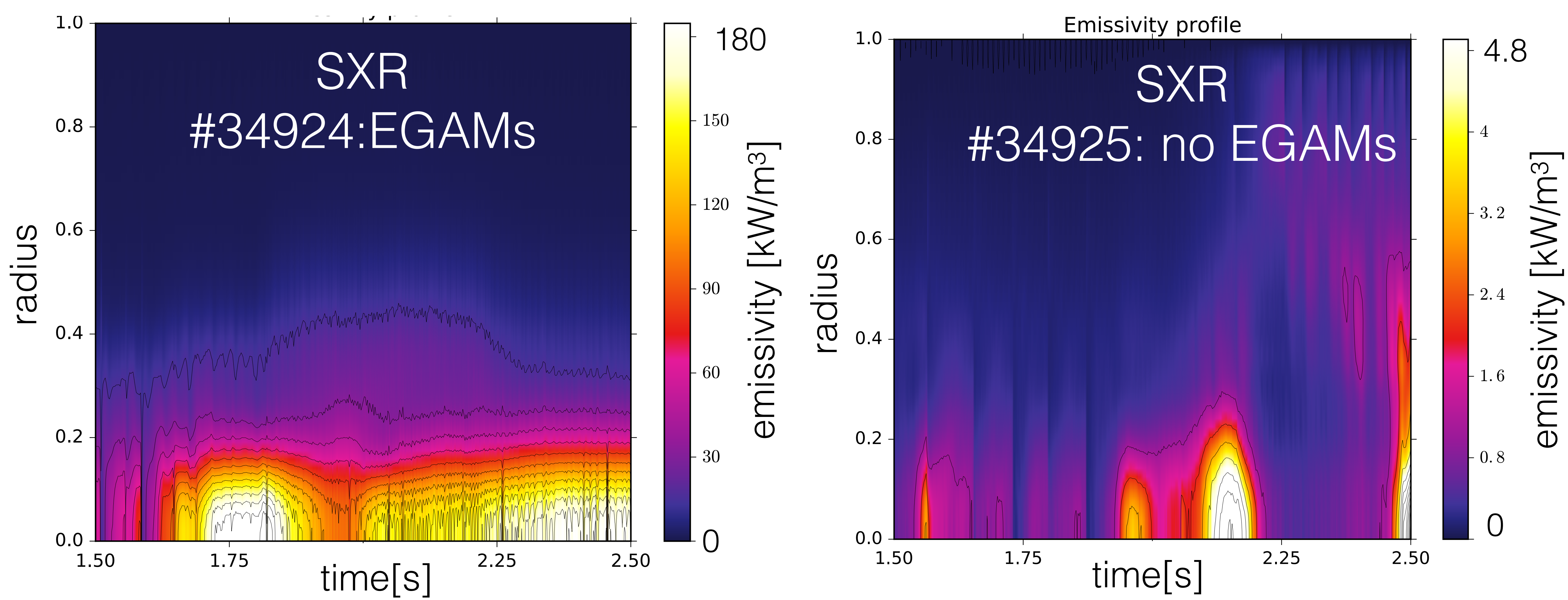




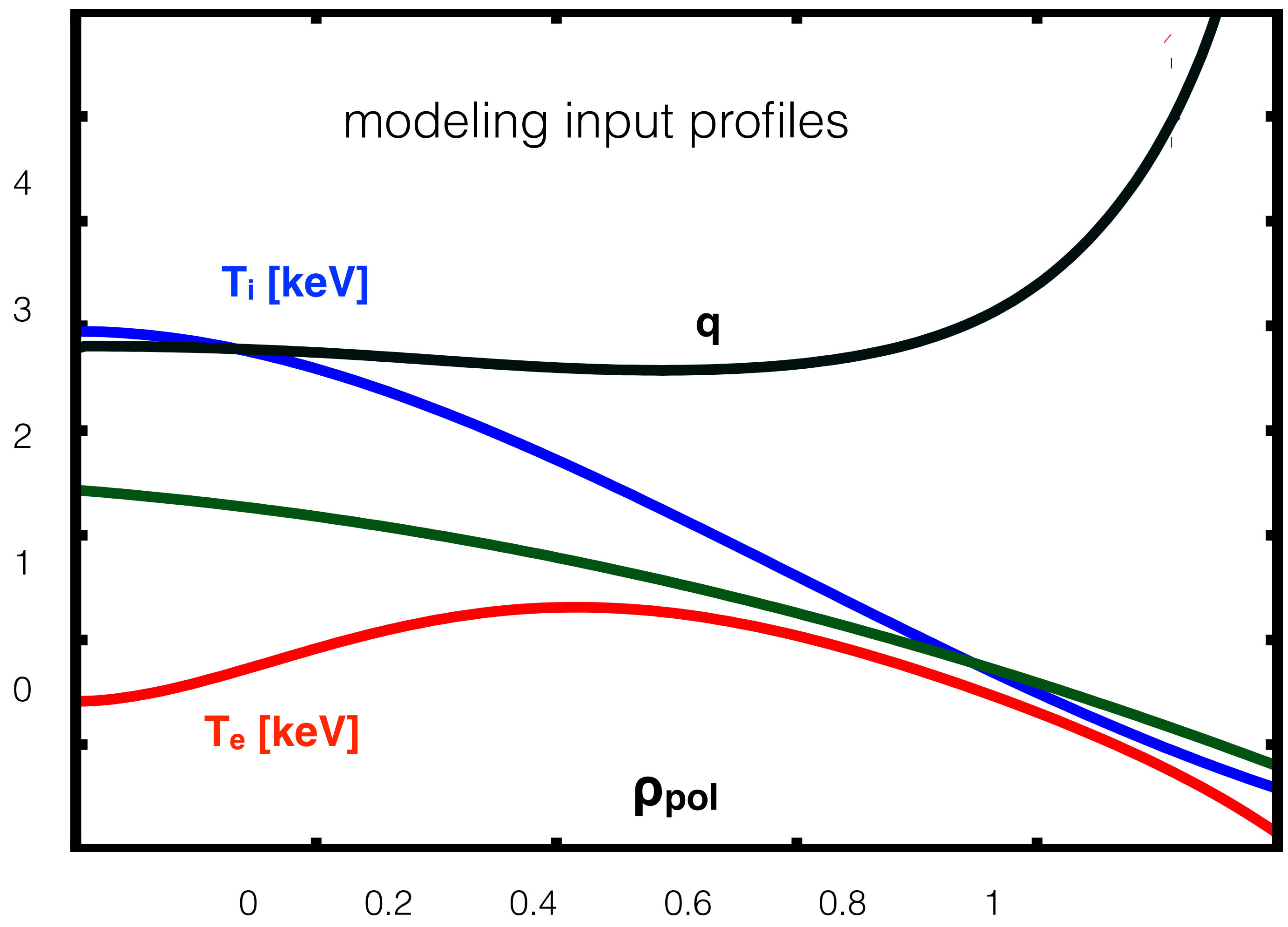
EGAM excitation conditions: comparison of discharges w/o EGAMs

