Isotope effects on the Energetic Particle dynamics induced by off-axis neutral beam injection on ASDEX Upgrade

Ph. Lauber, G. Papp, B. Geiger, B. Vanovac, V. Igochine, M. Maraschek, M. Weiland A. Gude
ASDEX Upgrade Team

and MET ENR Team

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background and motivation

- for predicting (EP) transport in a future burning plasma, models have to go beyond the regimes where present-day experimental data is available for validation
- cover whole parameter space on present day devices to learn about scaling and transitions of EP transport
- not only develop hierarchical models for linear and non-linear EP physics but also start to develop and implement various (hierarchical) models for EP transport and its impact on background profiles— important role of IMAS
- reduced models need special attention in order to deal with complex physics in a huge parameter space
- for comparison: non-linear multi-mode runs for (hybrid) models are available (MET hierarchy)
- within MET: provide set of experimental reference cases to address different aspects of EP transport that will be needed for developing reliable predictive tools
- go beyond near-marginal stability regimes - validate codes for intermittent EP transport regimes
- need for suitable experimental data, featuring different levels of complexity
- this talk: summarise history and present status of experiments, suggest further steps

outline

- reminder: NLED base case
- beam angle scan
- beam power scan
- current/q scan
- isotope scan
- transport

WP3-D1

description of MET reference cases:
AUG,JT-60U, ITER
http://www2.ipp.mpg.de/~pwl/

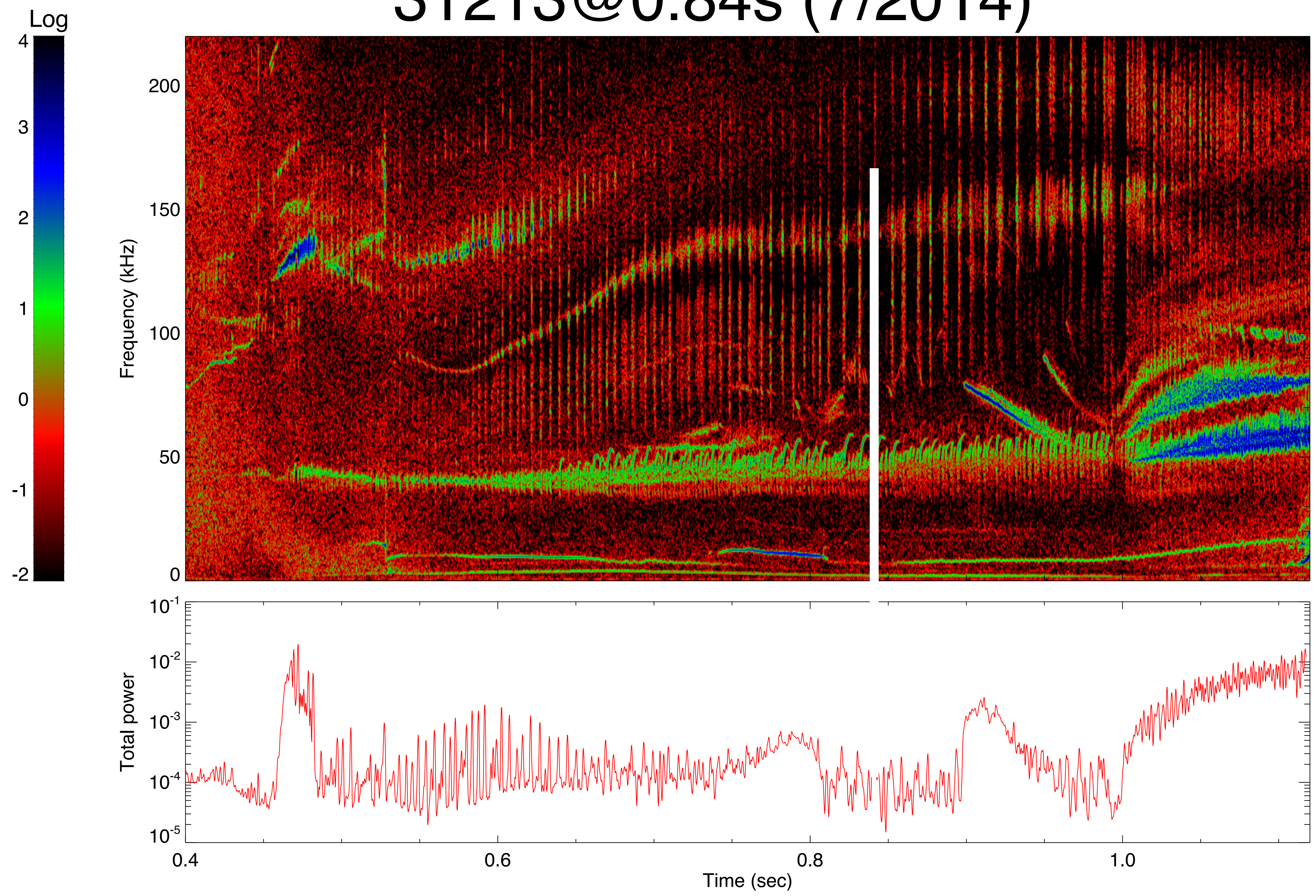
for DTT: refer to G. Vlad's talk tomorrow

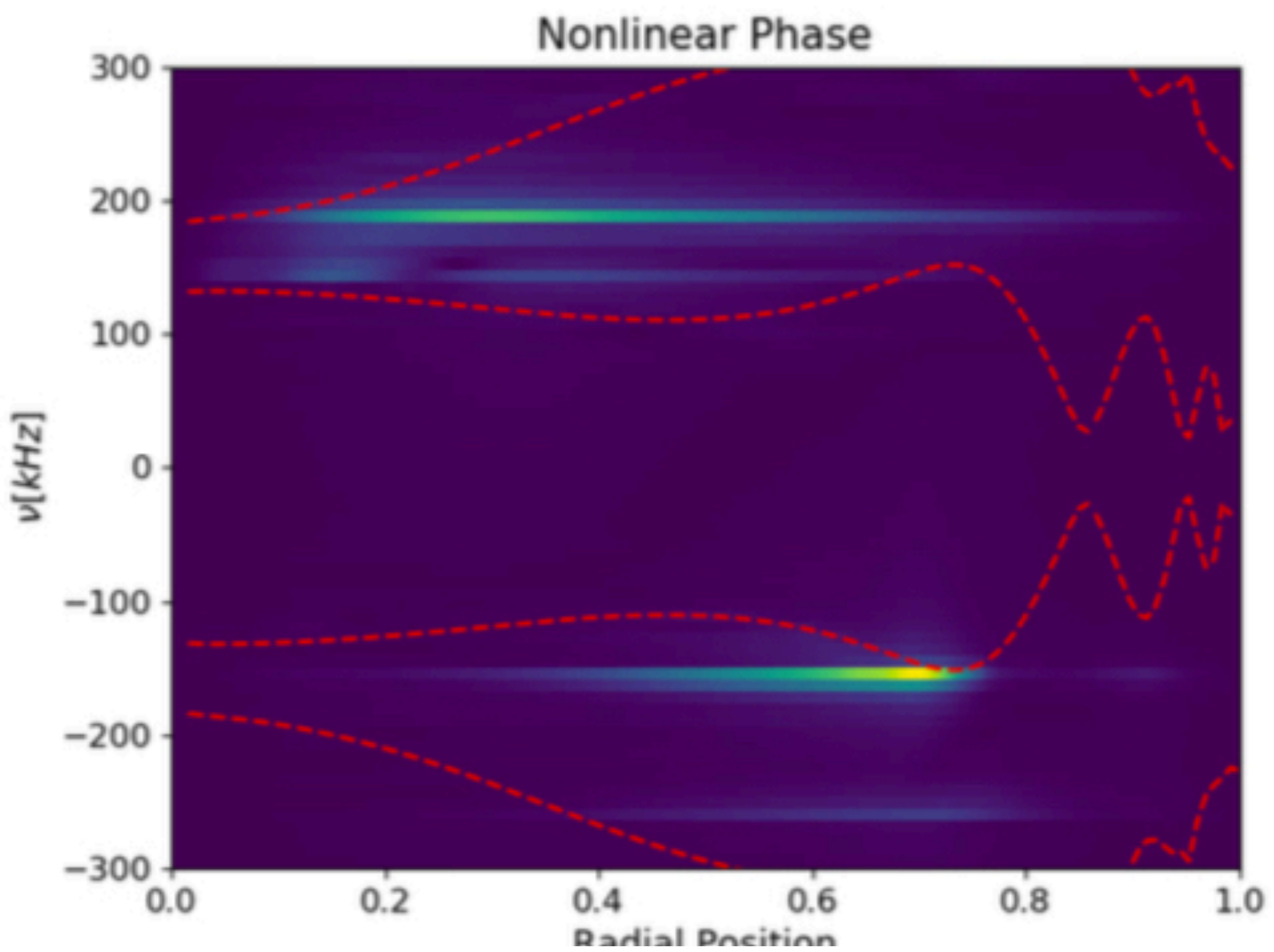
also JET data has been recently modelled
(with A. Bierwage)