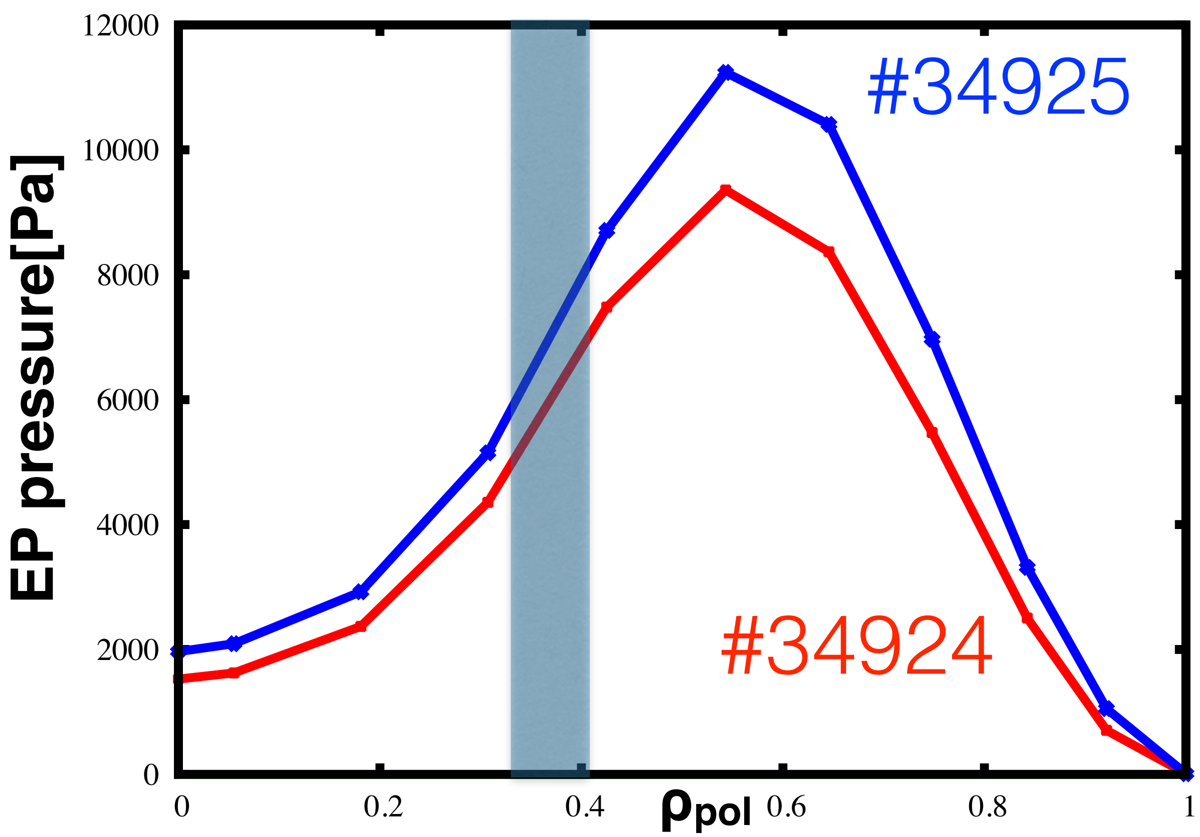






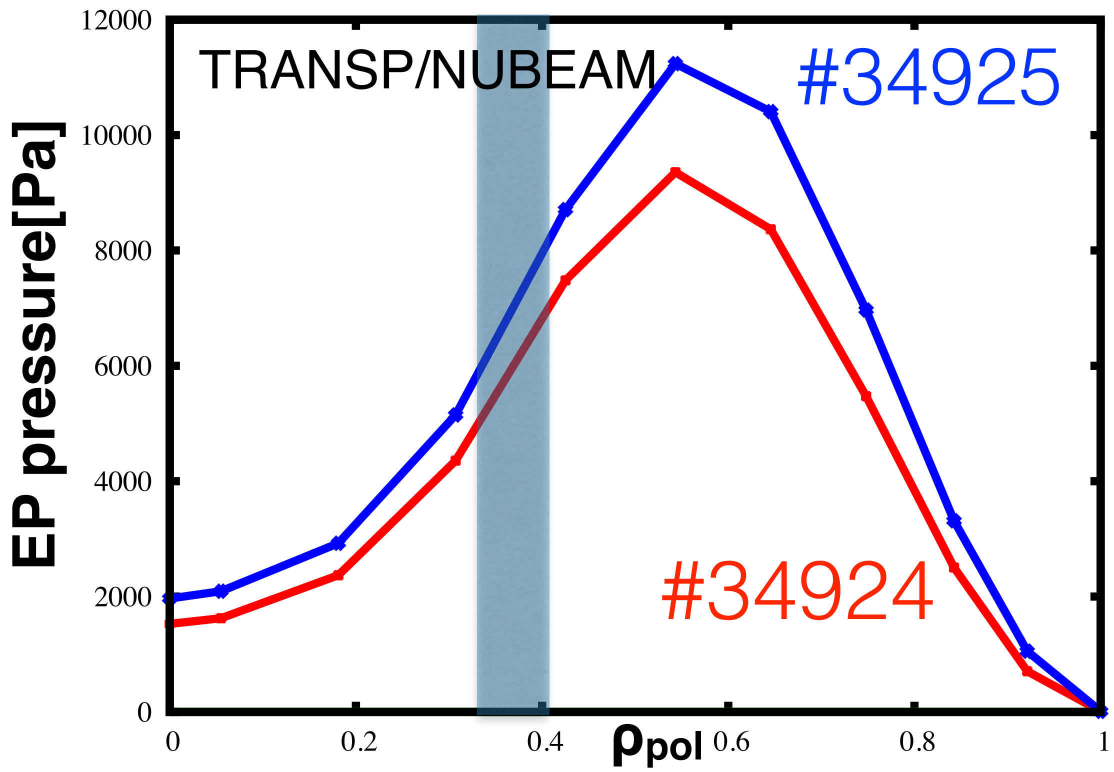
profiles very similar to NLED case

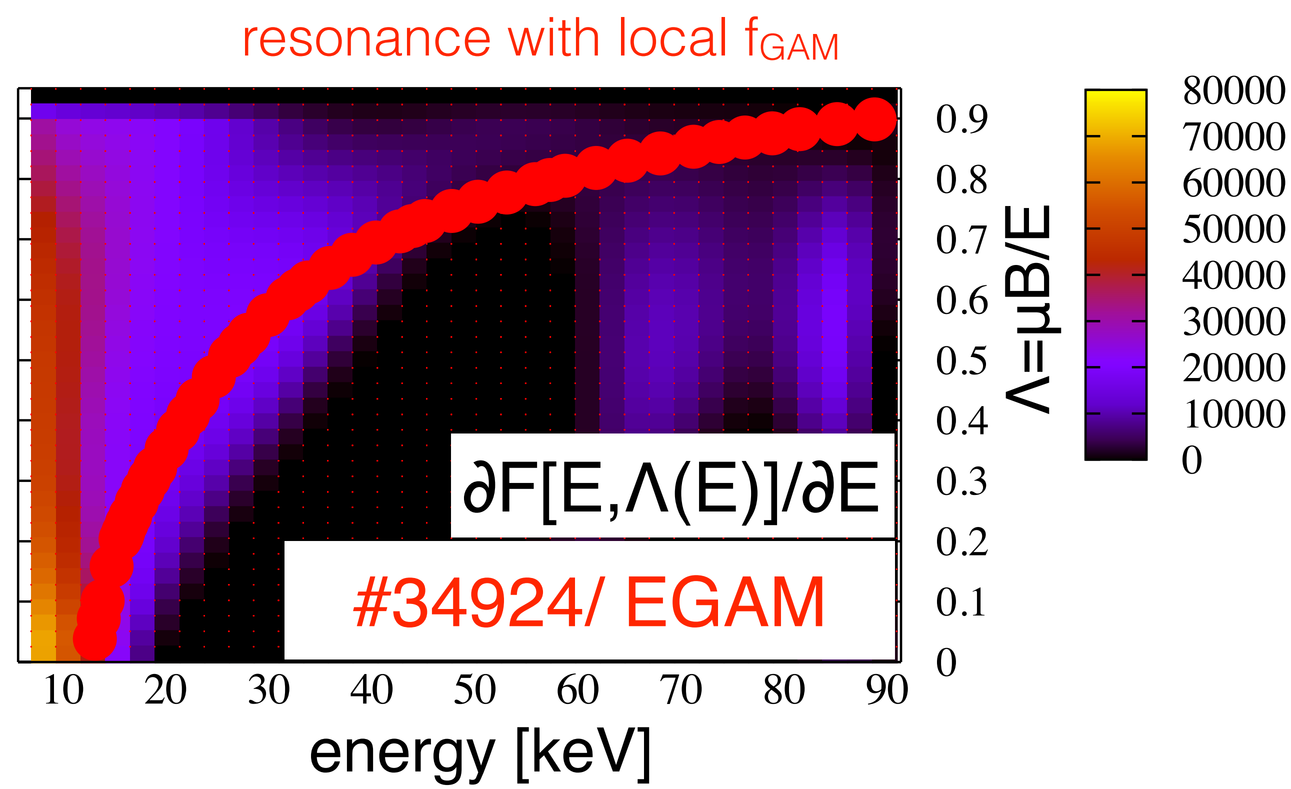


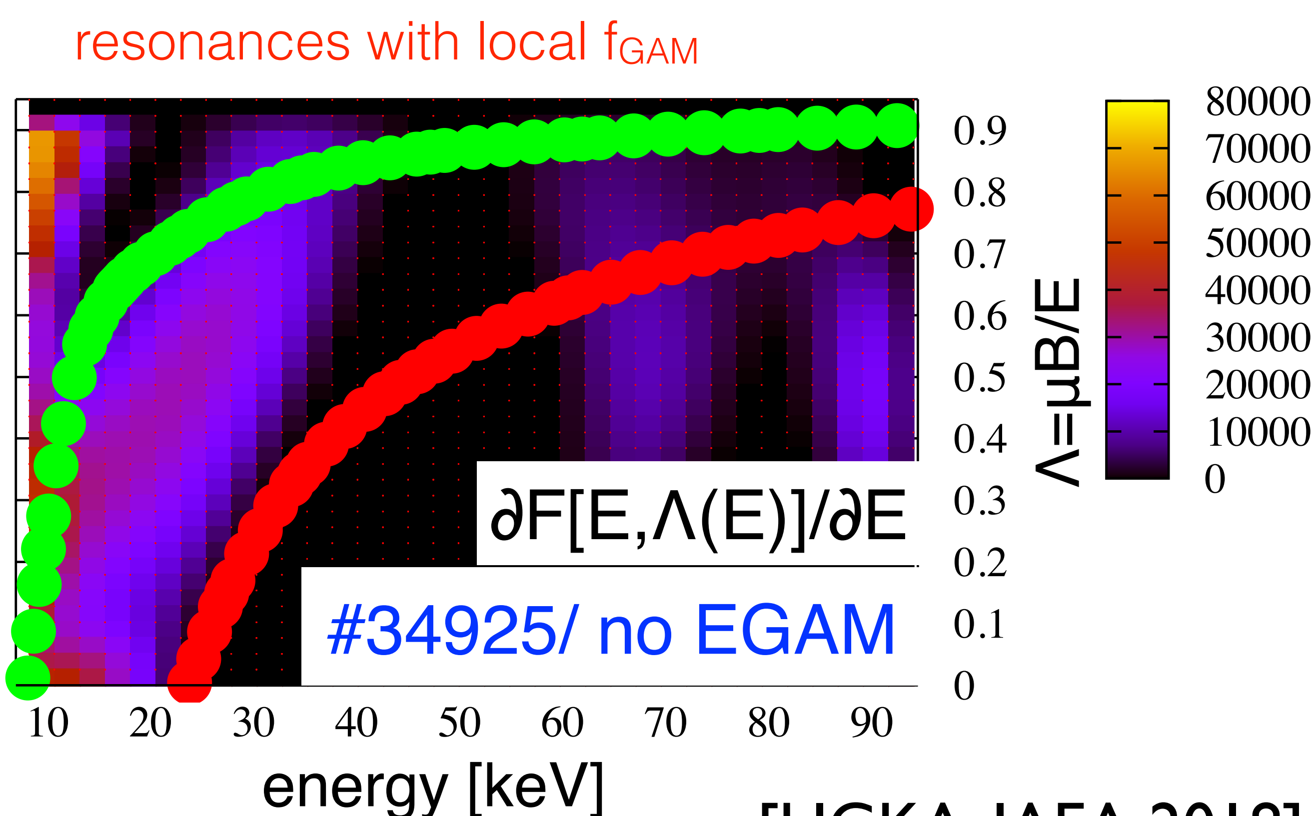


difference: slightly higher, 5MW off-axis beams instead of 2.5MW

EP phase space analysis: ∂F/∂E



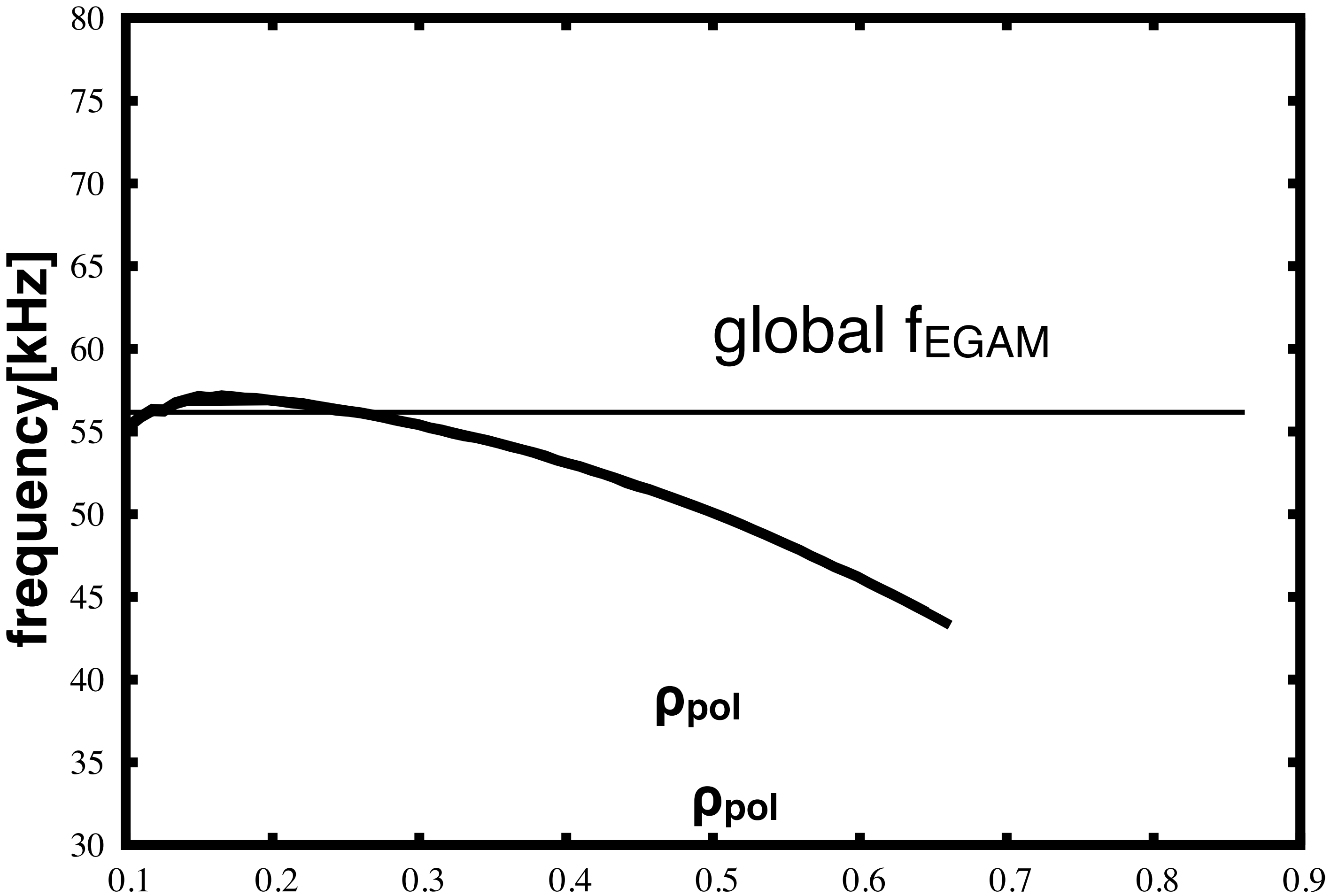


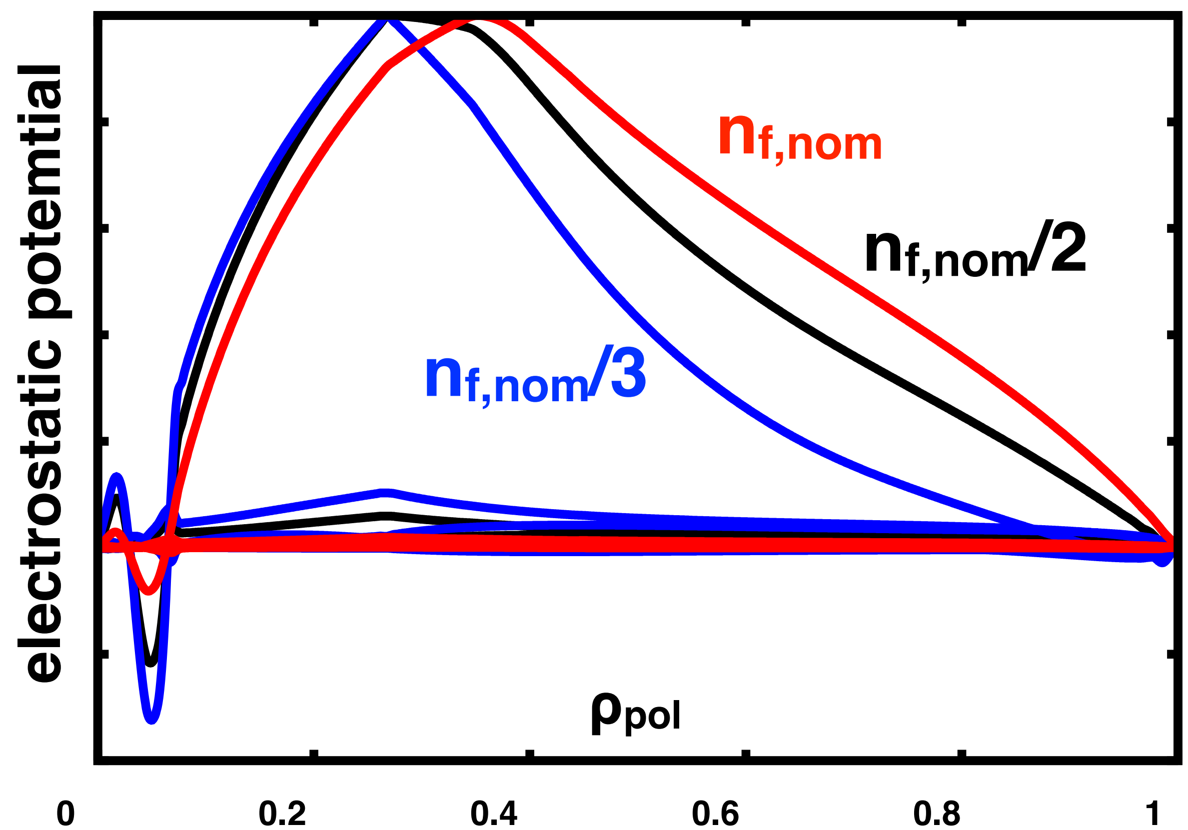


- EGAM drive is determined by integral along resonance line $\omega-\omega_t=0$
- no drive due to mismatch of drive region and local GAM frequency
- 2nd resonance $\omega - 2\omega_t=0$ suffers from damping of thermal background - ‘anomalous ion heating’ *[LHD, Ido 2014, H. Wang 2018]*

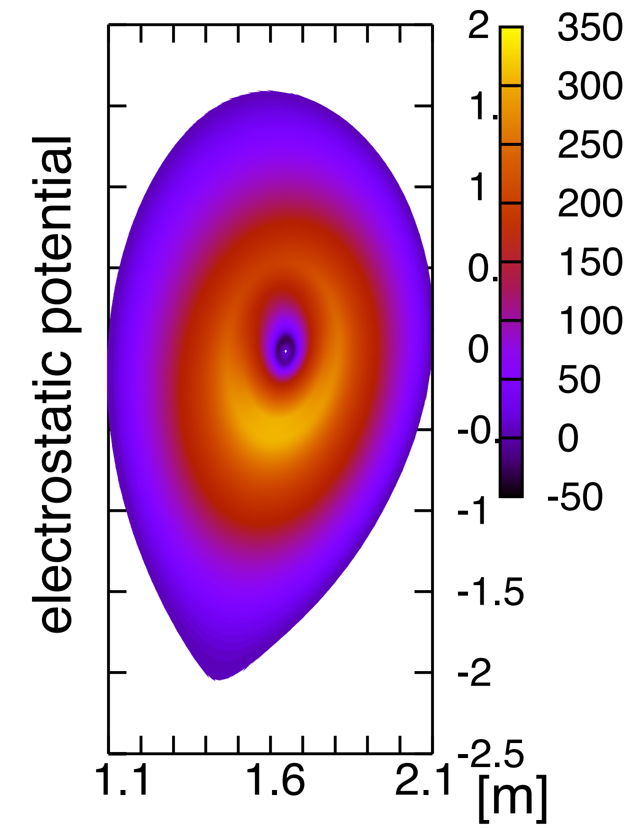
[LIGKA, IAEA 2018]

global EGAM structure [LIGKA]





- global EGAM frequency stays roughly constant with increasing n_{EP}, and close to flat part of the GAM continuum
- change in mode structure is observed with increasing n_{EP}

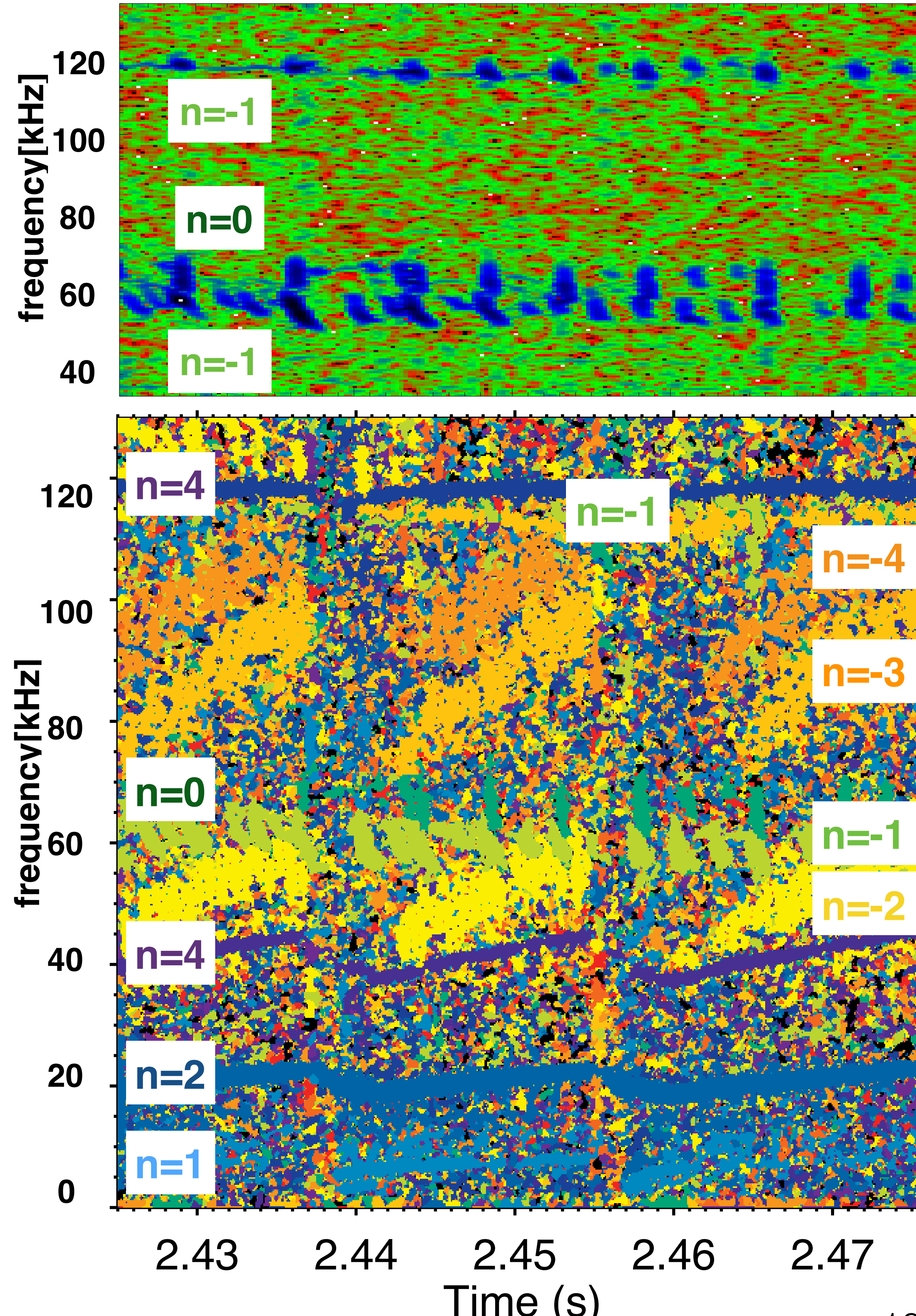


global EGAM also found by ORB5/GENE [I. Novikau, A. di Siena]- however, no realistic F_{NBI} was used yet that would be needed for quantitative analysis … see below

3 types:

1. simultaneous mode onset, no phase correlation: triggering
2. phase correlation between different frequency bands: significant bicoherence indicating nonlinear wave-wave coupling
3. **both** mechanism can be observed together

note: due to off-axis peak modes propagating in ion (+) and electron(-) diamagnetic directions are found



local and global LIGKA analysis

1st type:

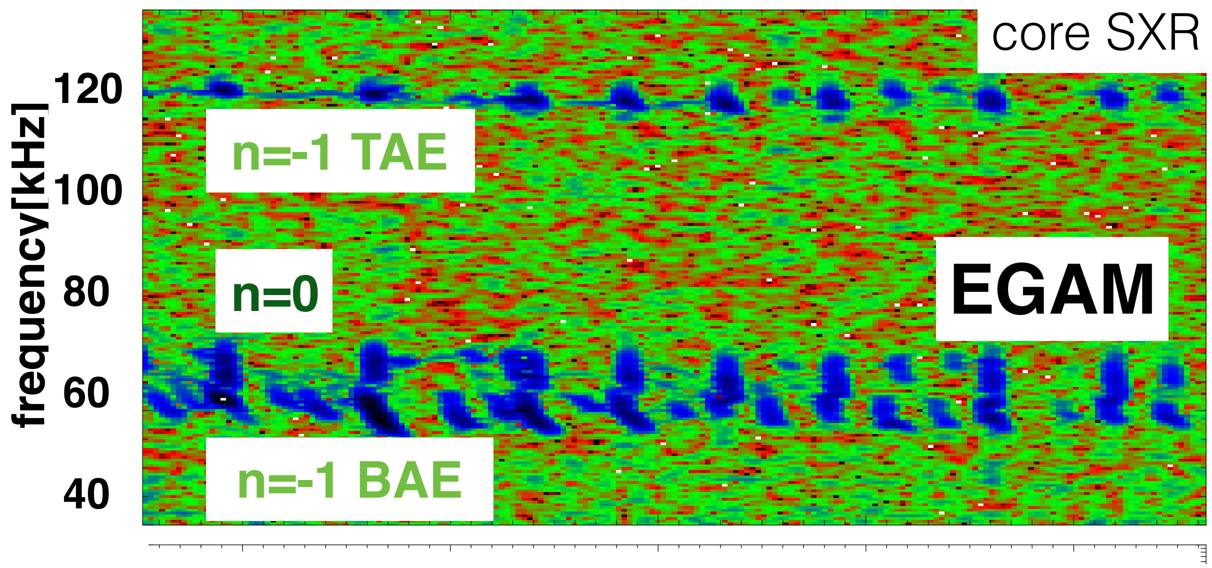
global mode structures:
[arb units for amplitudes]

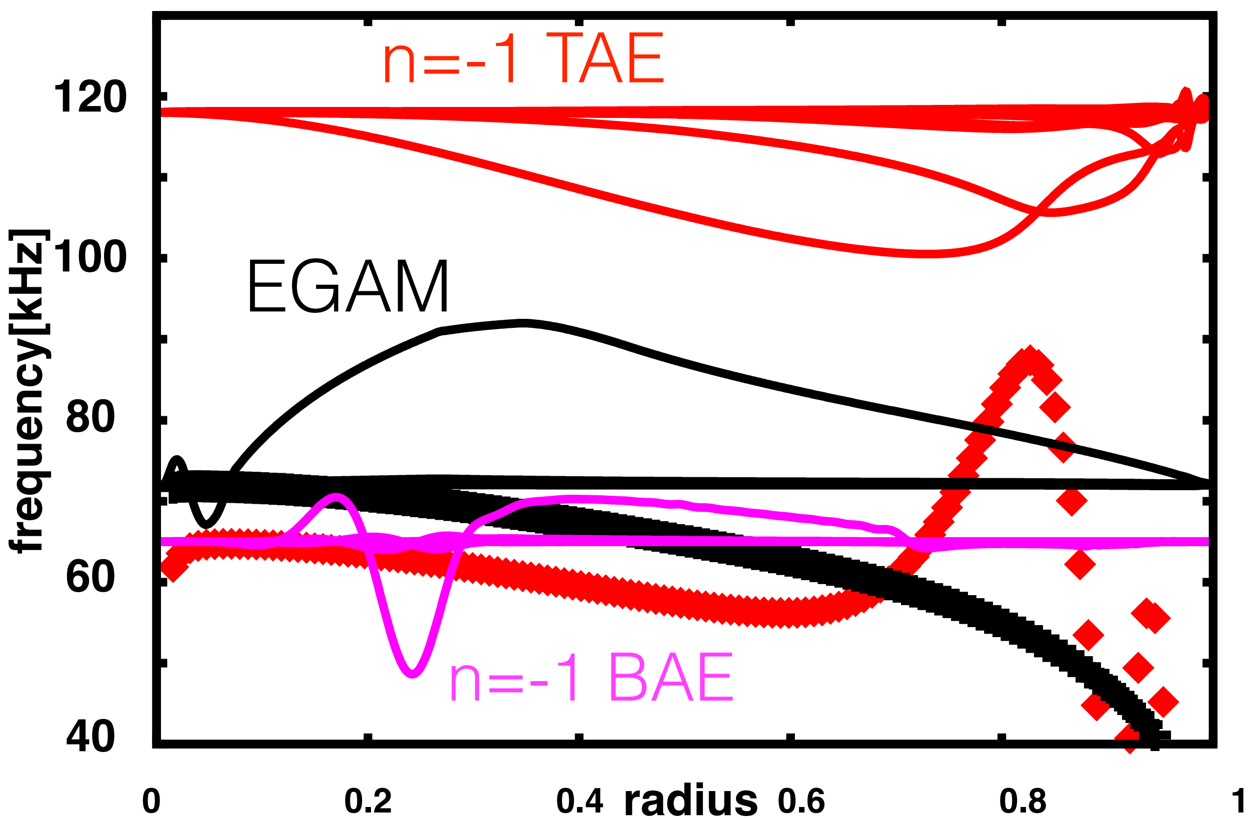
resonance analysis shows that:

- BAEs can tap energy from gradient both in velocity space and real space: most unstable mode

$$\gamma \sim \frac{\omega\, \partial F/\partial E - n\, \partial F/\partial P_\Phi}{\omega - \omega_t}$$

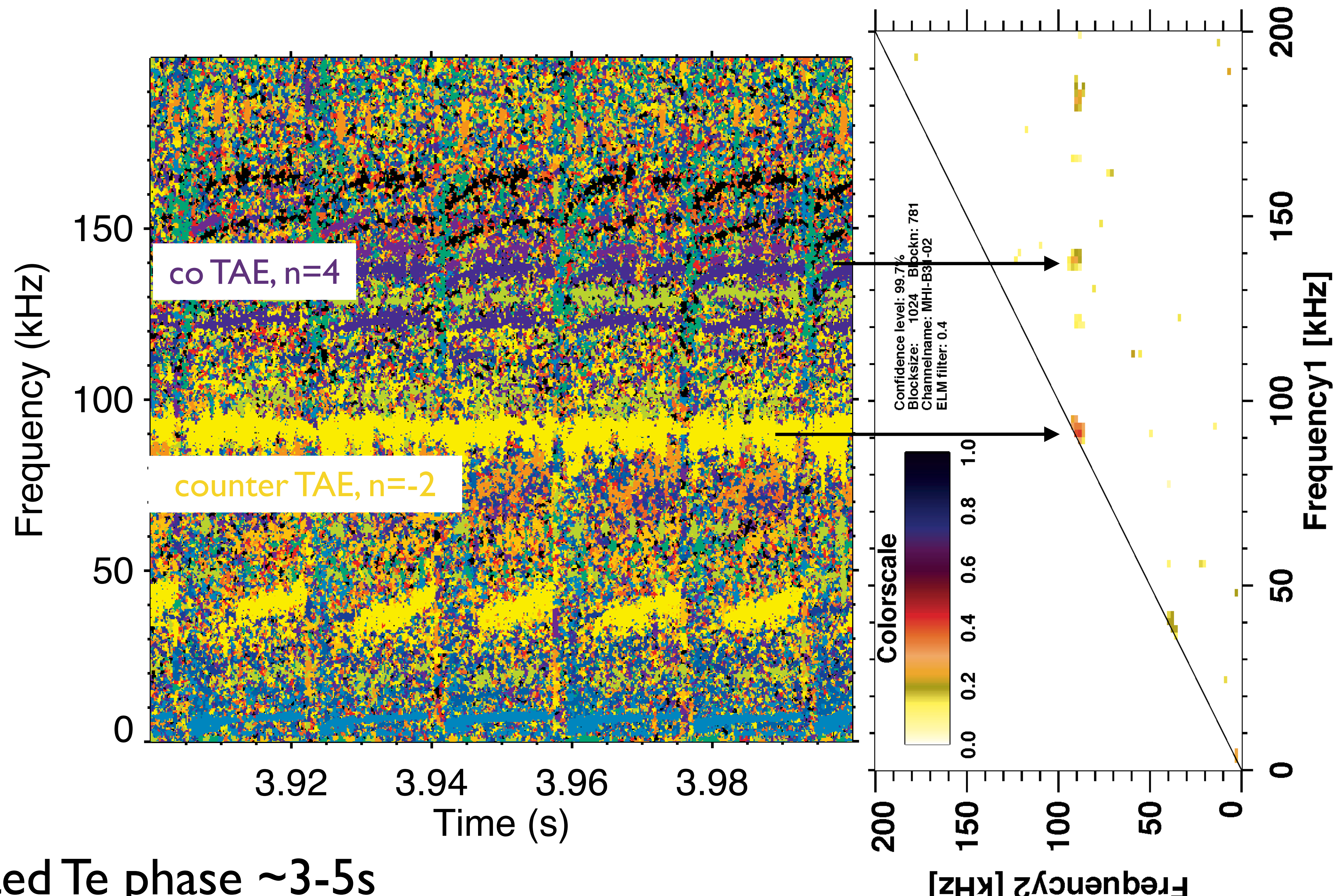
- BAE redistributes mainly in radial direction and thus triggers the EGAM (increased EP density) and TAE (higher order resonances)





non-inverted Te phase

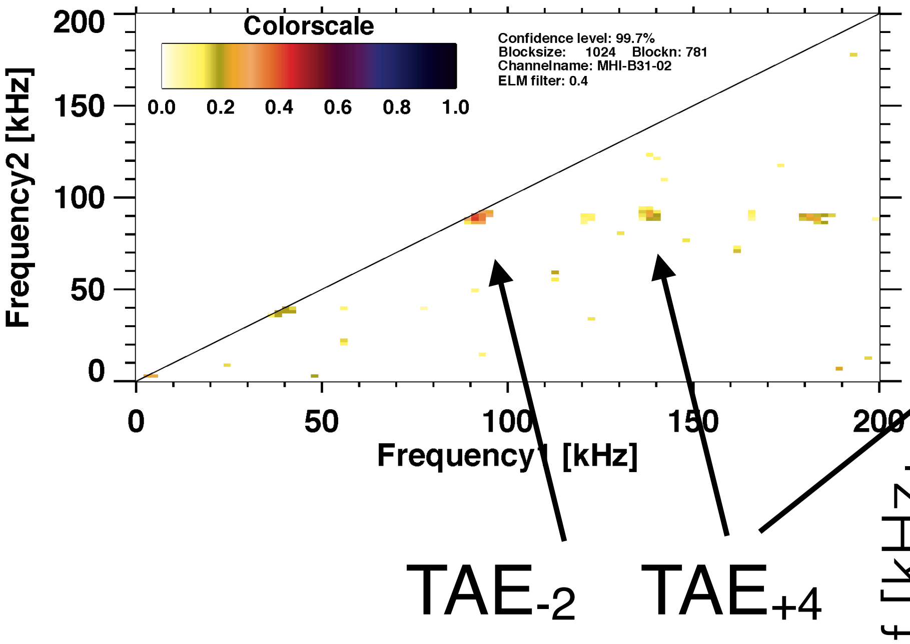
2nd type: ELM filtered bicoherence analysis shows evidence of mode-mode interaction

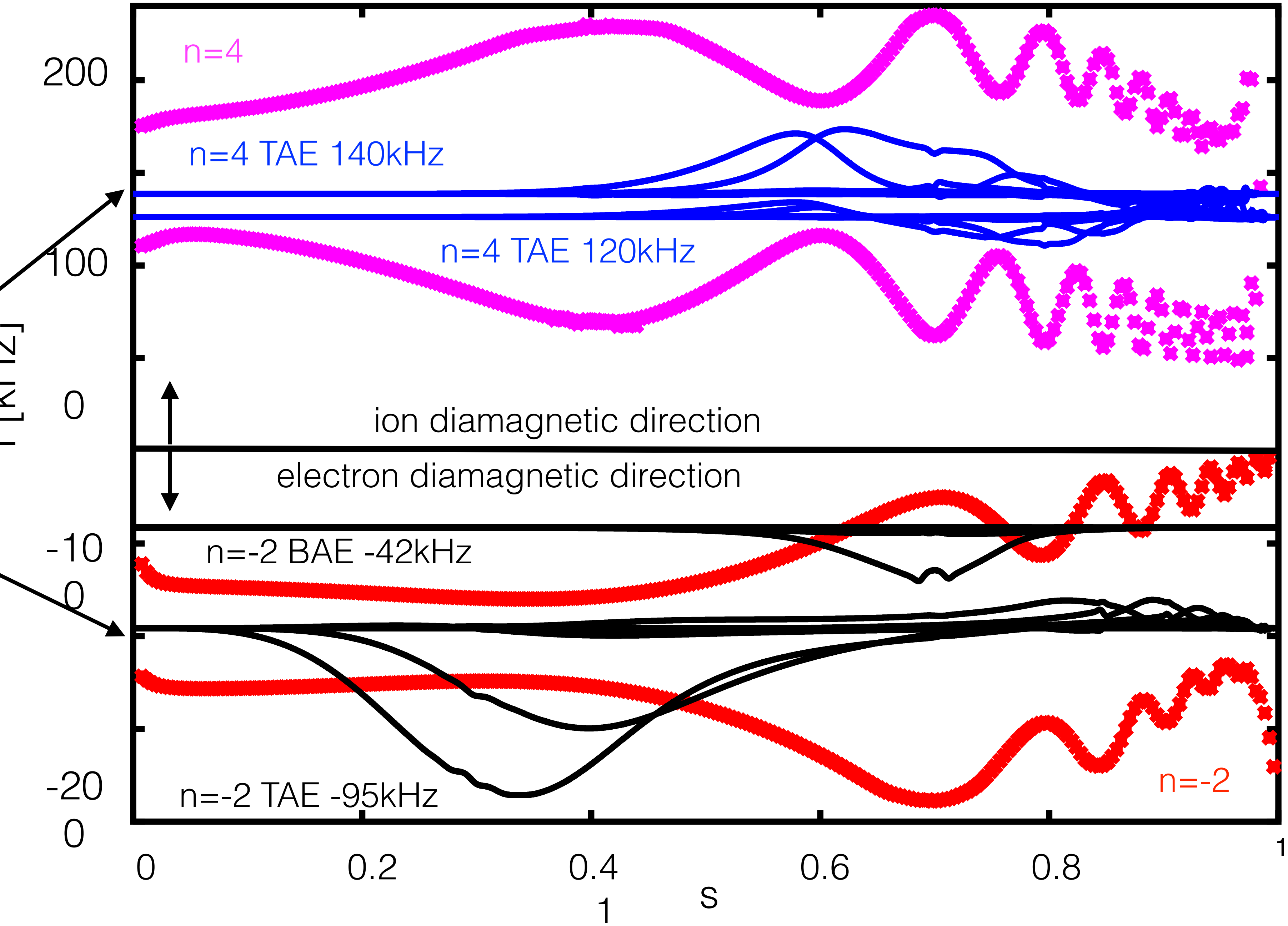


inverted Te phase ~3-5s

bicoherence measures phase coherence between the frequency bands that indicates a **non-linear (i.e. quadratic) interaction: n=-2 TAE and n=4 TAE bands**

LIGKA: unstable modes, 3 wave coupling analysis





2nd type:

- after subtracting/adding rotation (7kHz): $\omega_{TAE-2}-\omega_{TAE+4}=0$
- also: $k_{\parallel TAE-2}+k_{\parallel TAE+4}= 1/(2\ q_{TAE-2}\ R)-1/(2\ q_{TAE+4}\ R)=0.222-0.211\approx 0$
- fulfil matching conditions with zero frequency zonal structure: modified parametric decay constellation

[Biancalani FEC 2016, TH/P2-9 2018]