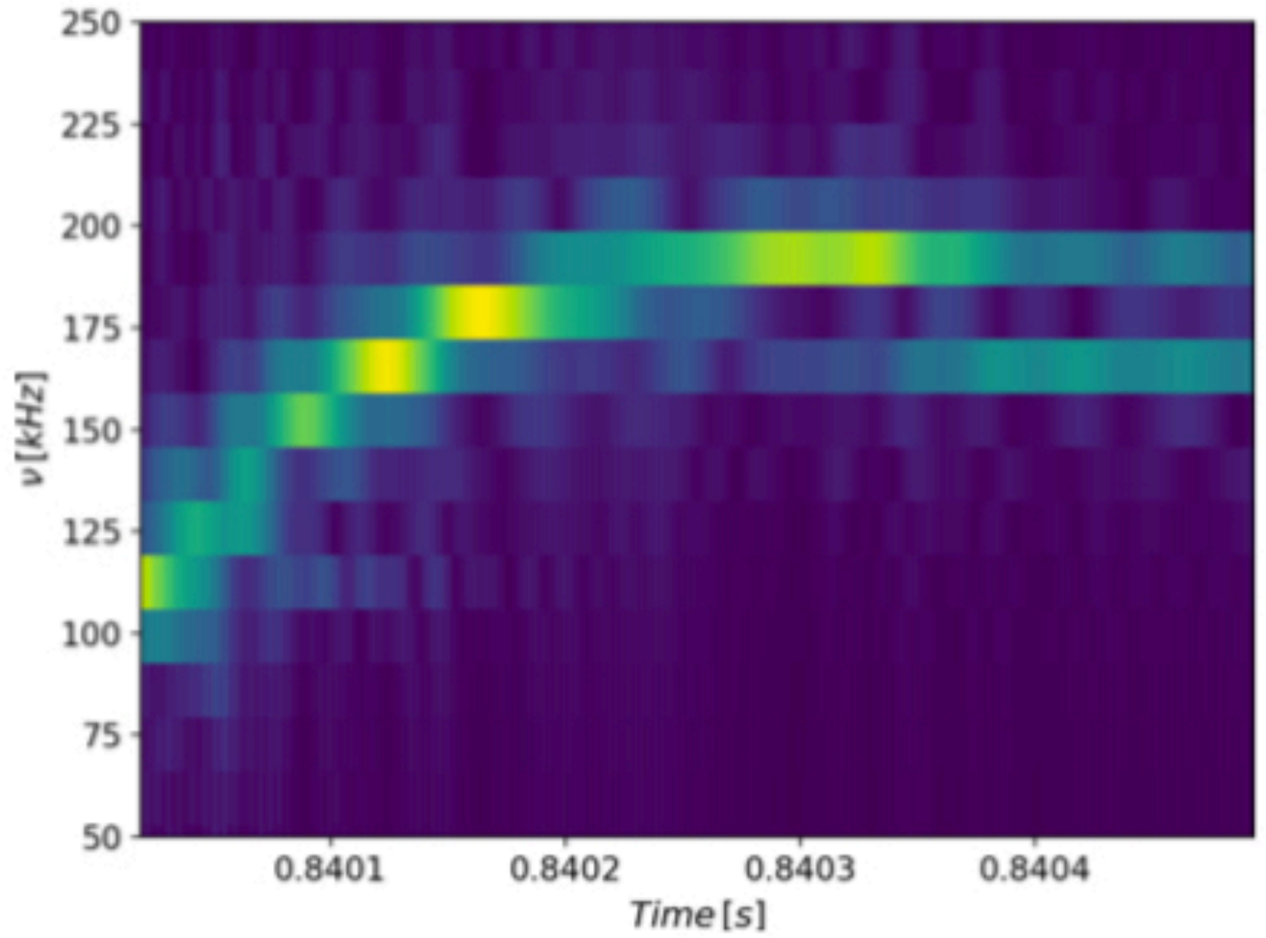
reminder: NLED base case

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

31213@0.84s (7/2014)





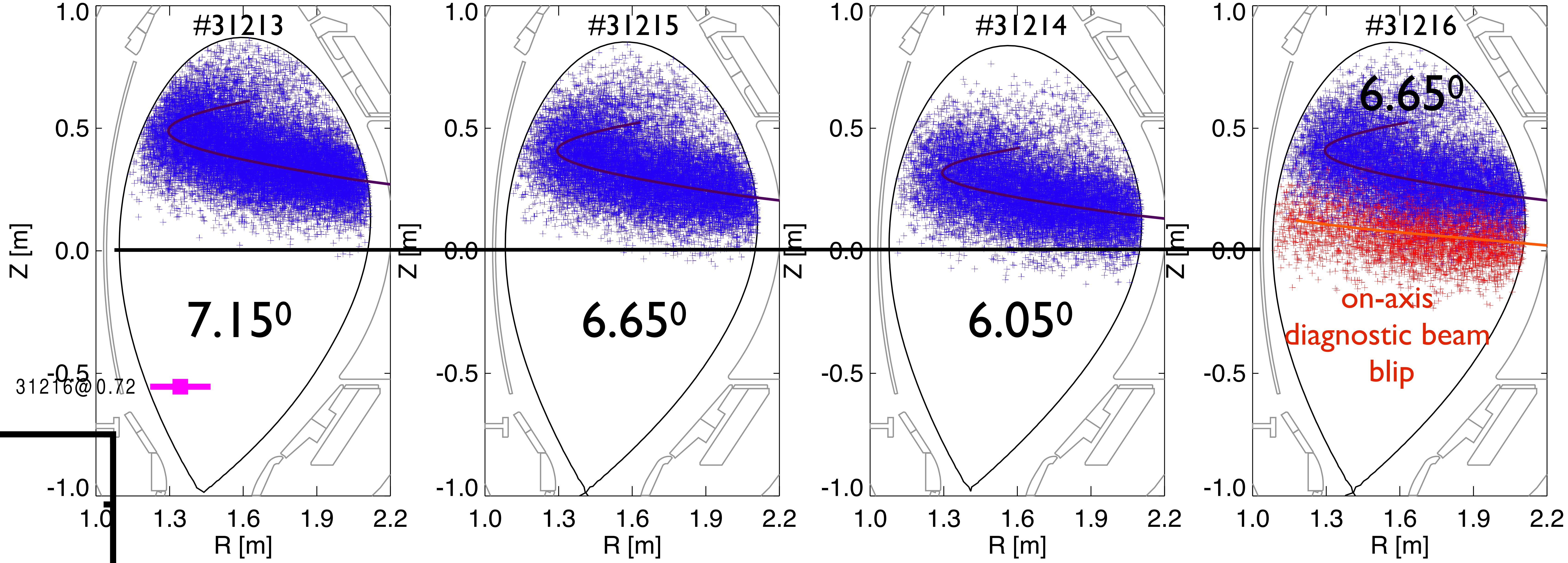


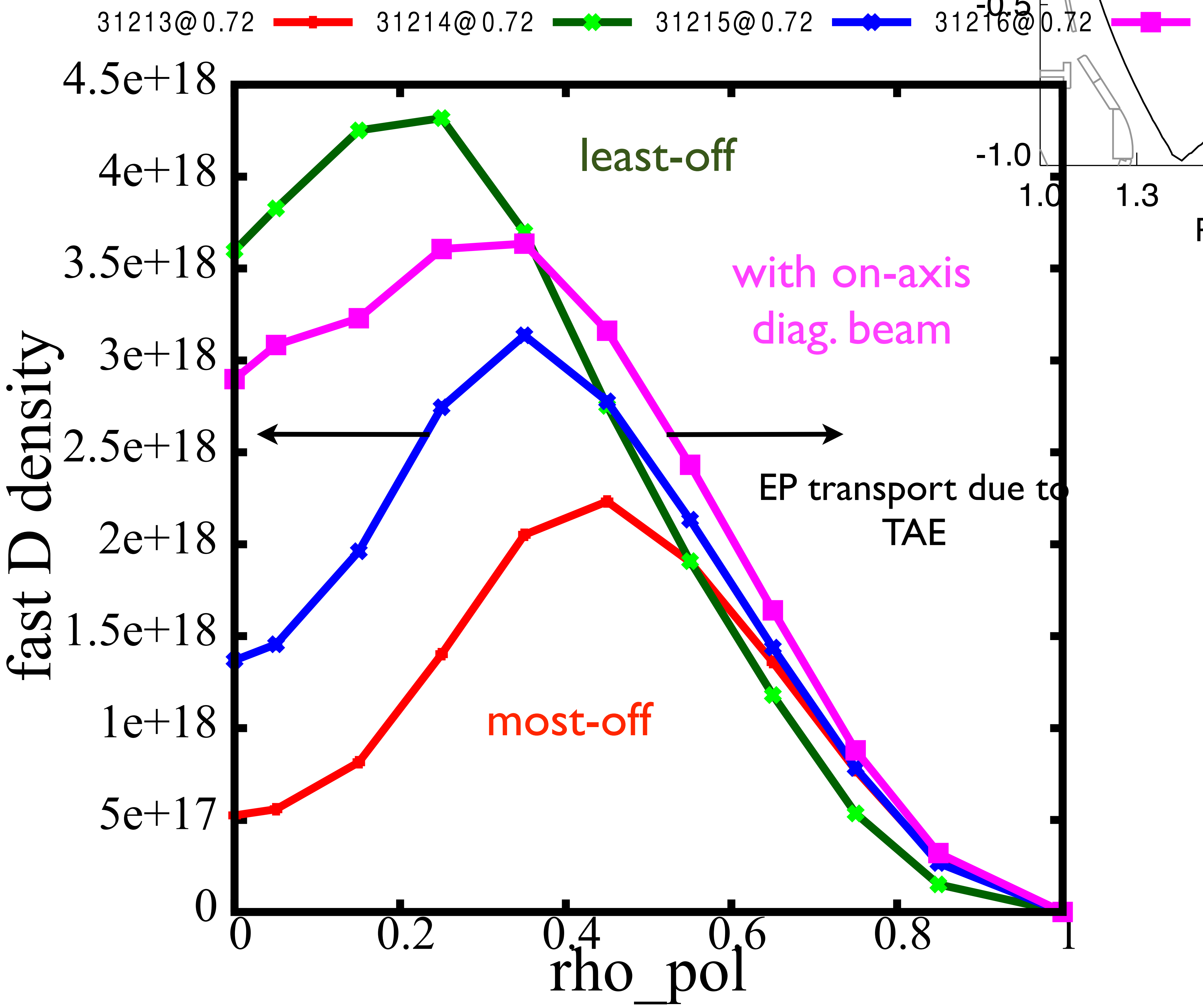
how to extend this benchmark?

see talk F. Vannini,
valuable benchmark involving ORB5, HYMAGYC,MEGA,LIGKA

reminder: NLED base case

scan of beam injection angle



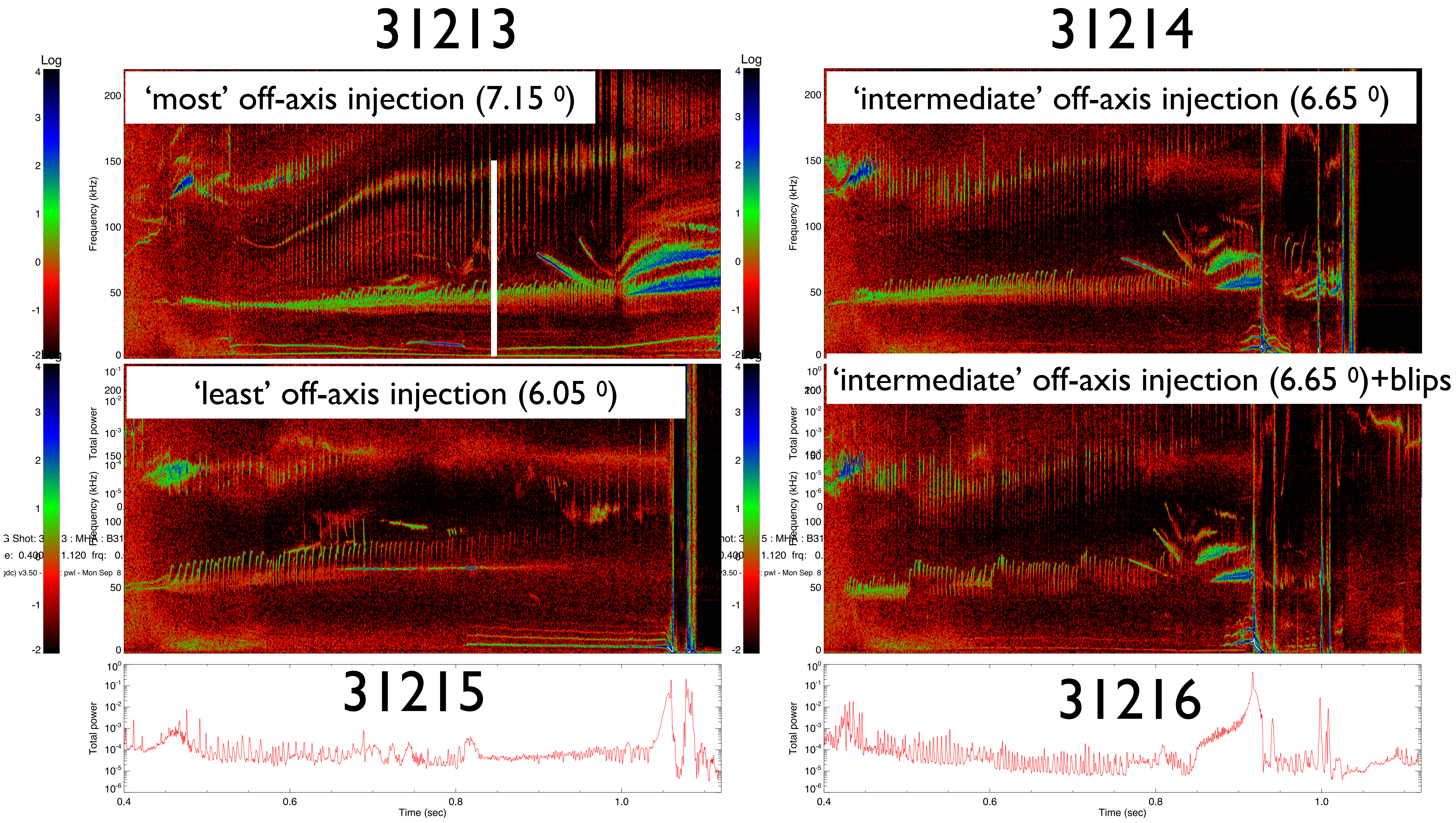


features:

- positive and negative radial EP gradient
- anisotropic in pitch angle
- (TRANSP/NUBEAM distribution functions available)

reminder: NLED base case

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



possible extension: scan of beam injection angle

scan of beam energy: EGAM persists, AEs disappear

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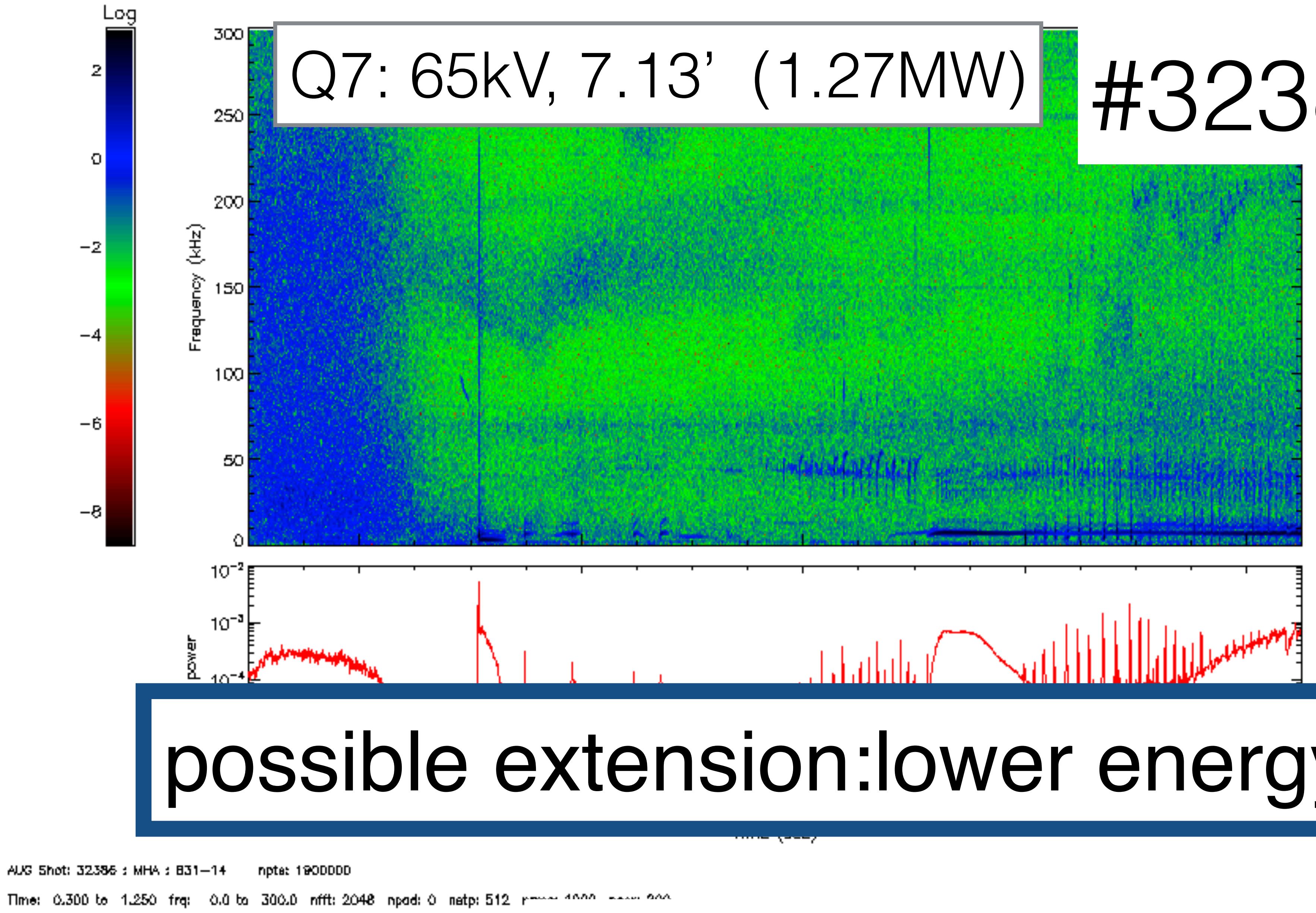