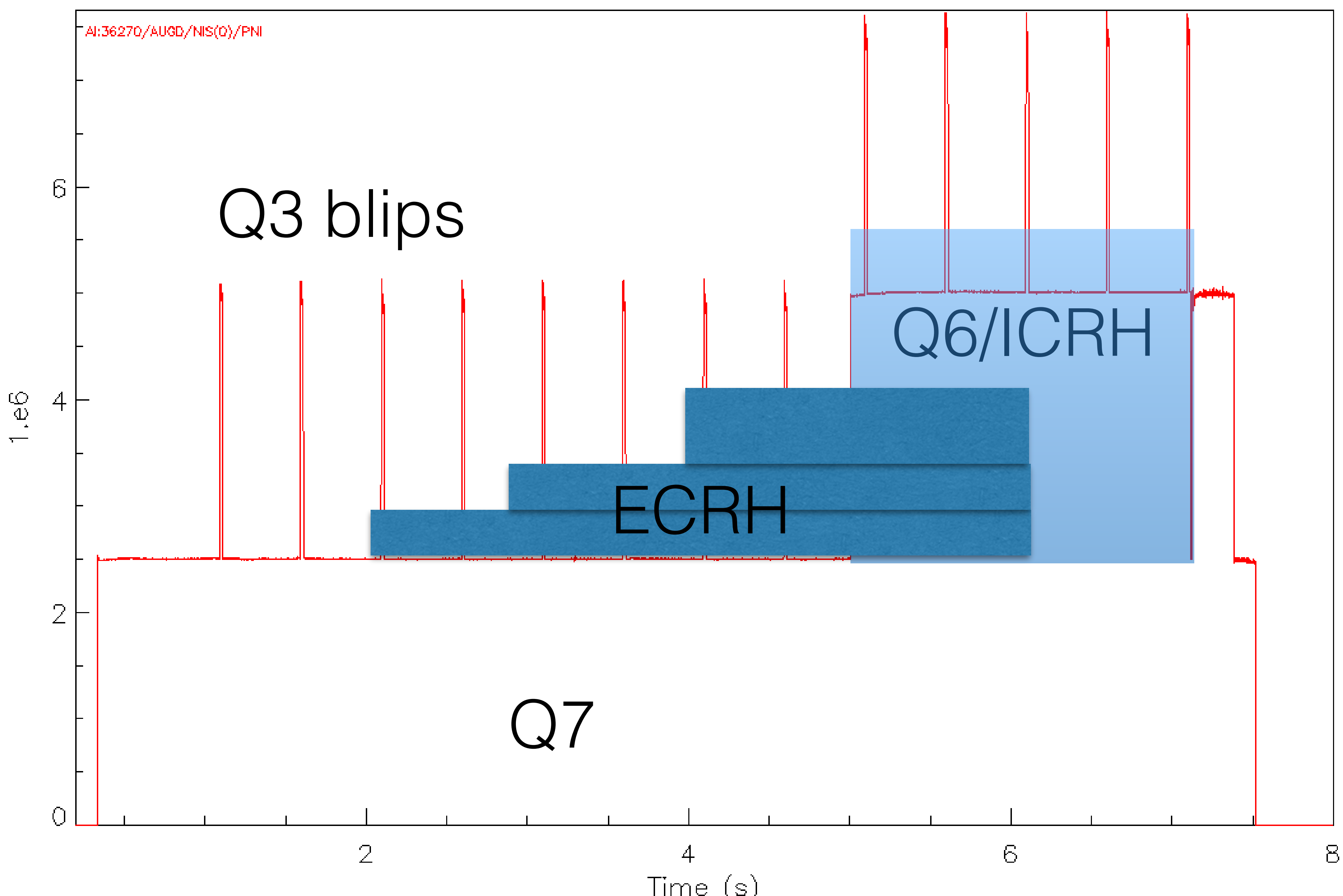
new: towards EP transport

before June 2019: two flat-top discharges only

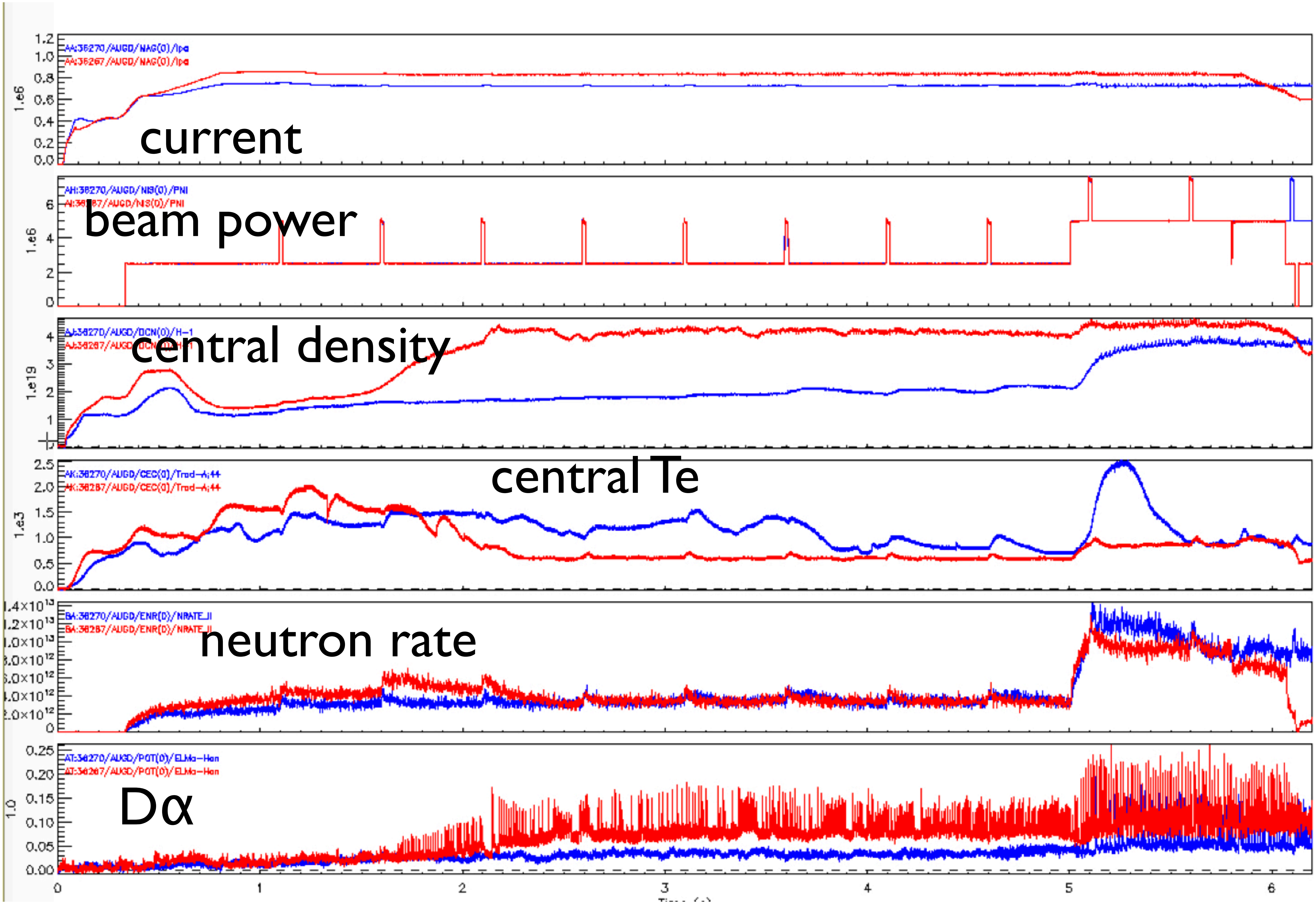
- June 2019: 6 successful EGAM flat-top discharges in H and L-mode (#36267,69,70; 36337,38,39)
- robust excitation in all shots (also Q6) in ramp-up, flat top and ramp-down
- at different Te,Ti,Te/Ti (0.5-2.5keV)
- at different densities (n_e=2 - 5 · $10^{19}m^{-3}$)
- in combination with various other heating: ICRH, ECRH
- also EGAMs in H plasmas! Isotope scaling checks possible

new discharges: scenario & heating

- off axis beam (7) is main driver
- optimised beam blips for Ti and rotation measurements
- replace beam power by ECRH to find marginal conditions

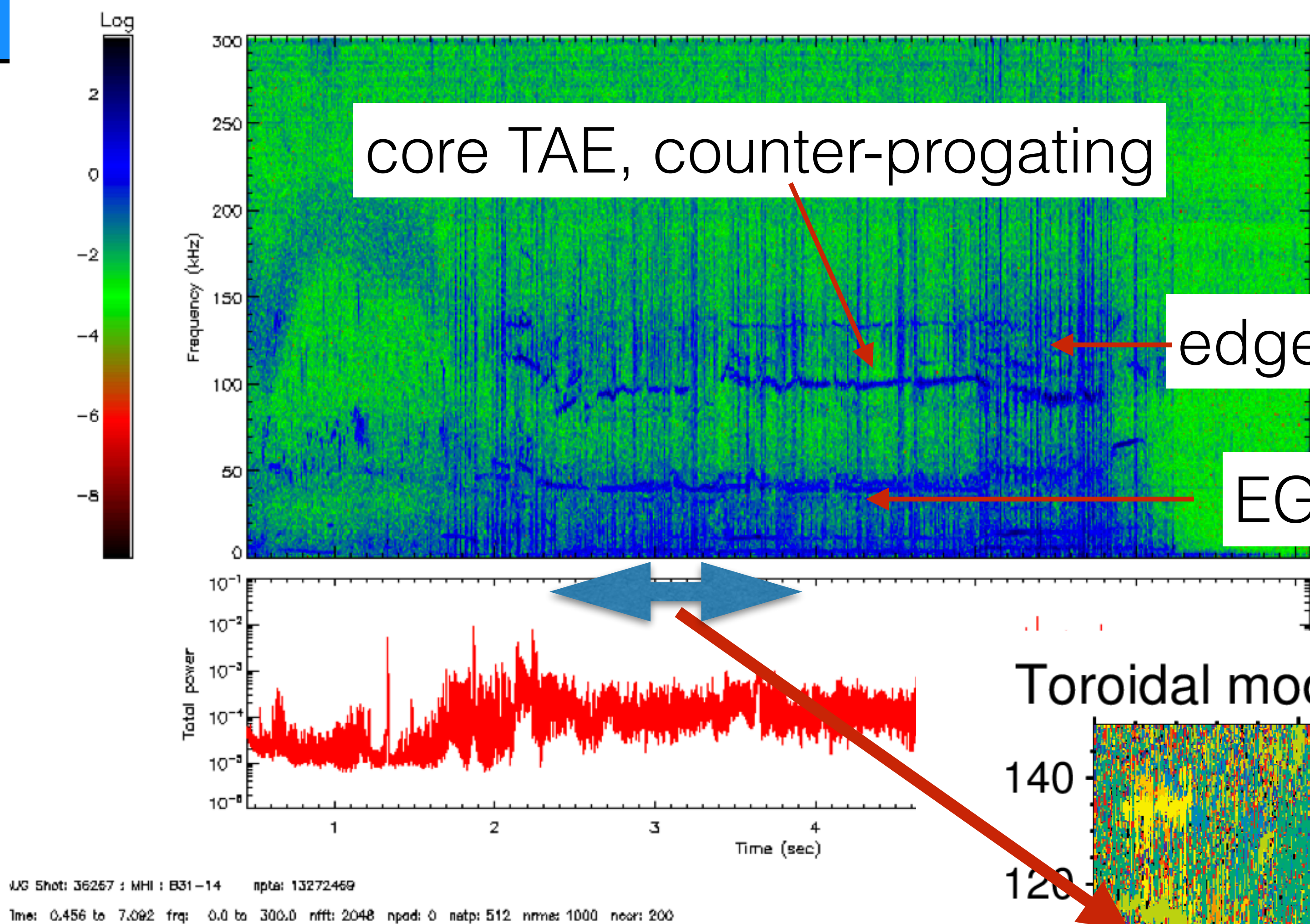


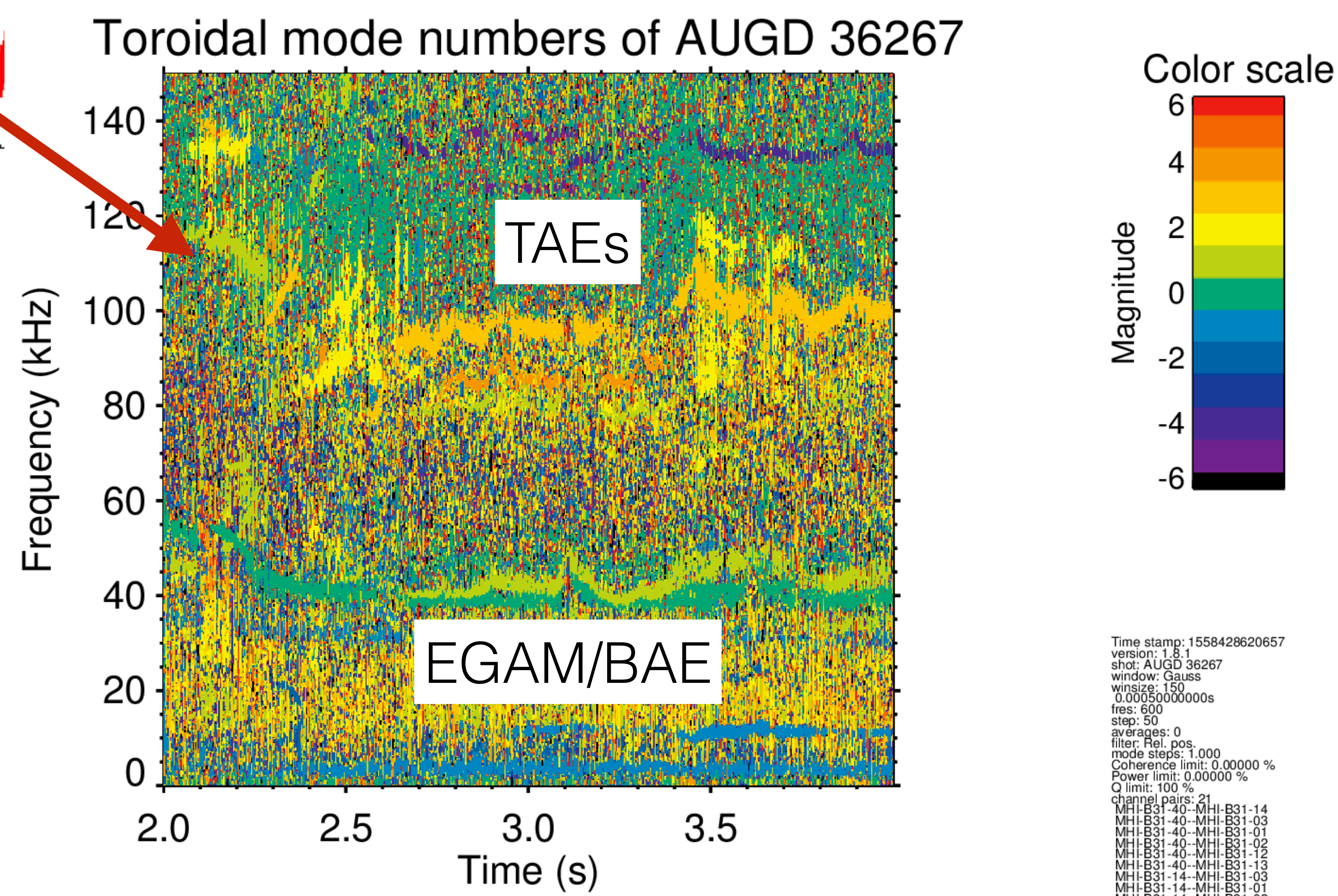
H and L modes: H mode more stable, L modes allow for better diagnostics, no ELMs