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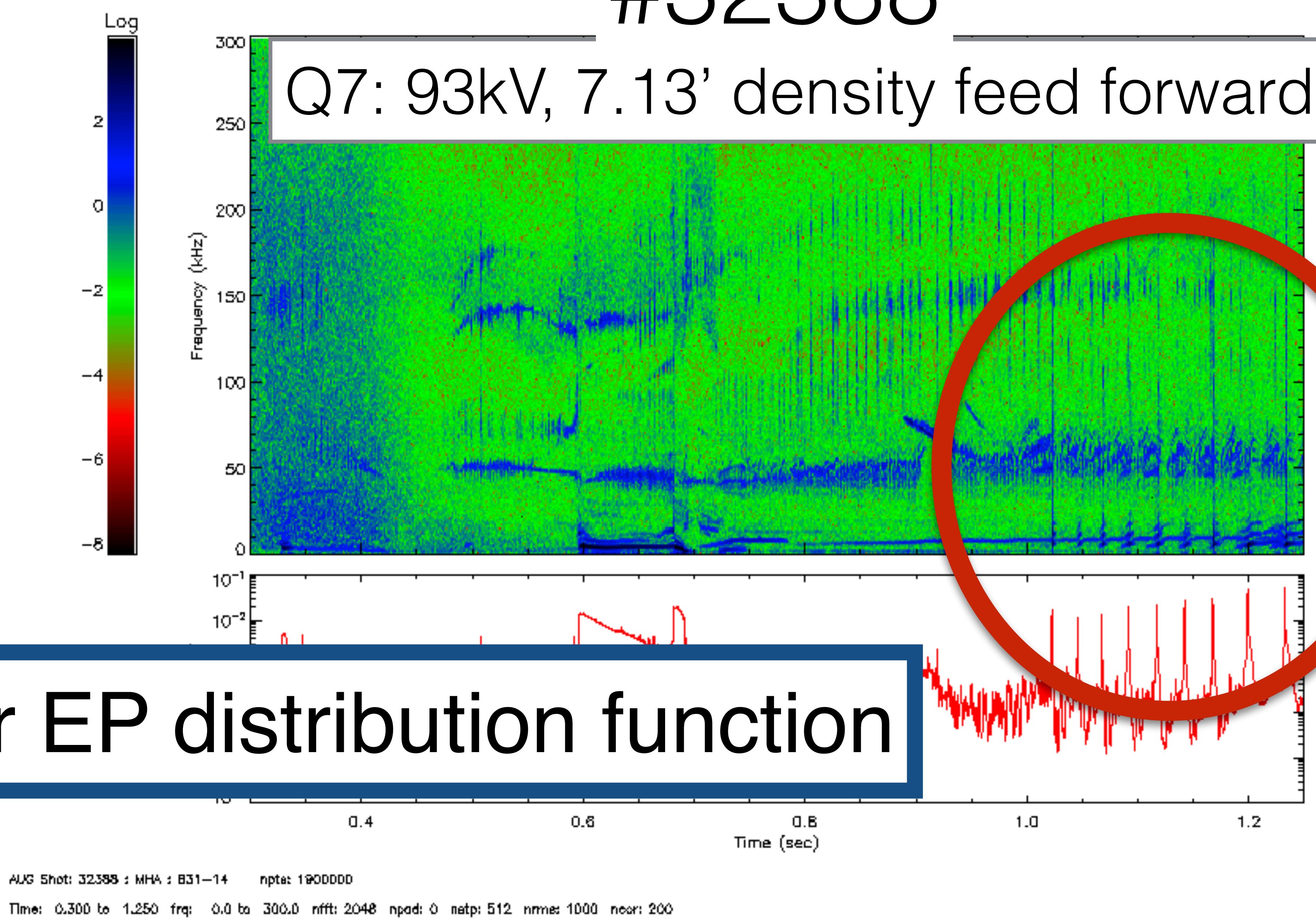

sawtooth like crashes at q=2 surface

possible extension:lower energy for EP distribution function

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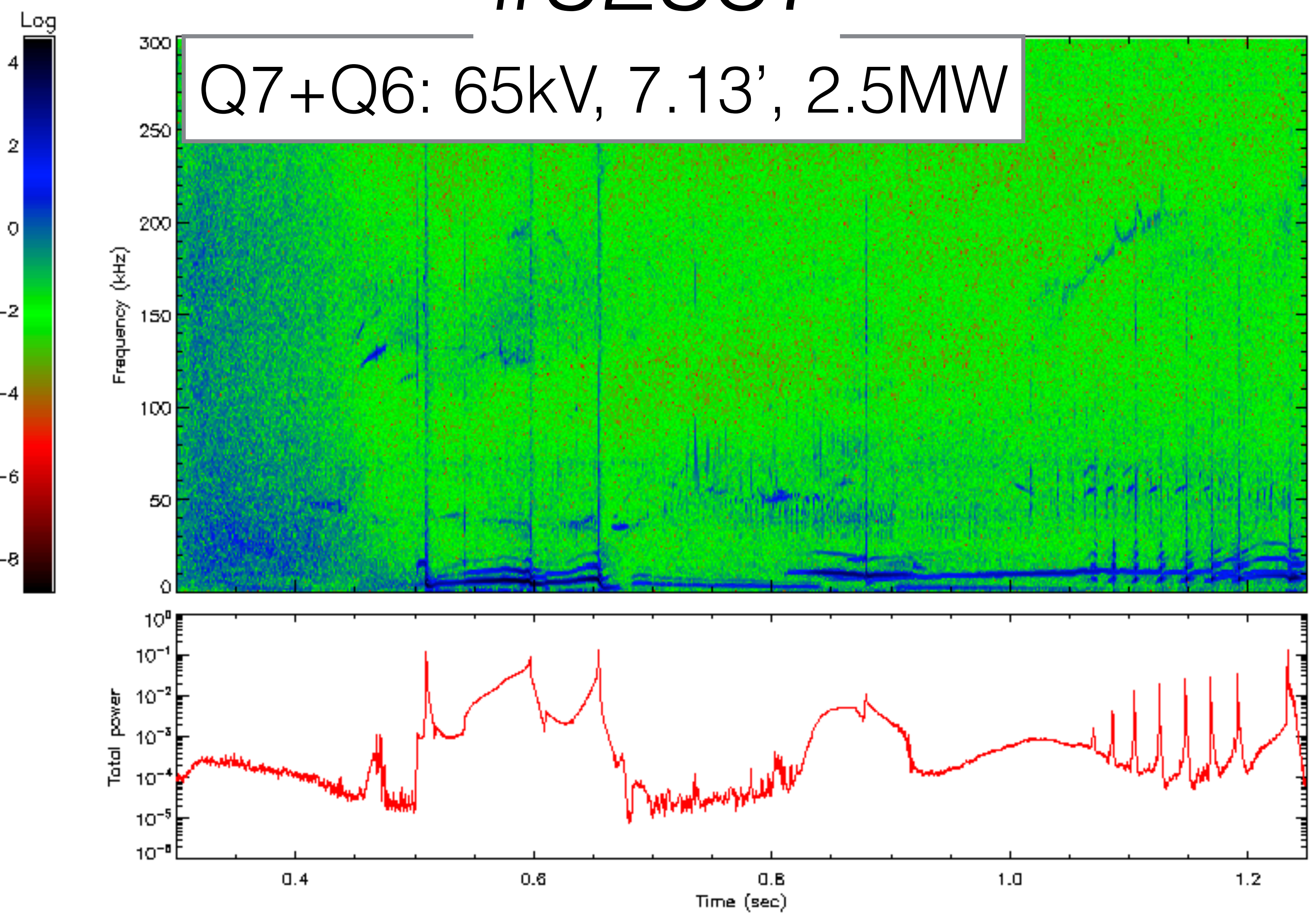
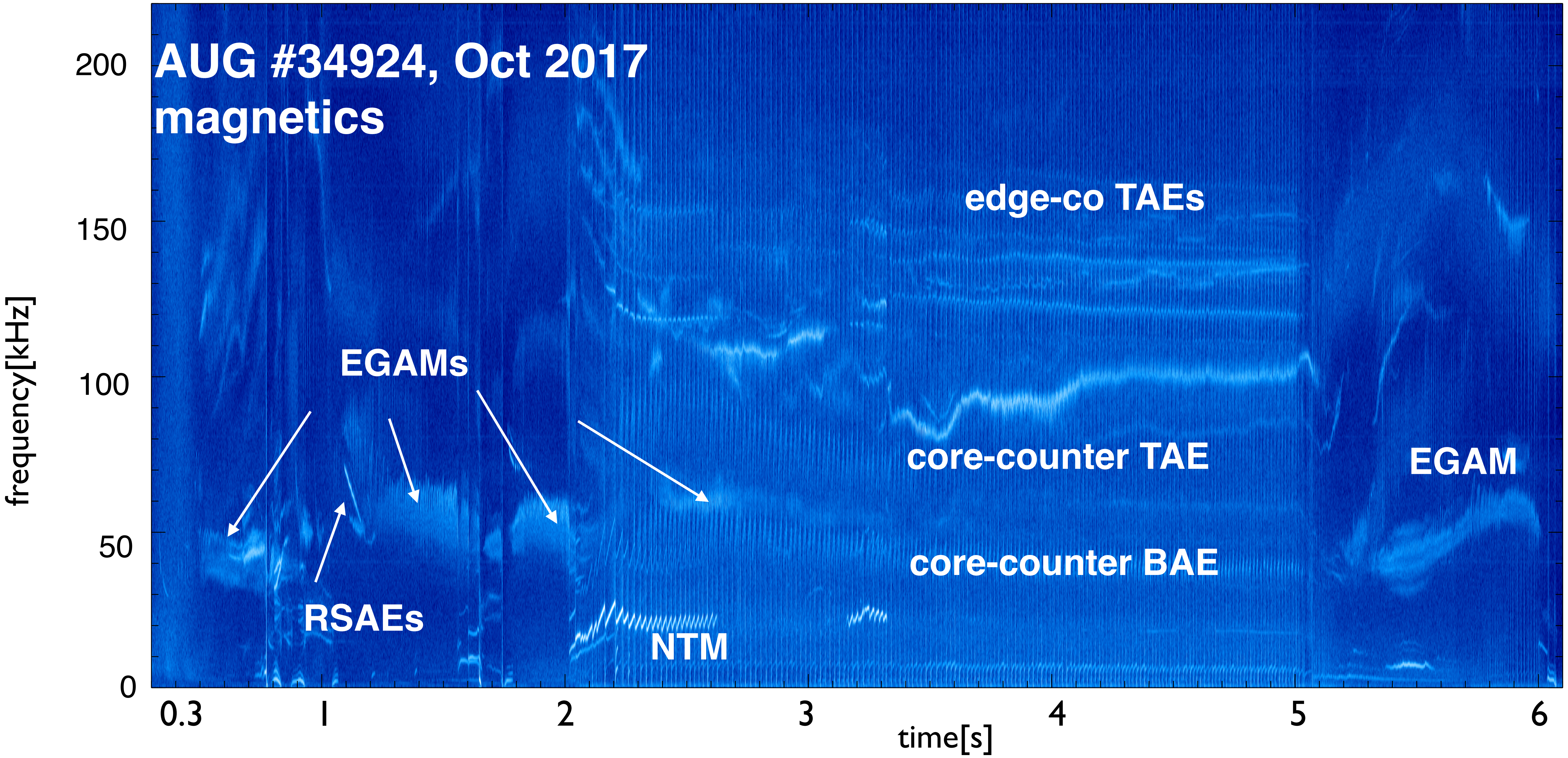