stable EGAM phases, co and counter propagating BAEs/TAEs

#36267
H Mode

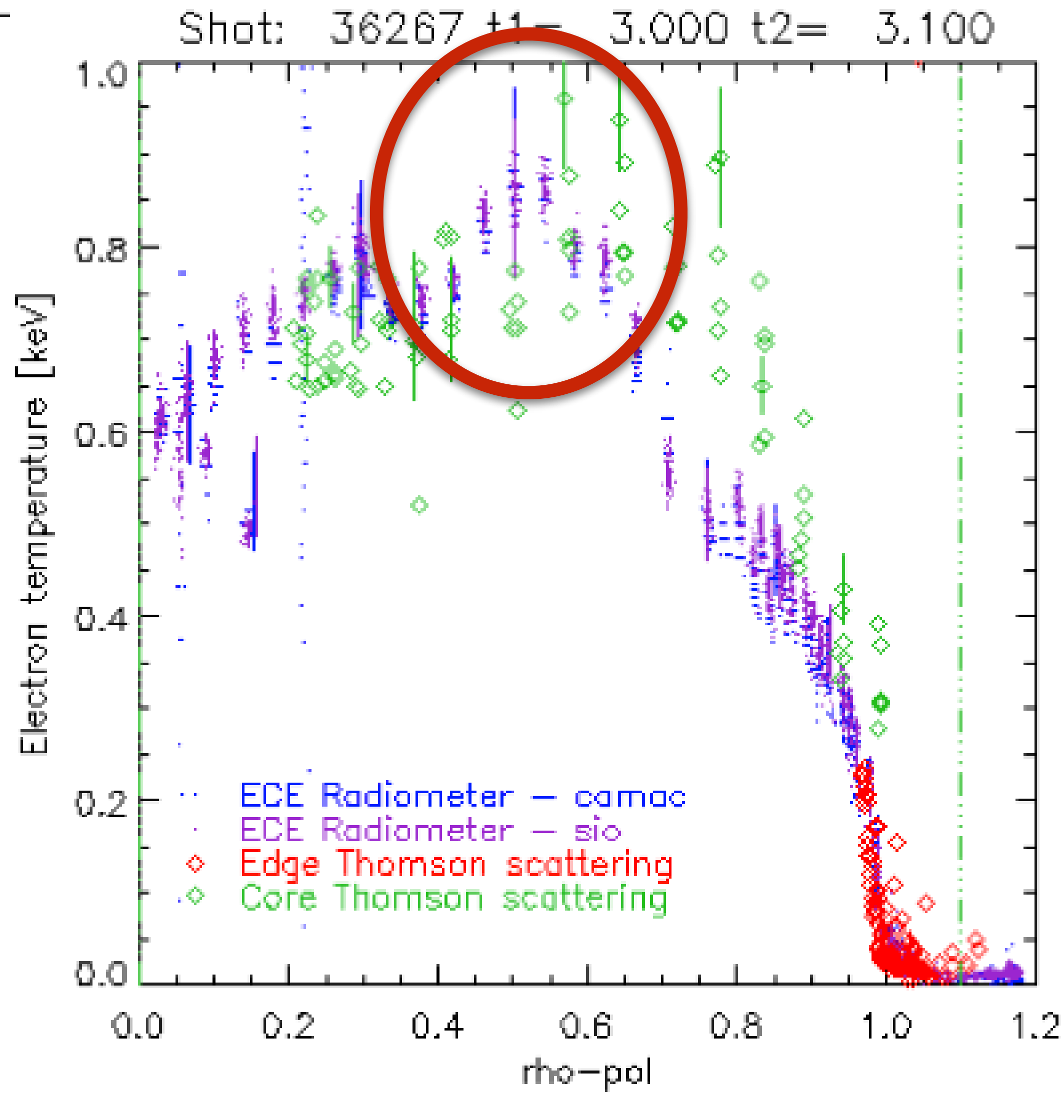


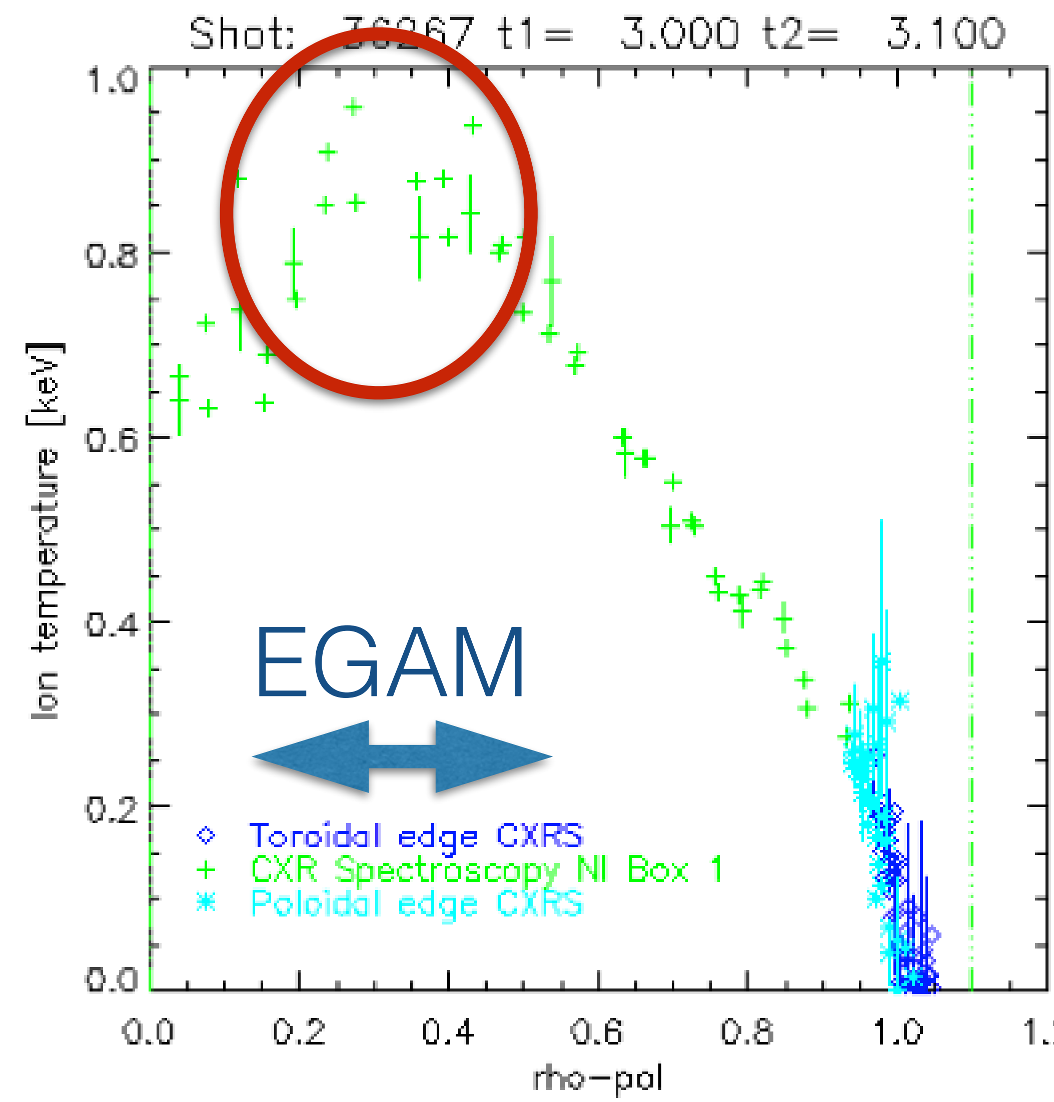


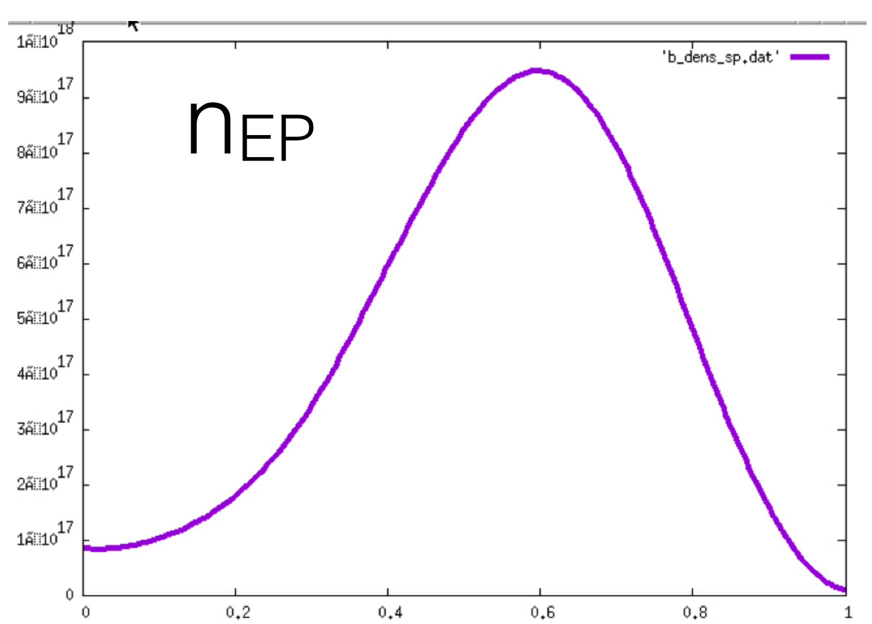
H-mode with cold and inverted Te,Ti

#36267@3s

ASDEX Upgrade

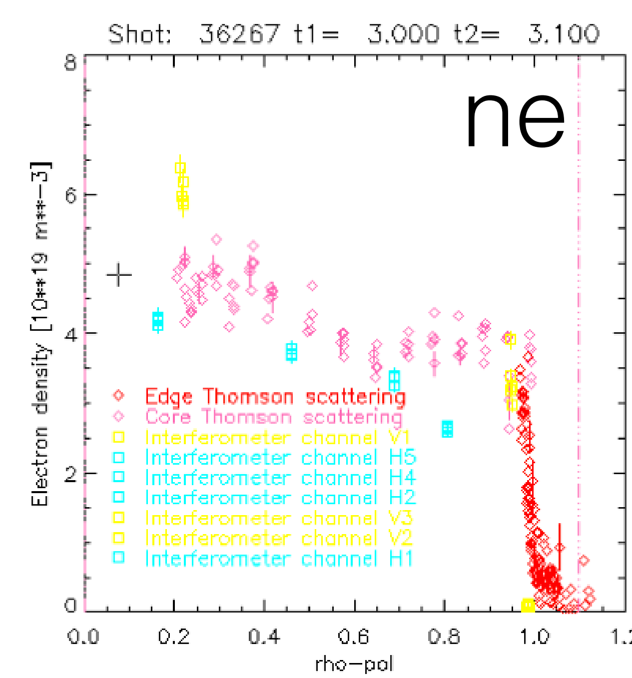






Te,Ti maxima radially shifted - indication for anomalous heating? or AE transport?

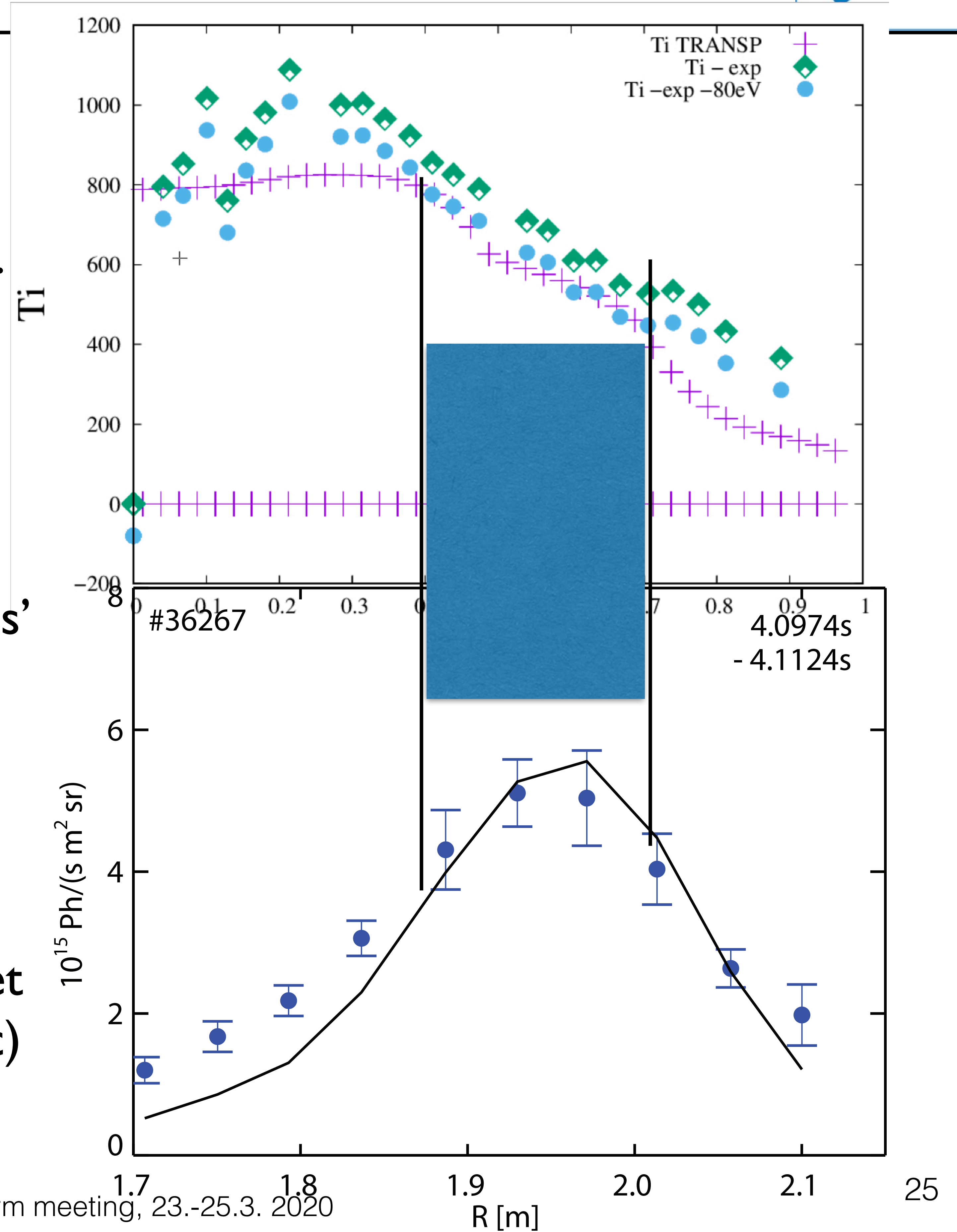
E_{beam}/T_i~120-150! (~3.5MeV/25keV)



EP transport, background ion heating?

TRANSP modelling (with B. Geiger):

- run in semi-interpretative mode: use profiles, in particular ne, Te,q from exp. measurements
- use gyro-bohm model for chi(ions)
- use Nubeam neoclassical model for calculating EP deposition
- compare T_i and n_{EP} with actually measured profiles to detect 'anomalous' effects
- in shaded region between s=[0.4-0.7] model predicts correct gradient
- in core s<0.4 and edge s>0.7 T_i is significantly increased
- at edge, situation is difficult to interpret (losses, change of transport regime etc)
- in core, clear effect on ion heating can be observed



EP transport, background ion heating?

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- use gy
- use N calcula
- compa measu effects
- in shad model
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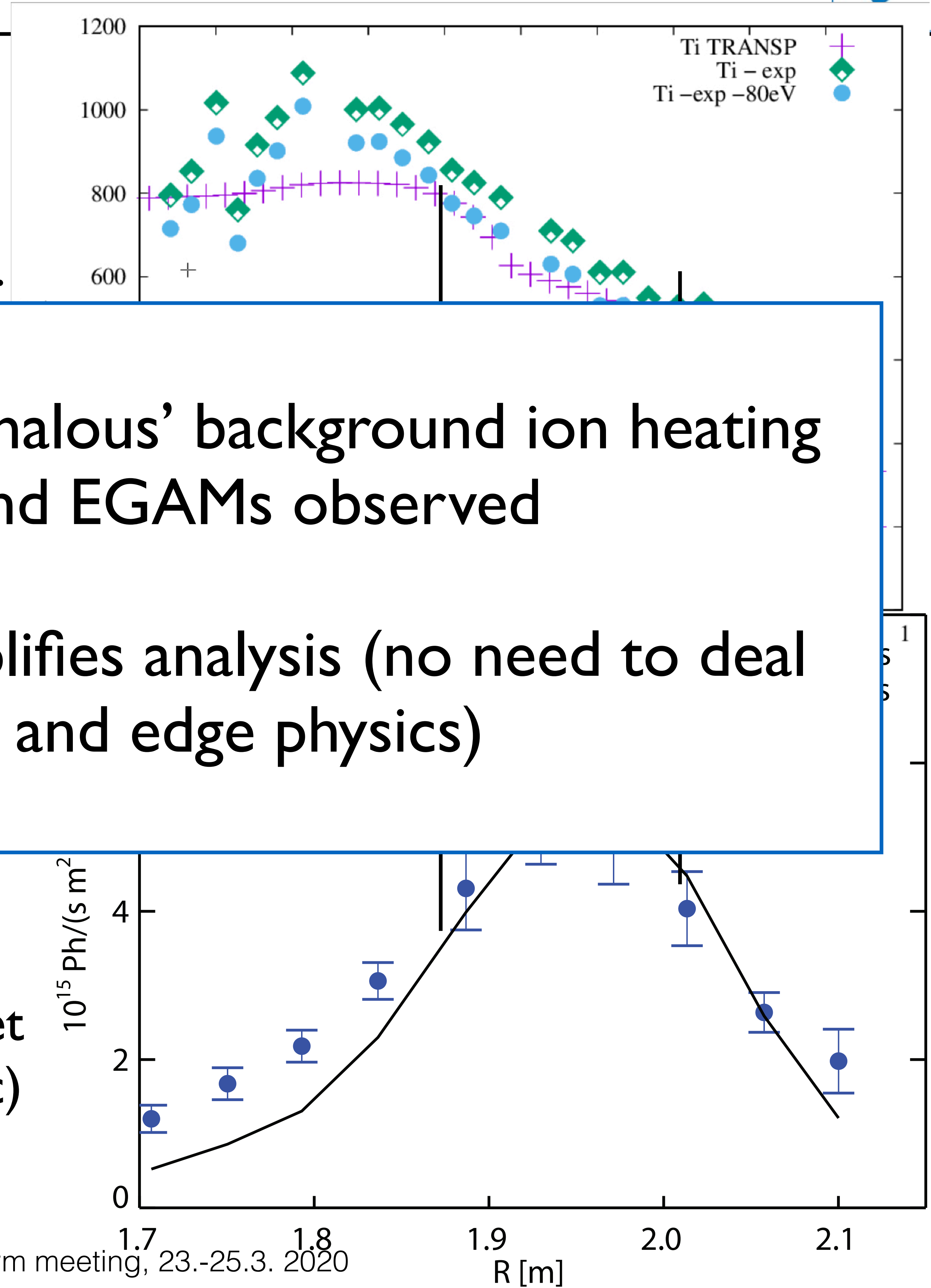
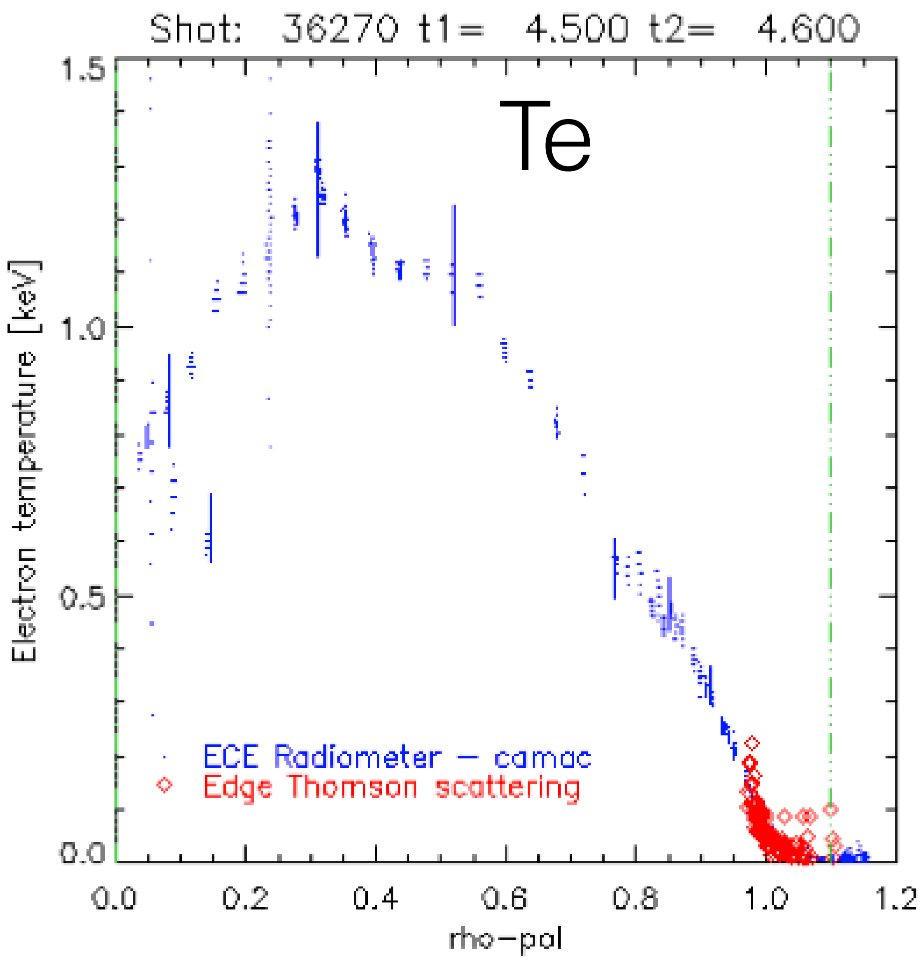
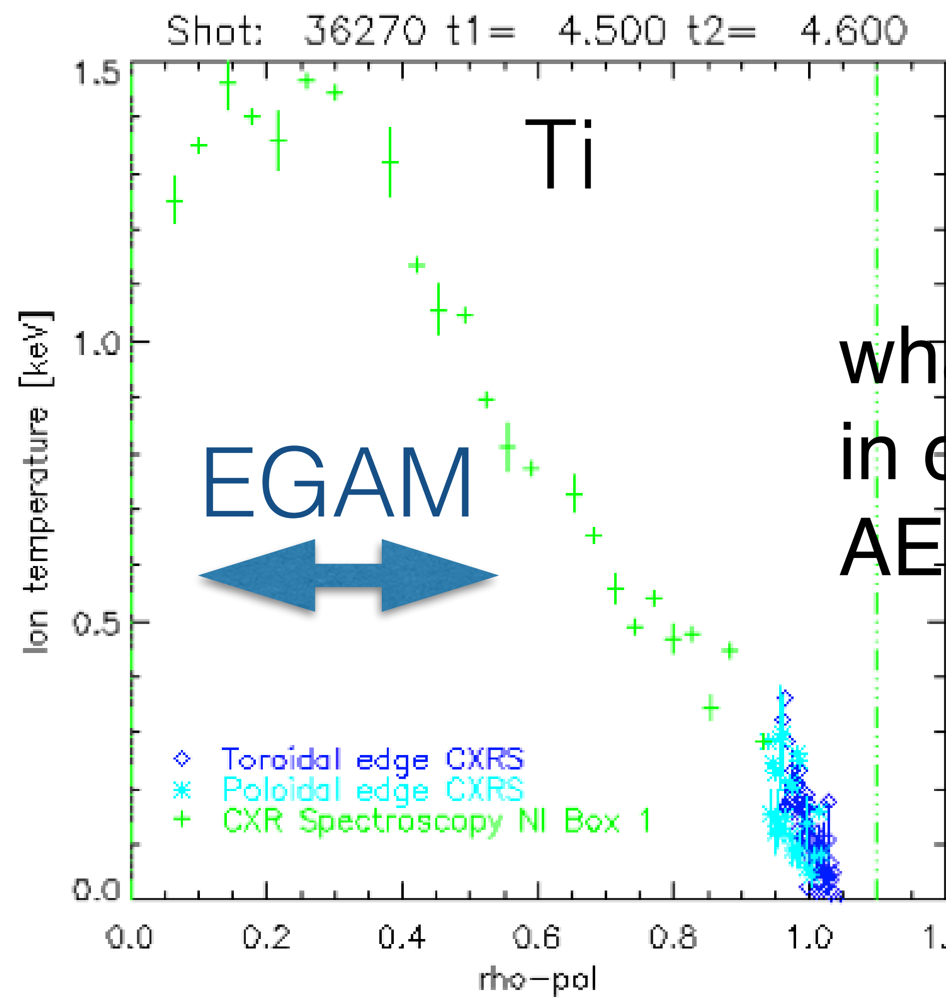


clear signature of 'anomalous' background ion heating due to AEs and EGAMs observed

inwards transport simplifies analysis (no need to deal with losses and edge physics)

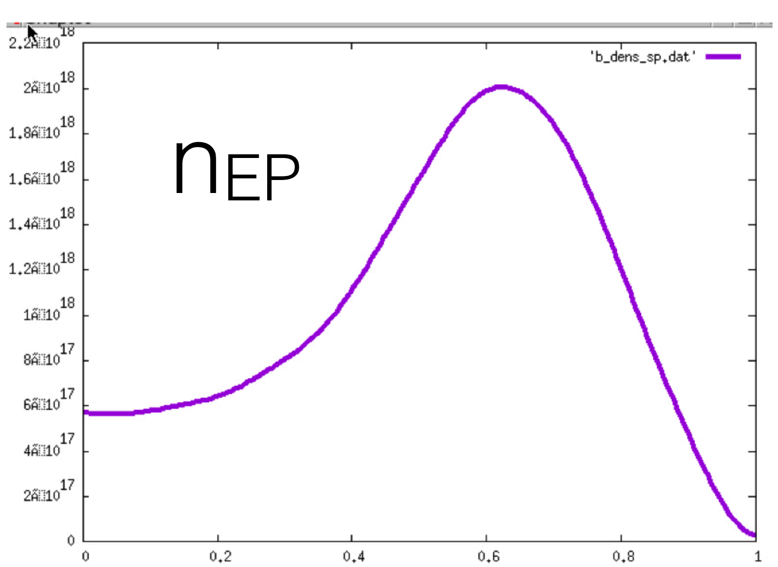
H-mode not ideal for measurements: decrease density: L-mode no ELMs



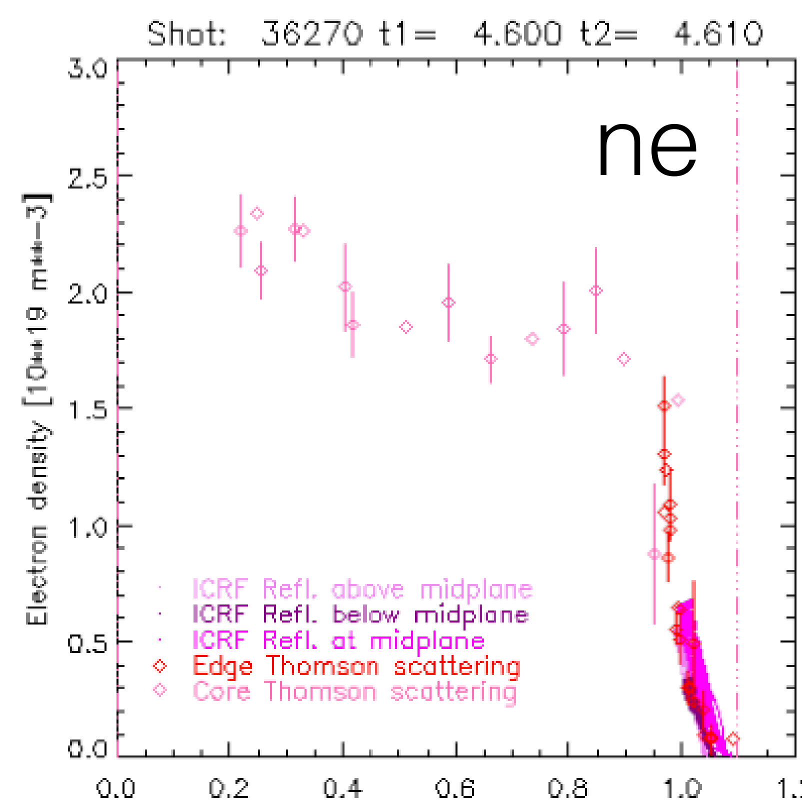


36270@4.5s

what heats ions in core?Ti>Te AEs? EGAMs?



Transp runs not yet finished…

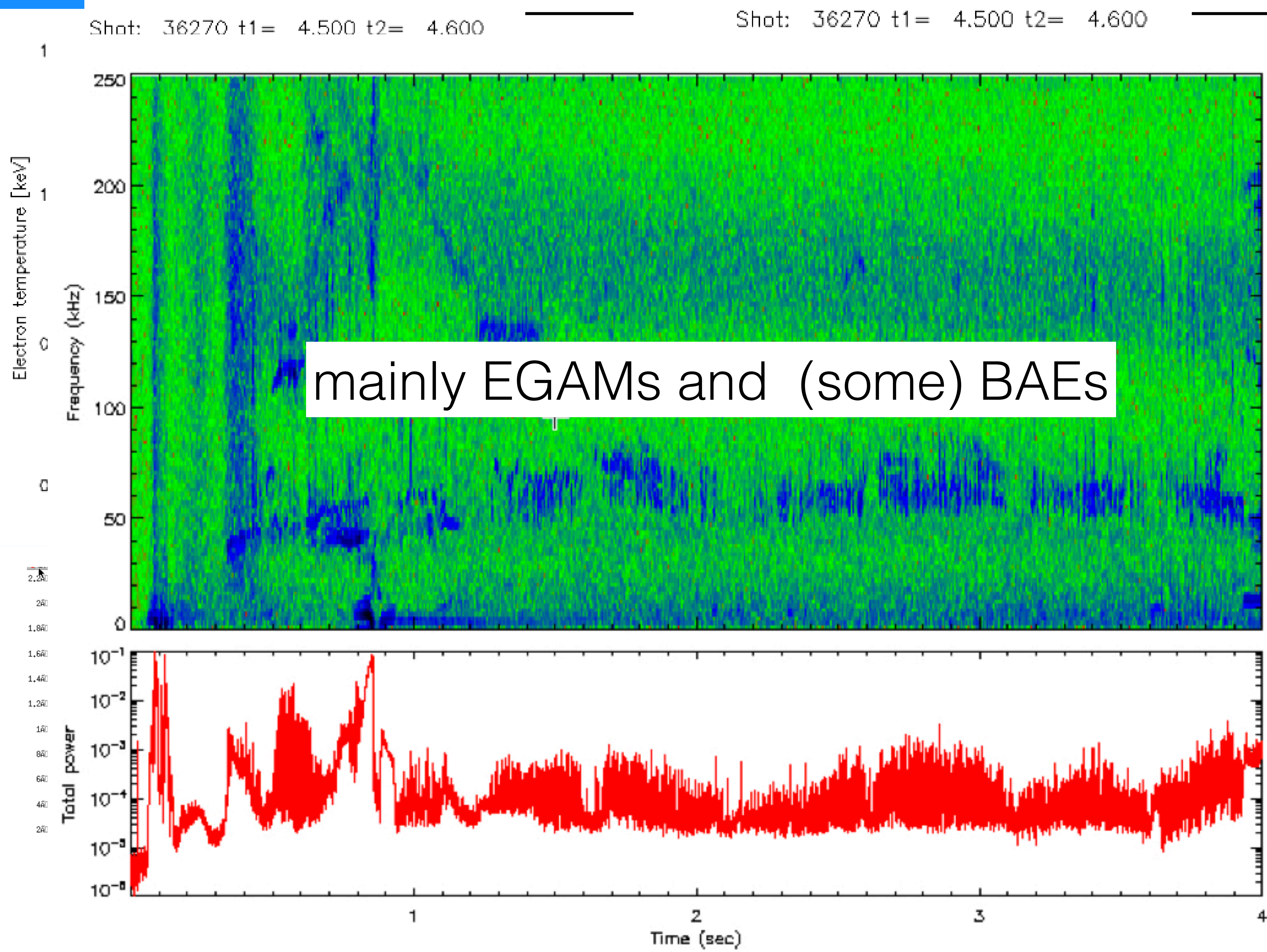


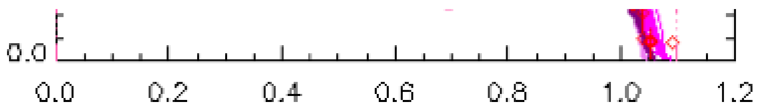
H-mode not ideal for measurements: decrease density
L-mode, no ELMs

)@4.5s

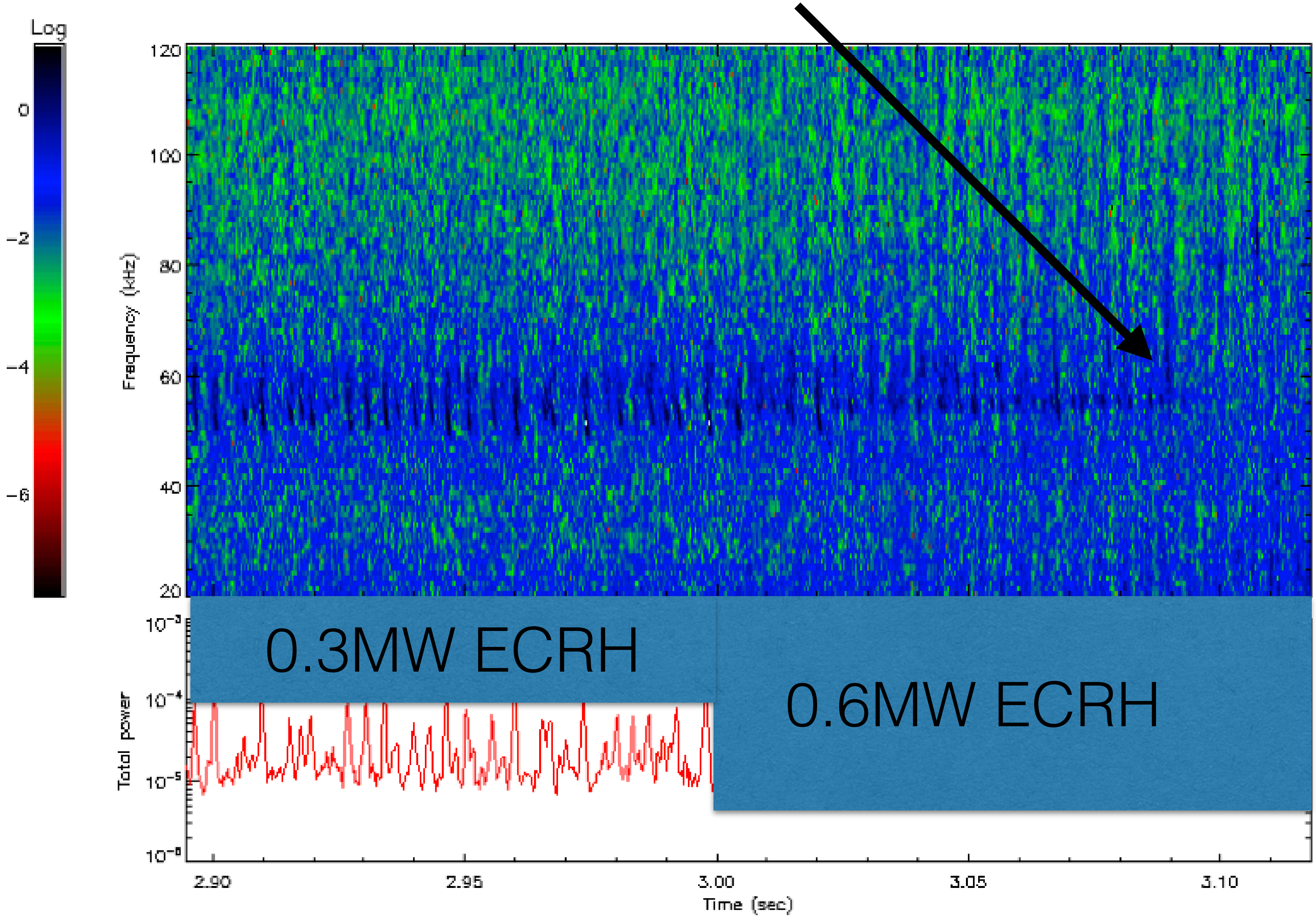
s ions

AMs?

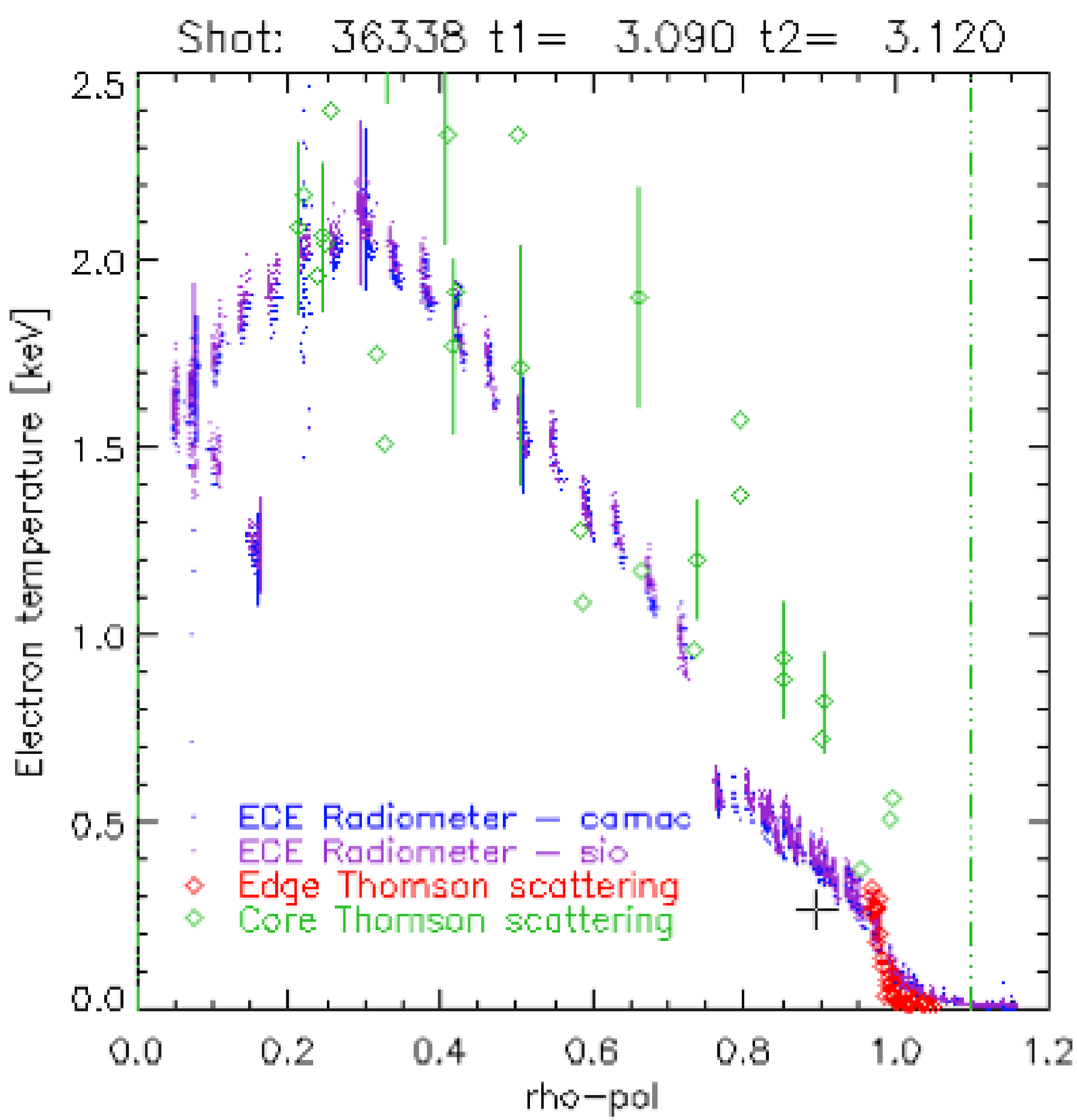


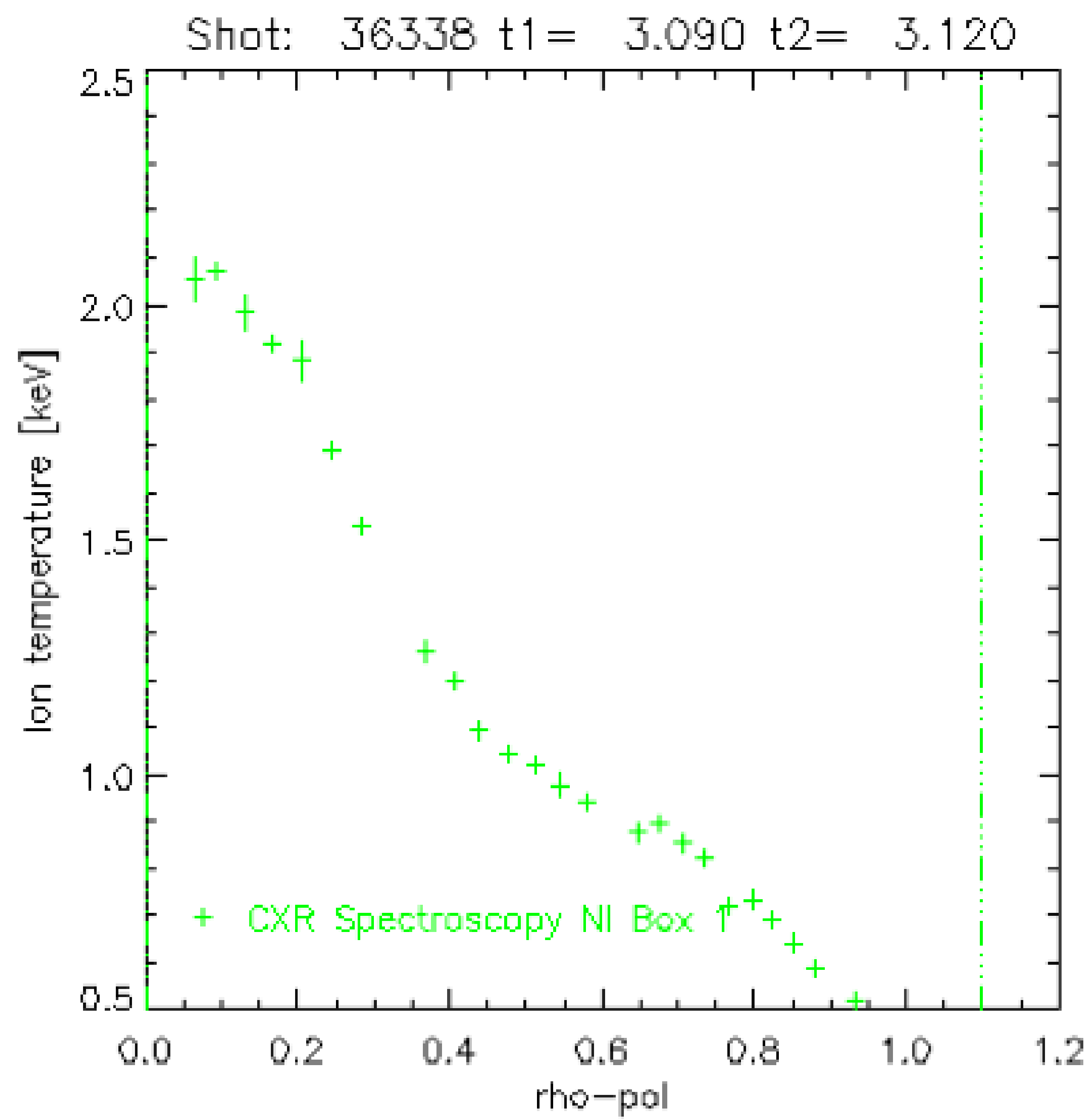


influence of ECRH on EGAMs: brings EGAMs at threshold (#36338@3.0s - 0.6MW ECRH)