scan of plasma current and change ramp-up timing:

reduce current to avoid q=2
see next slide

AUG 'EP supershot' scenario: extension to flat top



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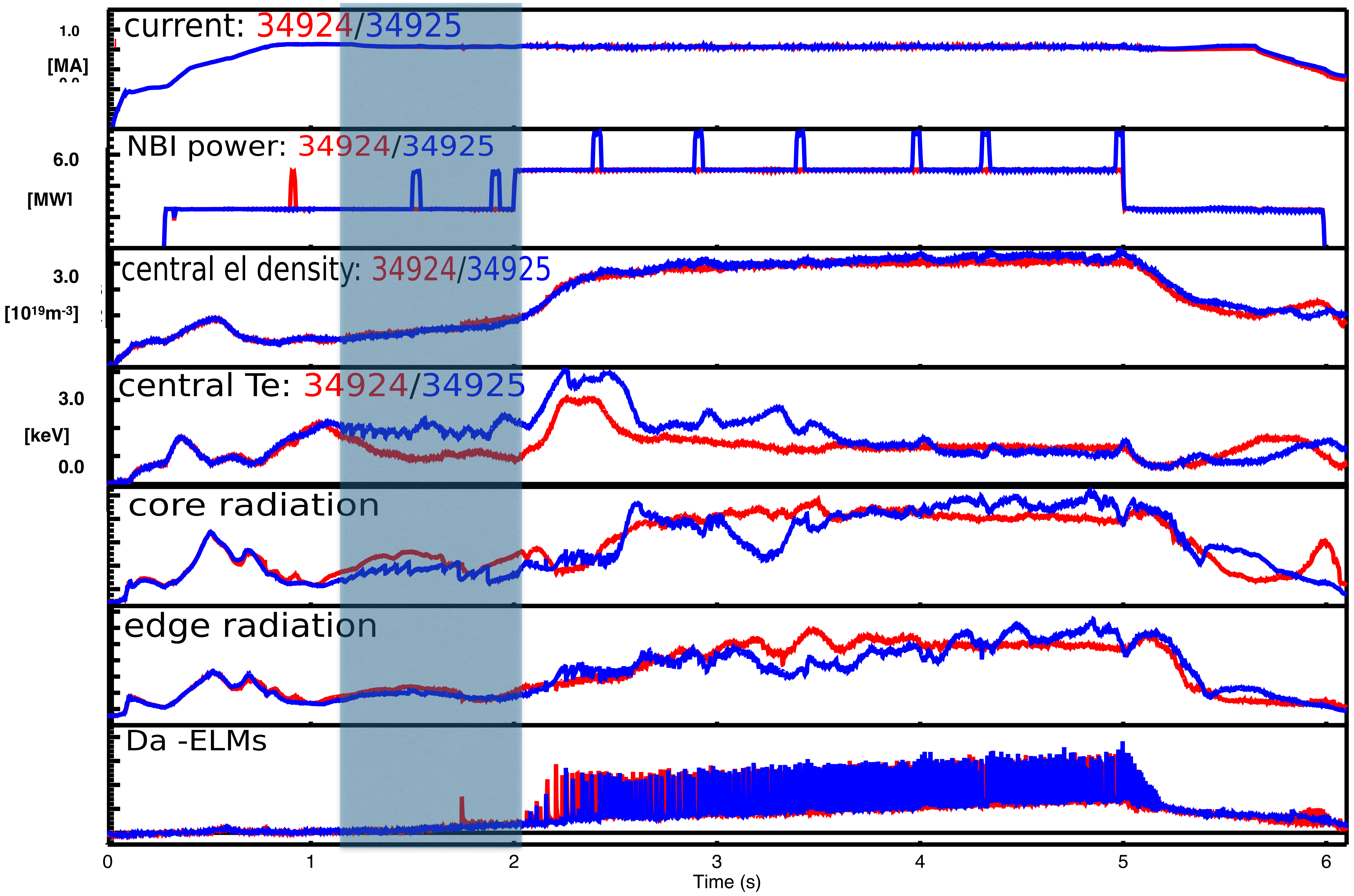
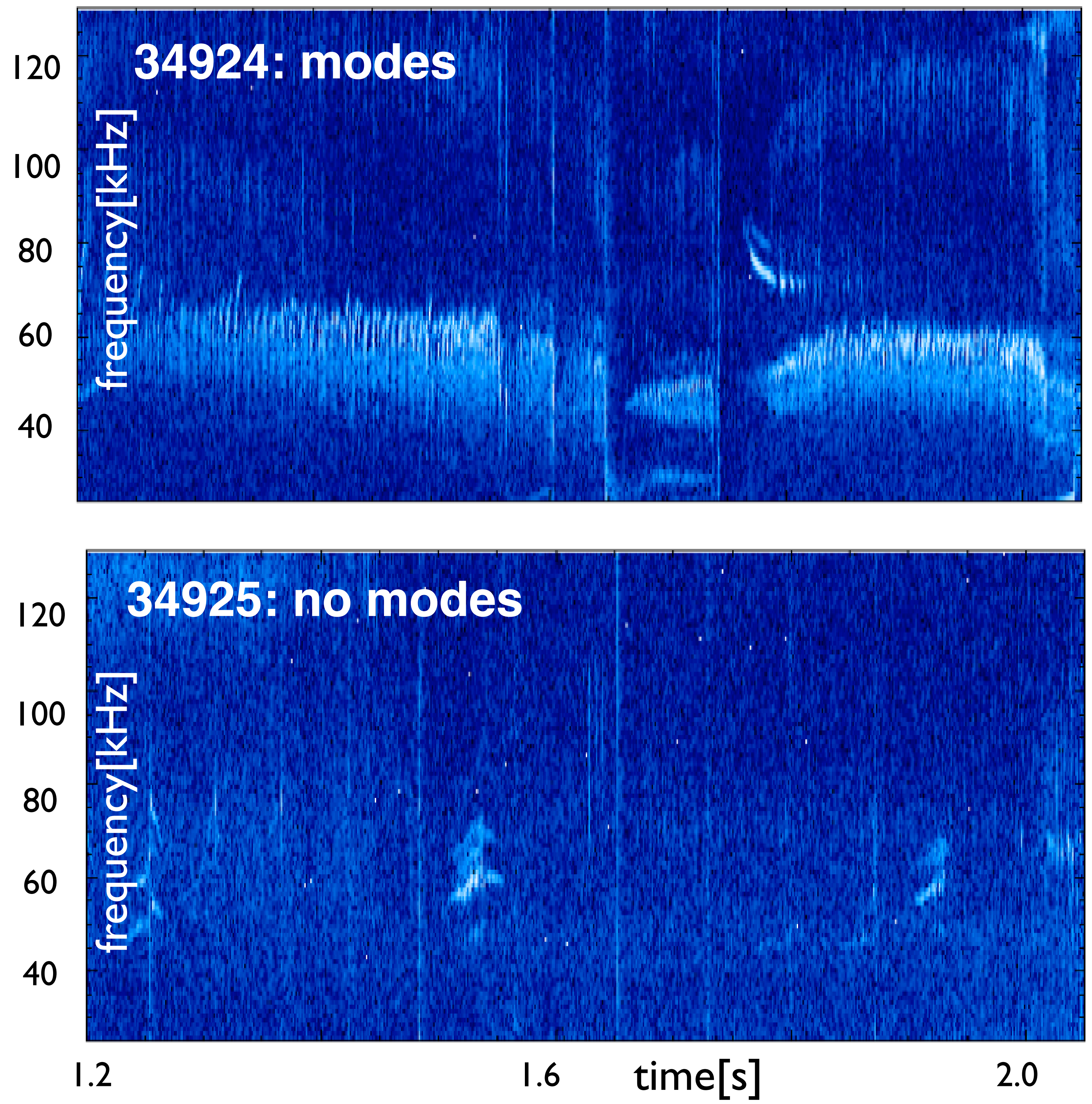
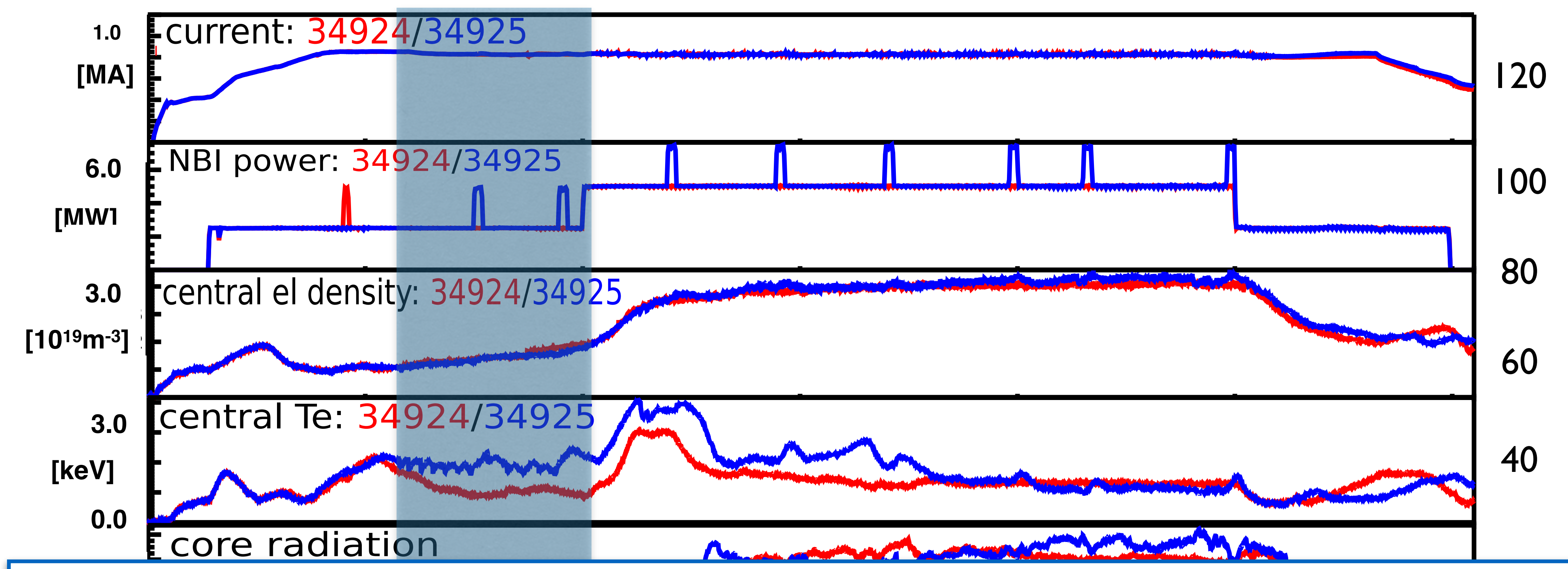
- with sub-Alfvénic beams (2.5-5MW)
- in current flat top with stationary plasma conditions
- compatible with tungsten wall
- for EP physics (at ITER) relevant parameters: $\beta_{EP}/\beta_{thermal}$ up to 1, $E_{NBI}/T_{i,e} \approx$ 100-150