EGAM ‘threshold’ profiles:



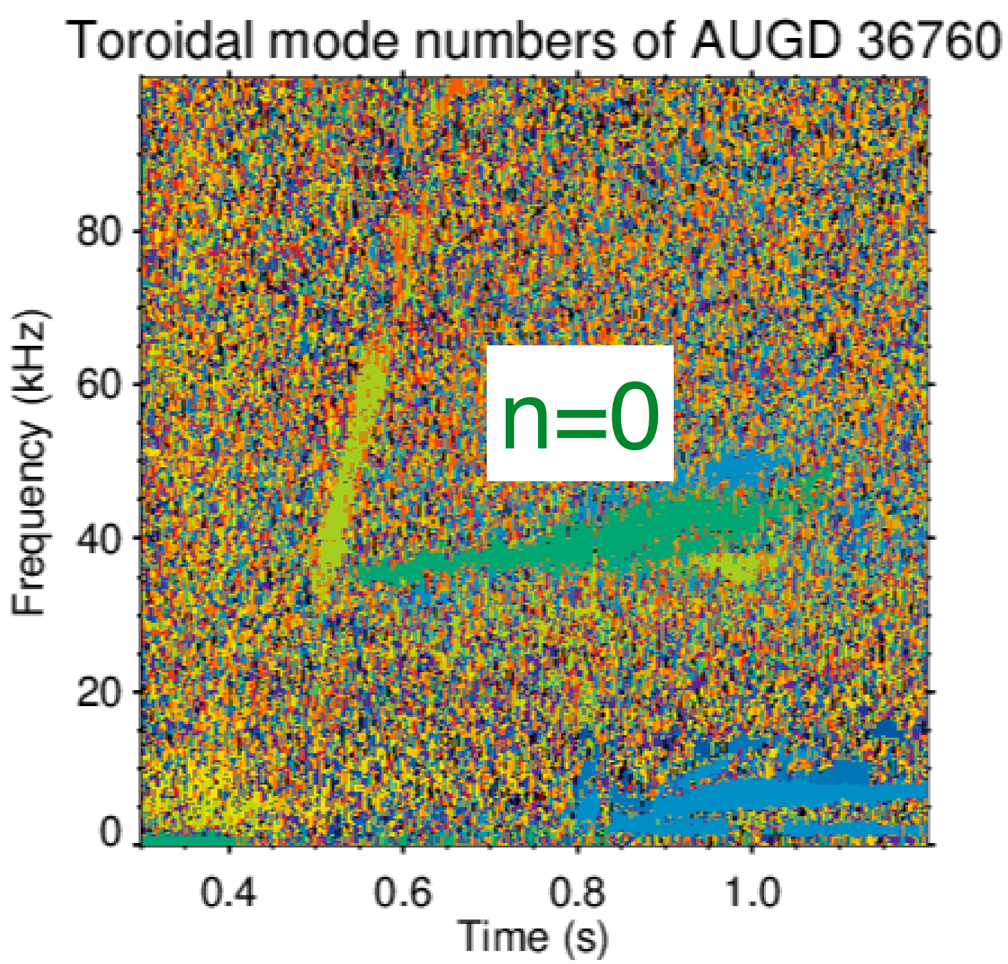


from previous ramp-up shots threshold T_i~1.8keV confirmed

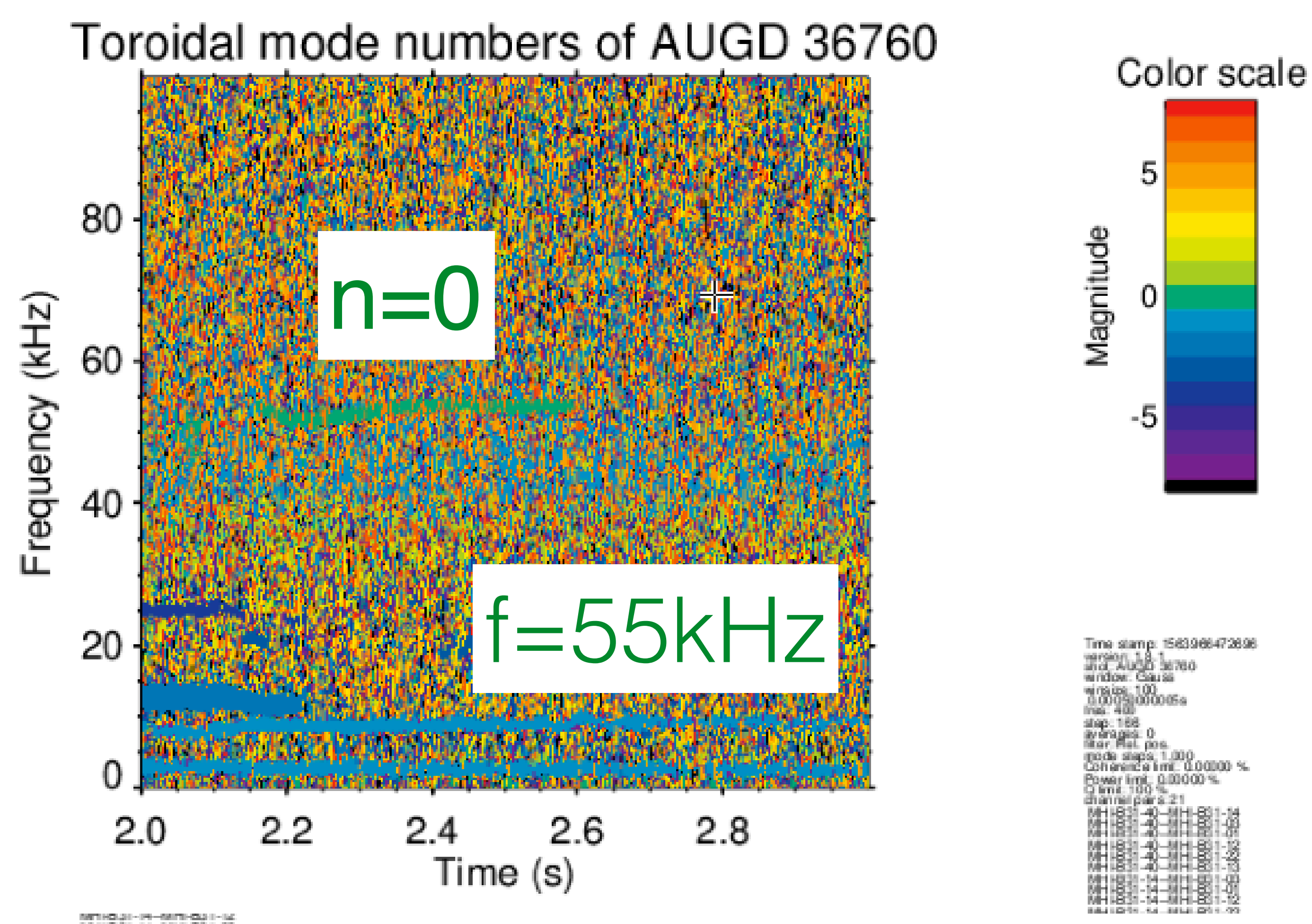
EGAMs in hydrogen plasmas

due to higher L-H threshold in hydrogen, L-mode density profiles are beneficial for (reflectometry) measurements: characterise modes and, if possible, change in turbulence

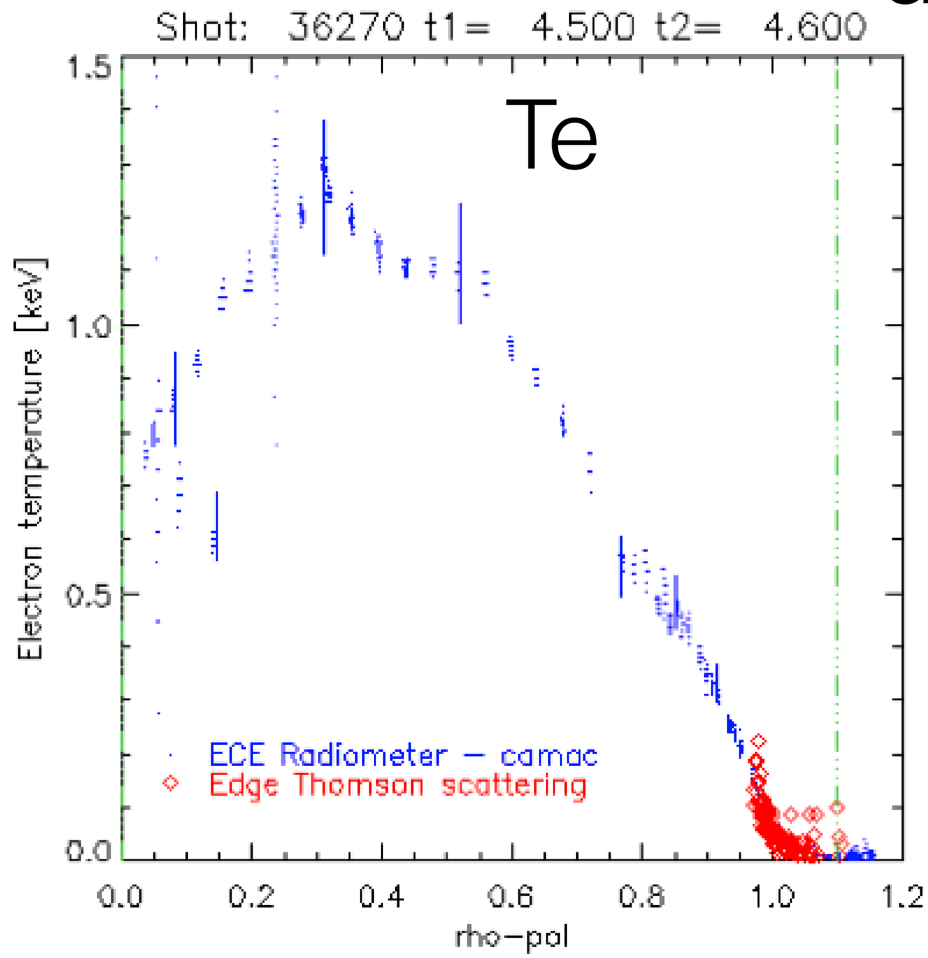
in all 3 H-discharges:
EGAMs in ramp-up

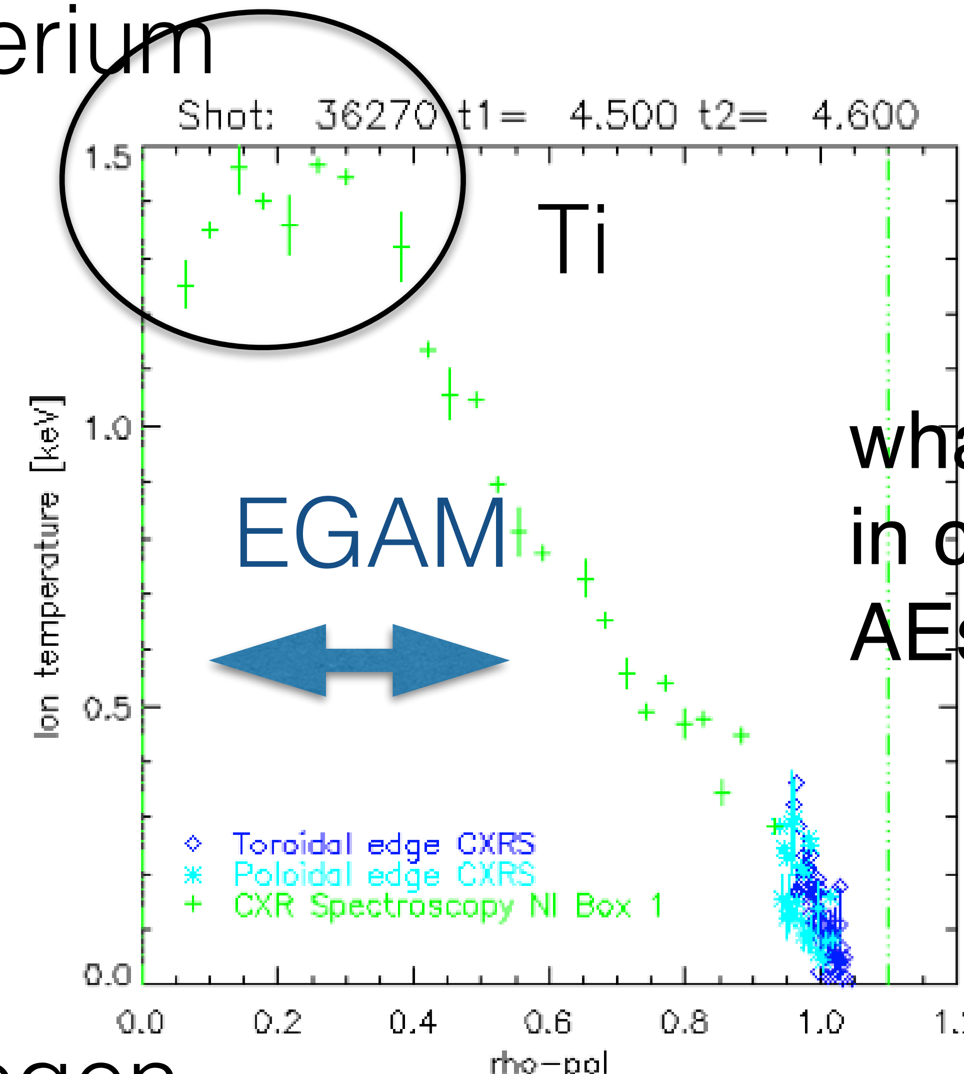


in Q6+7, most off axis case only:
weak EGAM in flat top



deuterium



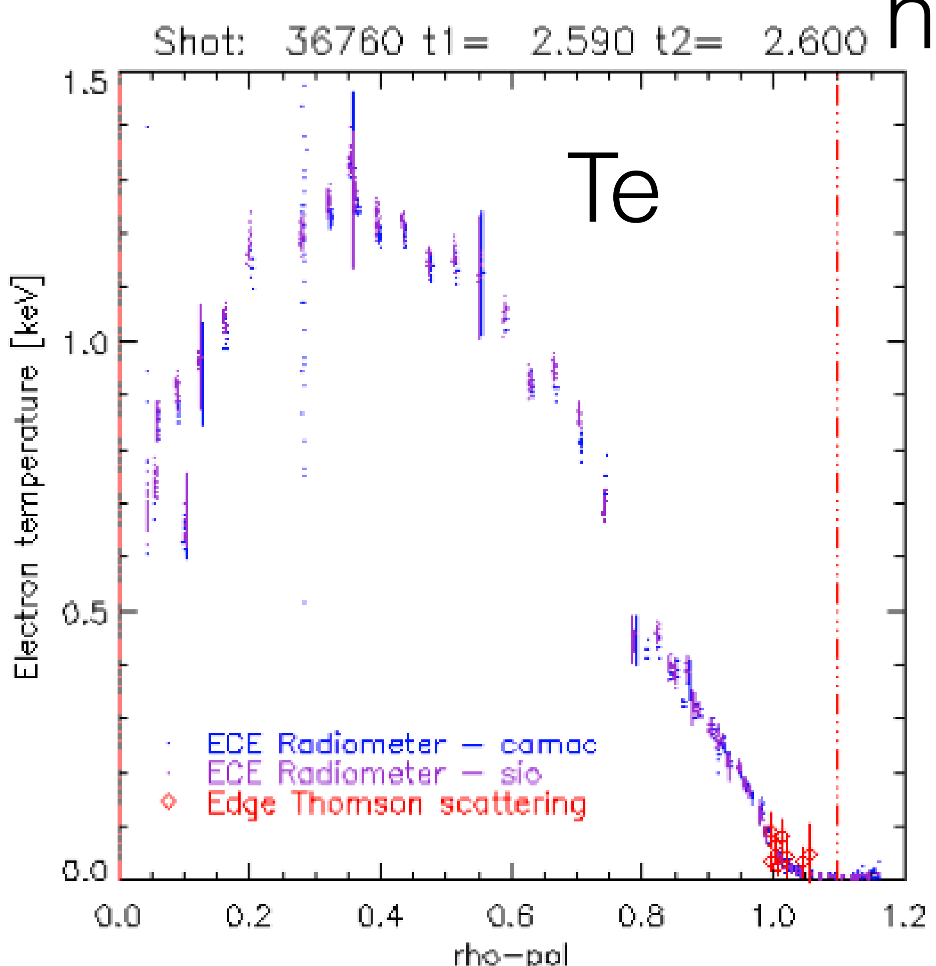


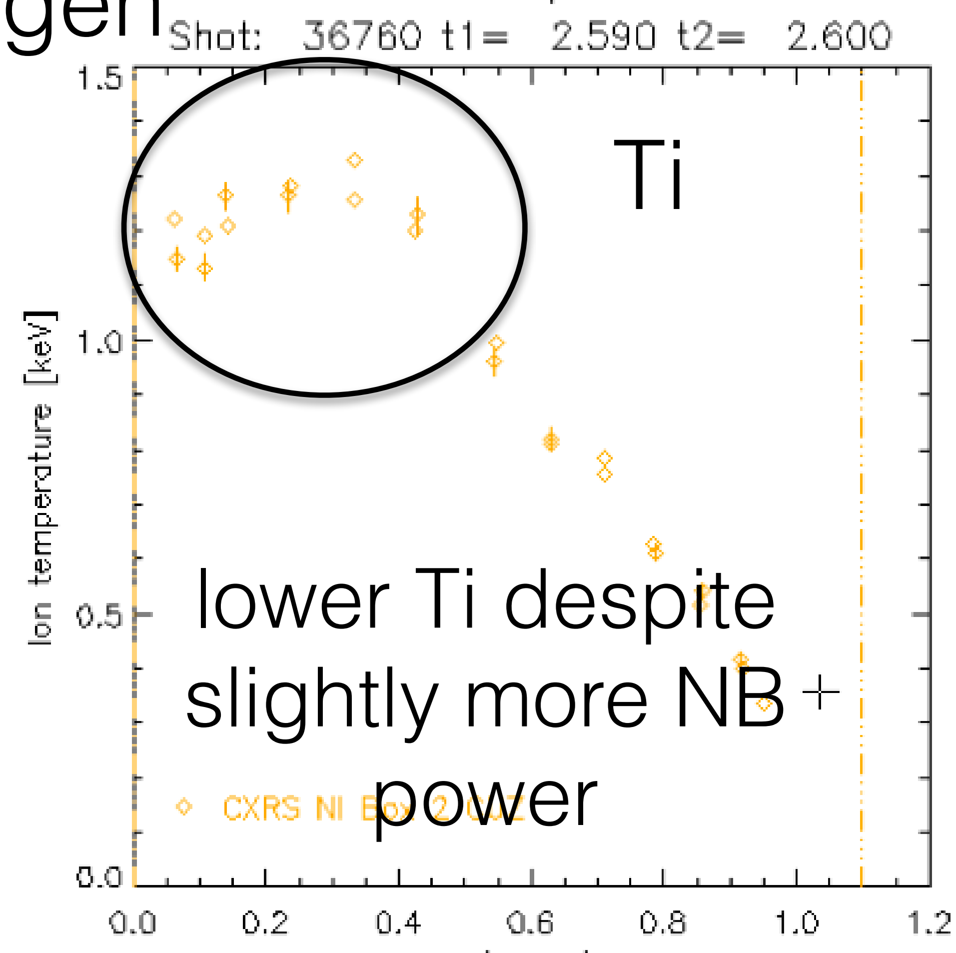
36270@4.5s

what heats ions in core?
AEs? EGAMs?