comparison of discharges w/o mode activity

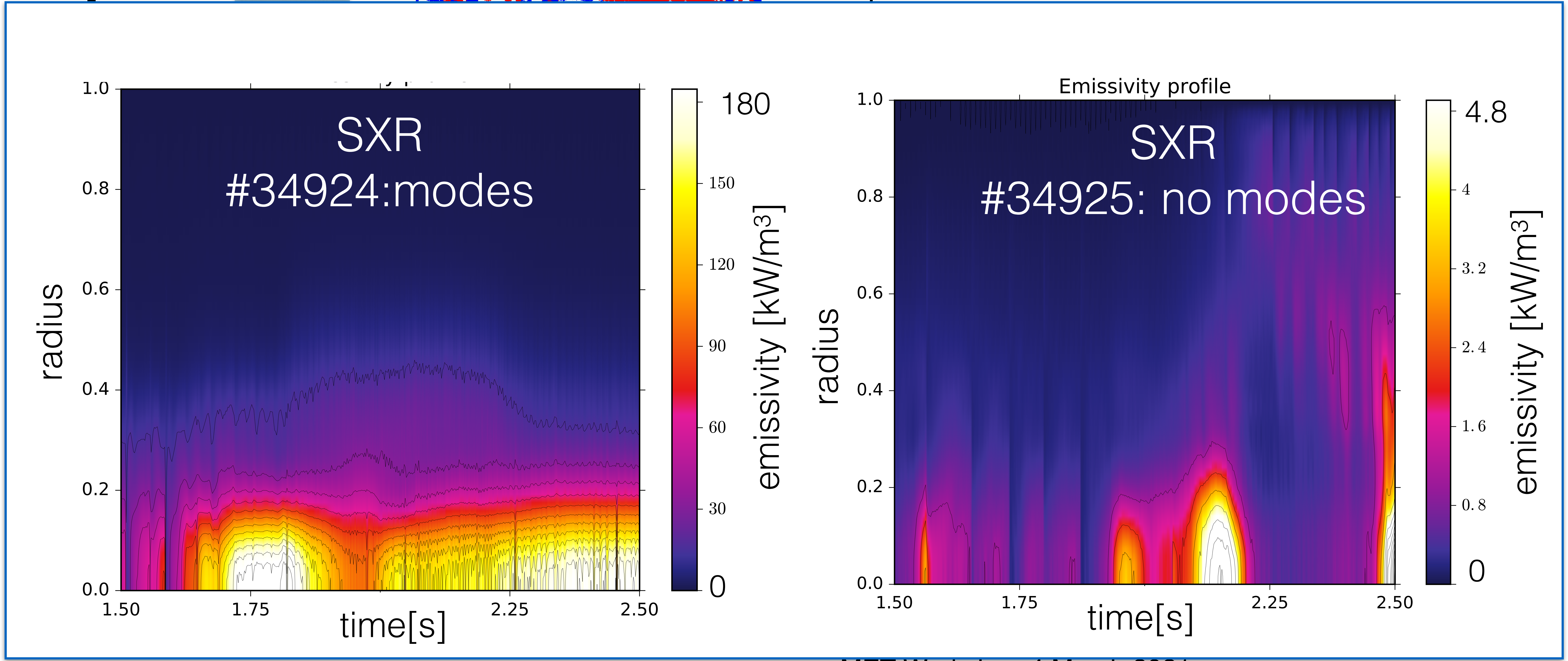




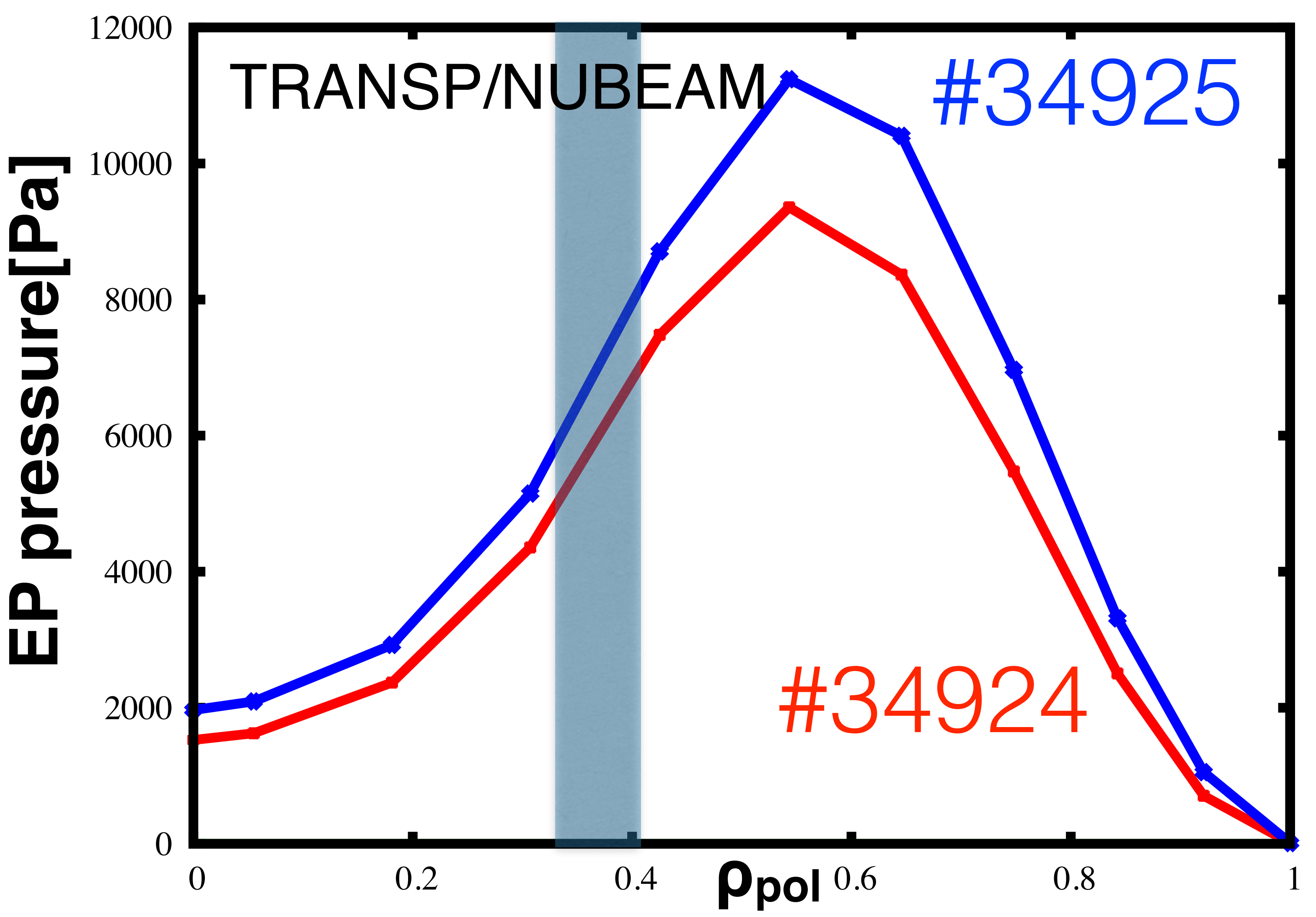
central impurity accumulation of W allows for low beta despite NBI heating