Q7

hydrogen





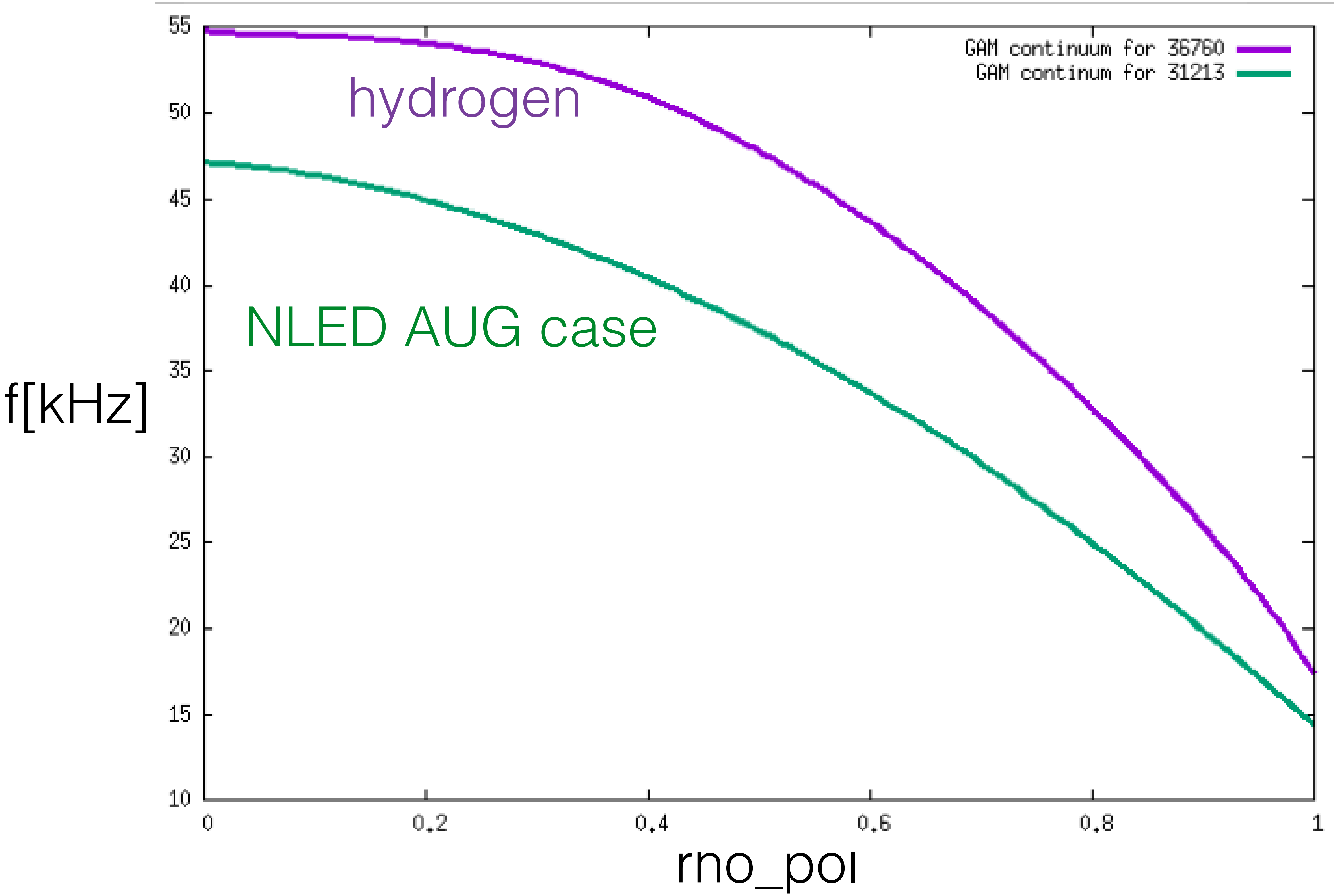
lower Ti despite slightly more NB power

36760@2.6s

Te~Ti!
no/weak EGAMs

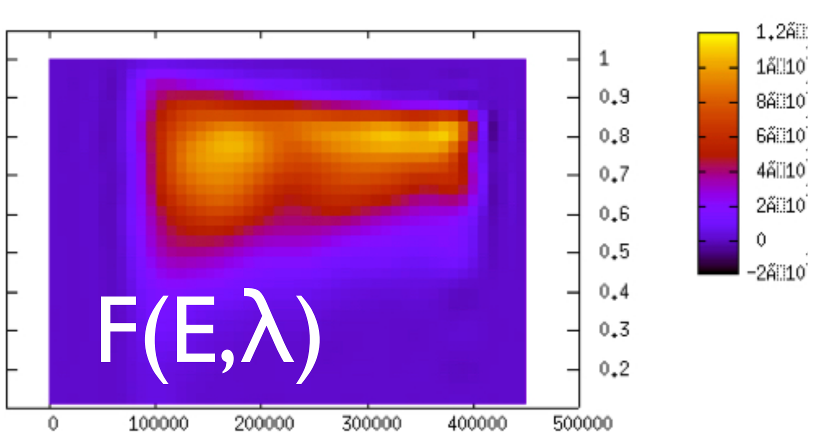
Q6+7

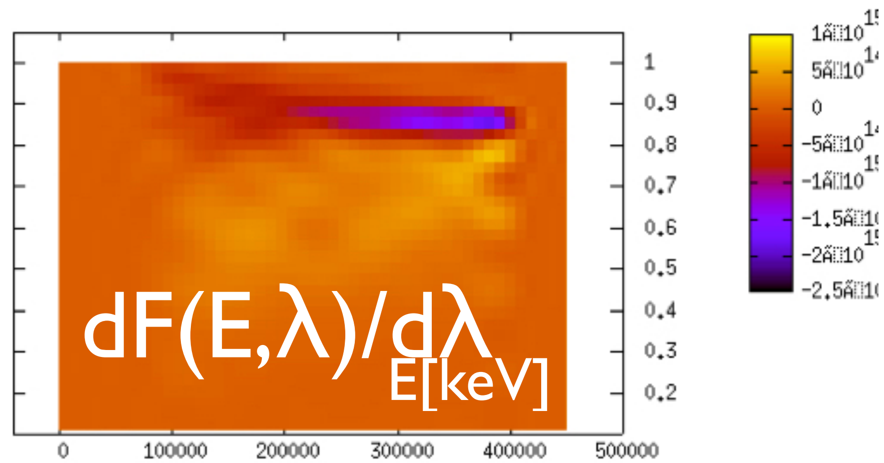
LIGKA local estimate of GAM continuum, no impurities yet (lower Ti leads to ~50kHz EGAMs despite lower H mass)

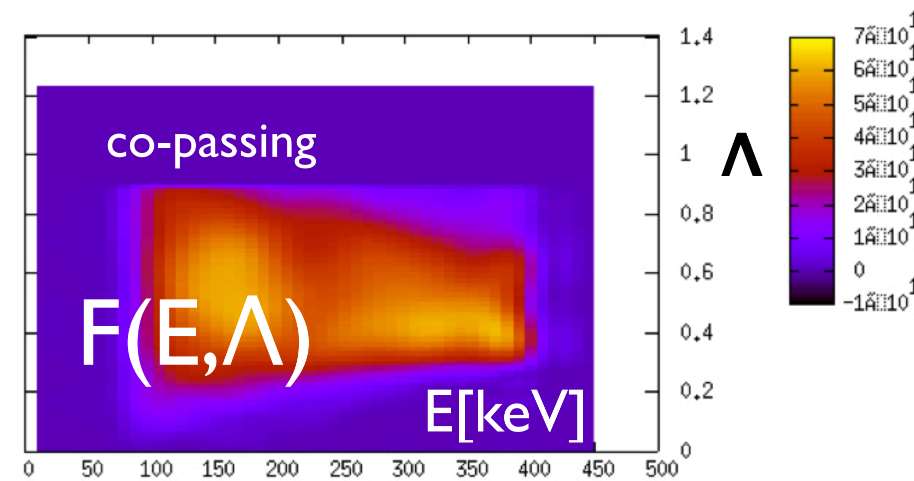


progress on JT-60SA and ITER

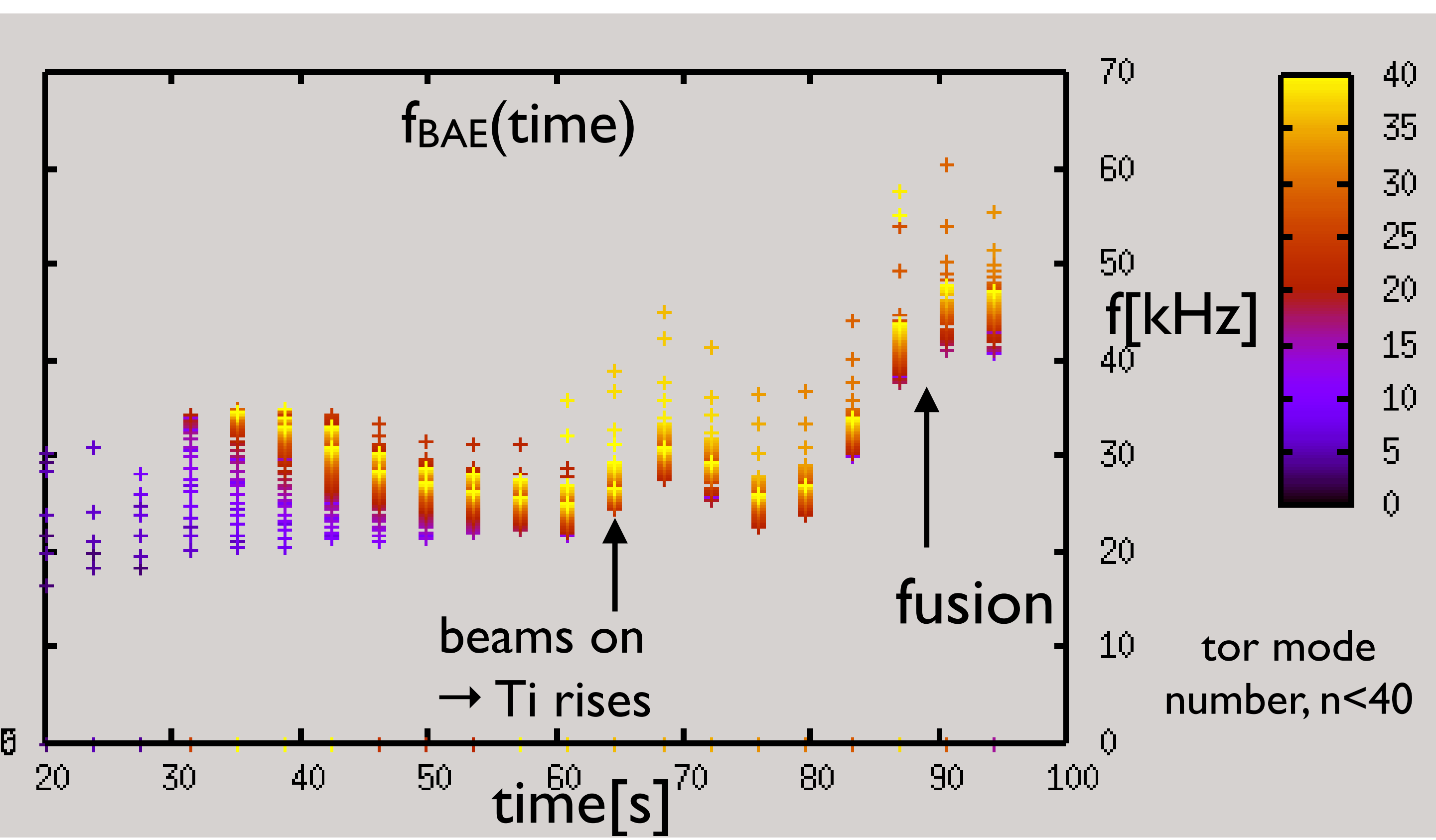
- JT-60U and JT-60SA: new interface MEGA-LIGKA interface for EP markers [w. A. Bierwage]

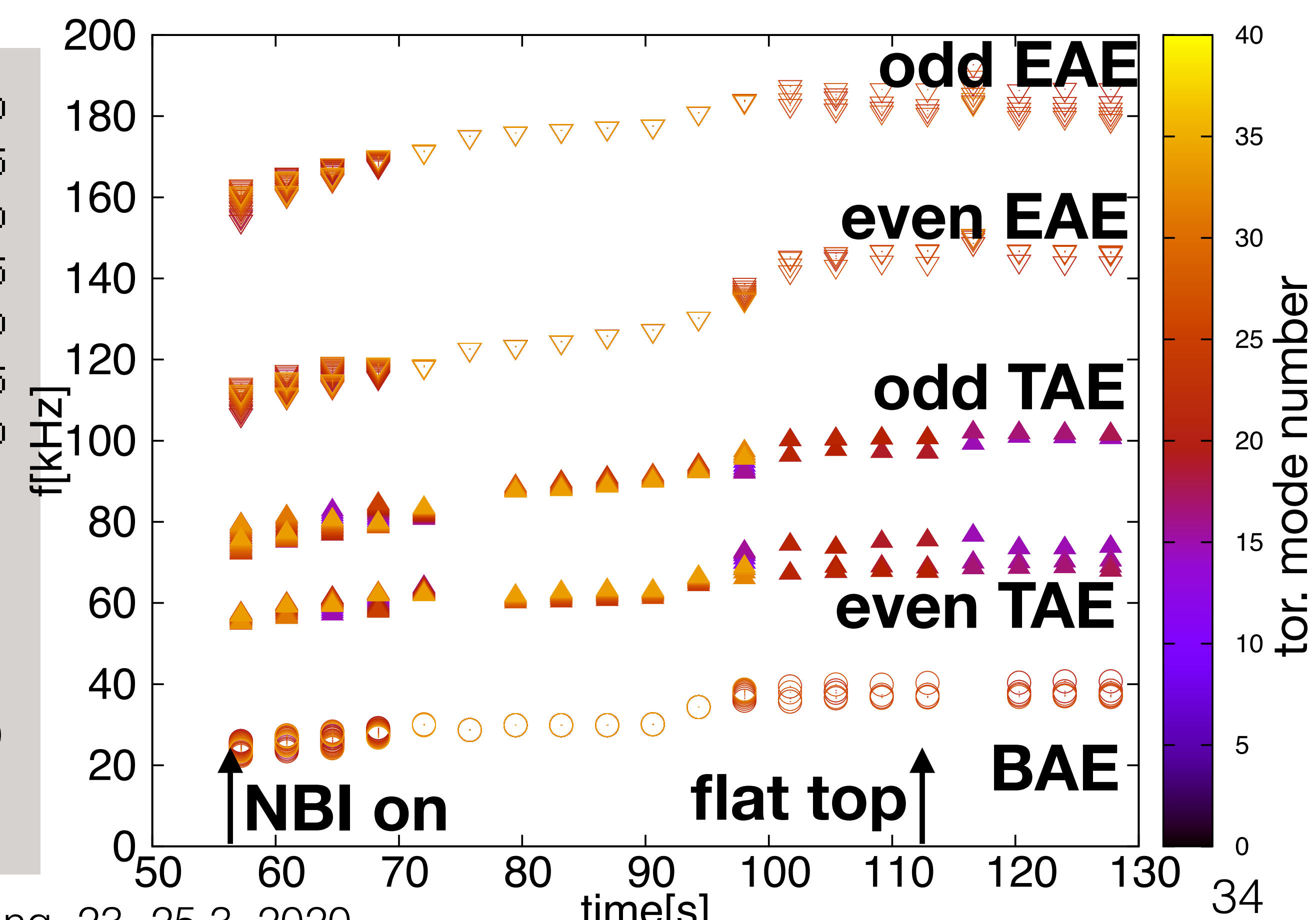






- overview studies for most relevant scenarios (SA, ITER) started with LIGKA-IMAS (python workflows): time-dependent workflows LIGKA workflows





conclusions

- extensive set of AUG data can be made available that can be used for validation of EP transport and effects of EP-driven modes on background plasma (‘self-organisation’)

- further experiments will focus on mode symmetry measurements (ECEI) and changes in underlying turbulence characteristics

- but: realistic F_{EP} is necessary for quantitative comparison

- impressive progress of various non-linear codes within MET; non-linear results (mode-mode; EP transport; ‘self-organisation’) are starting to be feasible

- AUG as first step for step ladder studies together with JT-60SA and ITER (off-axis NB); overview studies for selecting most relevant scenarios (SA, ITER) started with LIGKA-IMAS (python workflows)