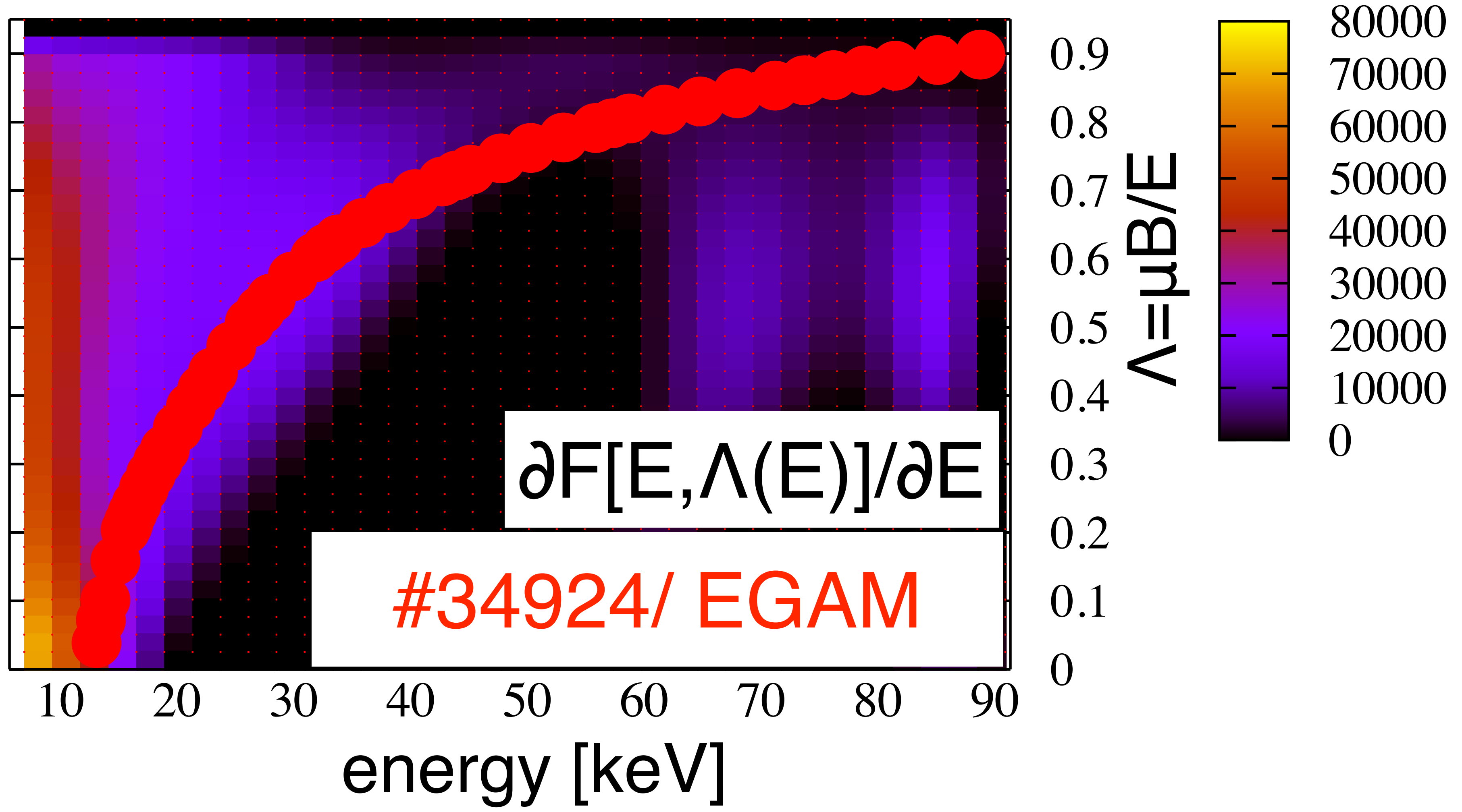
- reduced ion LD (exponential dependence)
- reduced el LD damping (beta)
- moves beam anisotropy in 'correct' frequency range
- co- and counter propagating modes: off axis EP peak



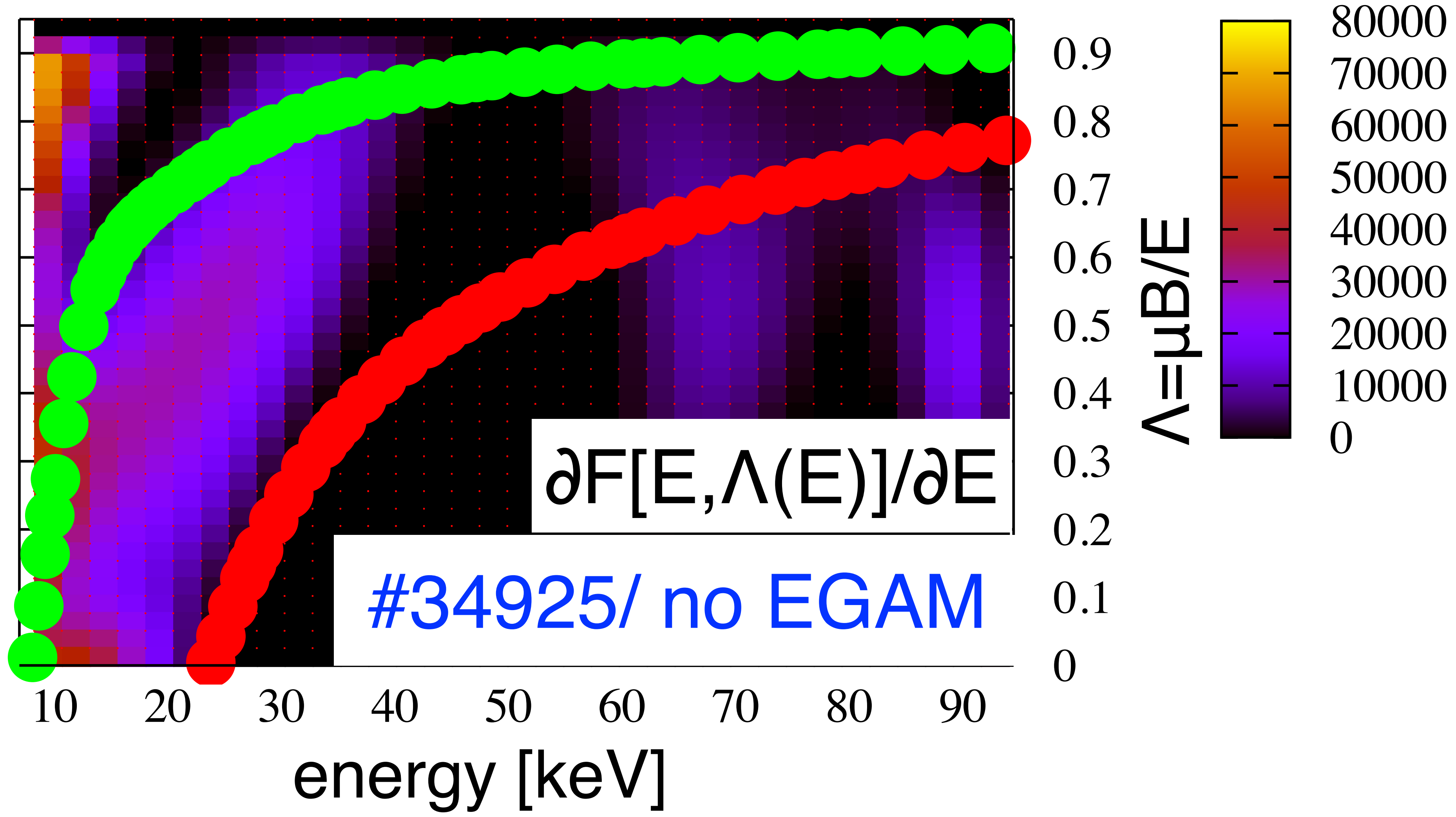
EP phase space analysis: ∂F/∂E



resonance with local f_{GAM}



resonances with local f_{GAM}



- 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]*

- D beams in D plasma
- H beams in H plasma
- D beams in H plasma

database:

~20 dedicated, low power discharges

aims:

- stationary flat top conditions
- strong EP induced activity
- study mode-mode interaction processes
- transitions between different nl behaviour
- if possible radially resolved mode structure measurements
- isotope effects: excitation conditions,FOW

#	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				1	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			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		Q7, 93	7.13				1	2.2
32327		Q7, 82	7.13				1	2.2
32328		Q7, 82 +0.5MW ECRH	7.13				1	2.2
32329		Q7, 93 +0.5MW ECRH	7.13				1	2.2
34924		Q7, 93 Q6 @2.0					0.8.	2.5
34925		Q7, 93 Q6 @2.0					0.8	2.5
36267		Q7, 93 Q6 @5.0	7.13	H mode			0.8	2.5
36269		Q6, 93	7.13	L mode			0.7	2.5
36270		Q7, 93	7.13				0.7	2.5
36337		Q7, 93	7.13				0.7	2.5
36338		Q7, 93	7.13				0.7	2.5
36339		Q7, 93	7.13				0.7	2.5
36759		Q7, 93	7.13	H in H			0.8	2.5
36760		Q7, 93	7.13	H in H			0.8	2.5
38159		Q7, 93	7.13	D in H			0.8	2.5
38160		Q7, 93	7.13	D in H			0.8	2.5

basic considerations

all experiments: off axis beam injector: (Q6/Q7) , either one or two beams, plus diagnostic beam

- 2.5MW , 93 kV per source for D
- 1.4MW , 72kV per source for H (technical limitation)

higher L-H threshold in H, stable conditions far from L-H threshold

very different plasmas (profiles) when crossing L-H threshold:
- in H mode, often stronger mode activity, smaller spectral width -> continuum
- in L mode, better diagnostic possibilities (density fluctuations: reflectometry)

frequency ratios of GAMs/BAEs and TAEs:

$$\omega_{TAE,H}/\omega_{TAE,D} = \omega_{A0,H}/\omega_{A0,D} = \sqrt{(2n_D/n_H)}$$

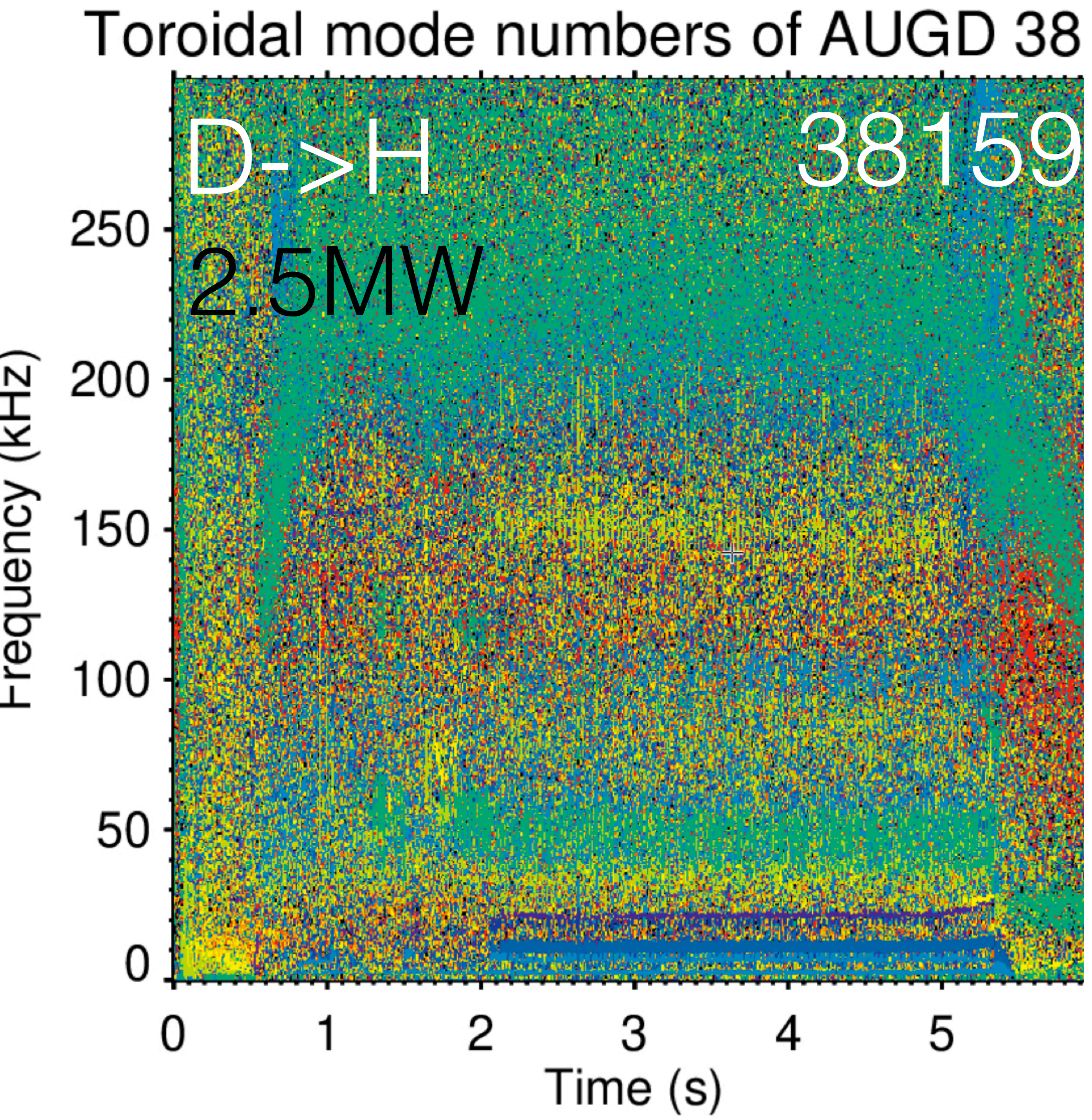
$$\omega_{GAM,H}/\omega_{GAM,D} = v_{th,H}/v_{th,D} = \sqrt{(2\ T_H/T_D)}$$

$$\omega_{GAM,D,H}/\omega_{TAE,D,H} = (v_{th}/R_0)/\omega_{A0} \sim \sqrt{nT} \sim \sqrt{\beta}$$

$\omega_{t,NBI,H}/\omega_{,tNBI,D} = \sqrt{(2\ E_H/E_D)}$: reduced H beam power should allow EGAMs but no TAEs

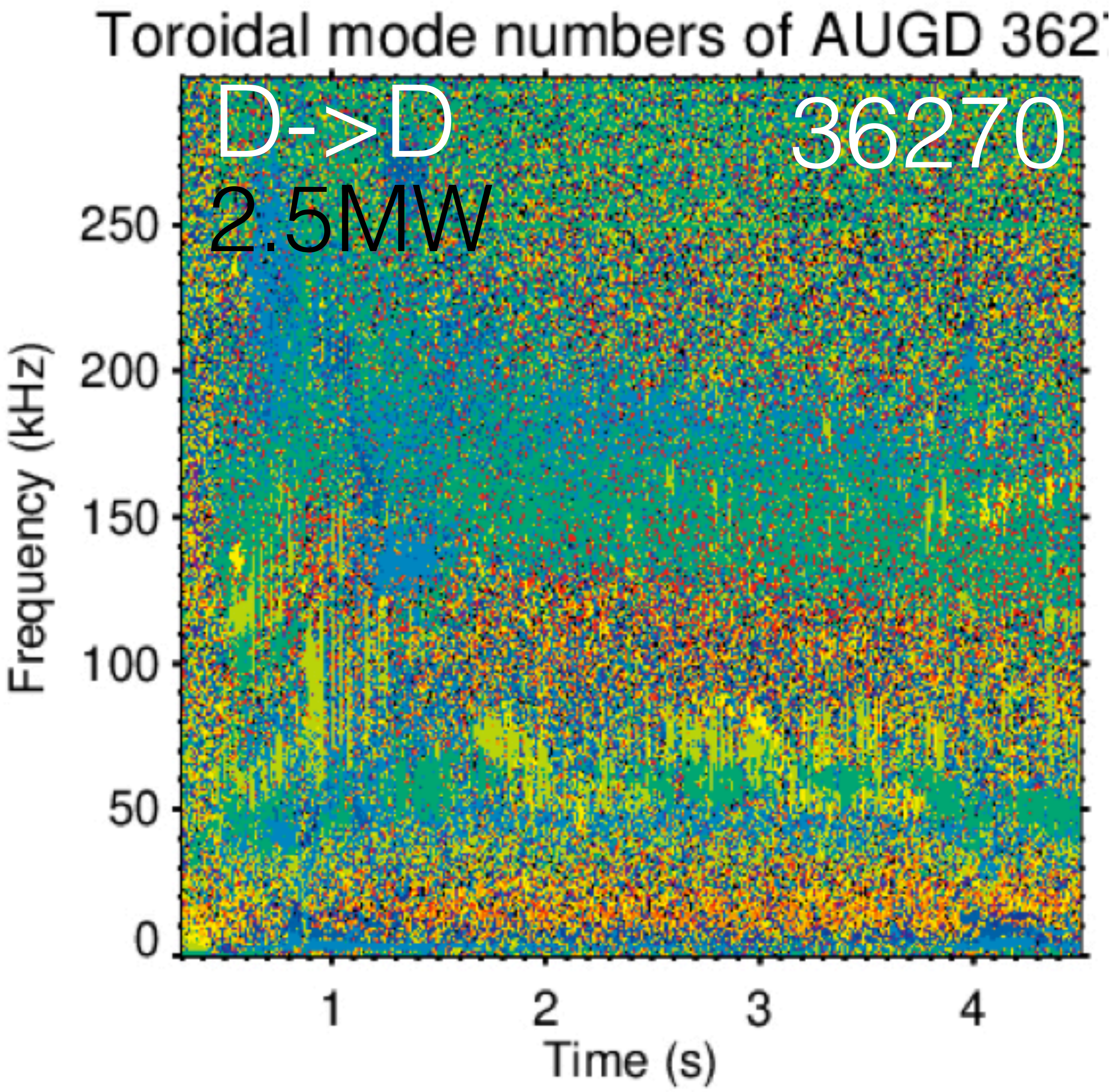
mode spectrum comparison (I)

L-mode

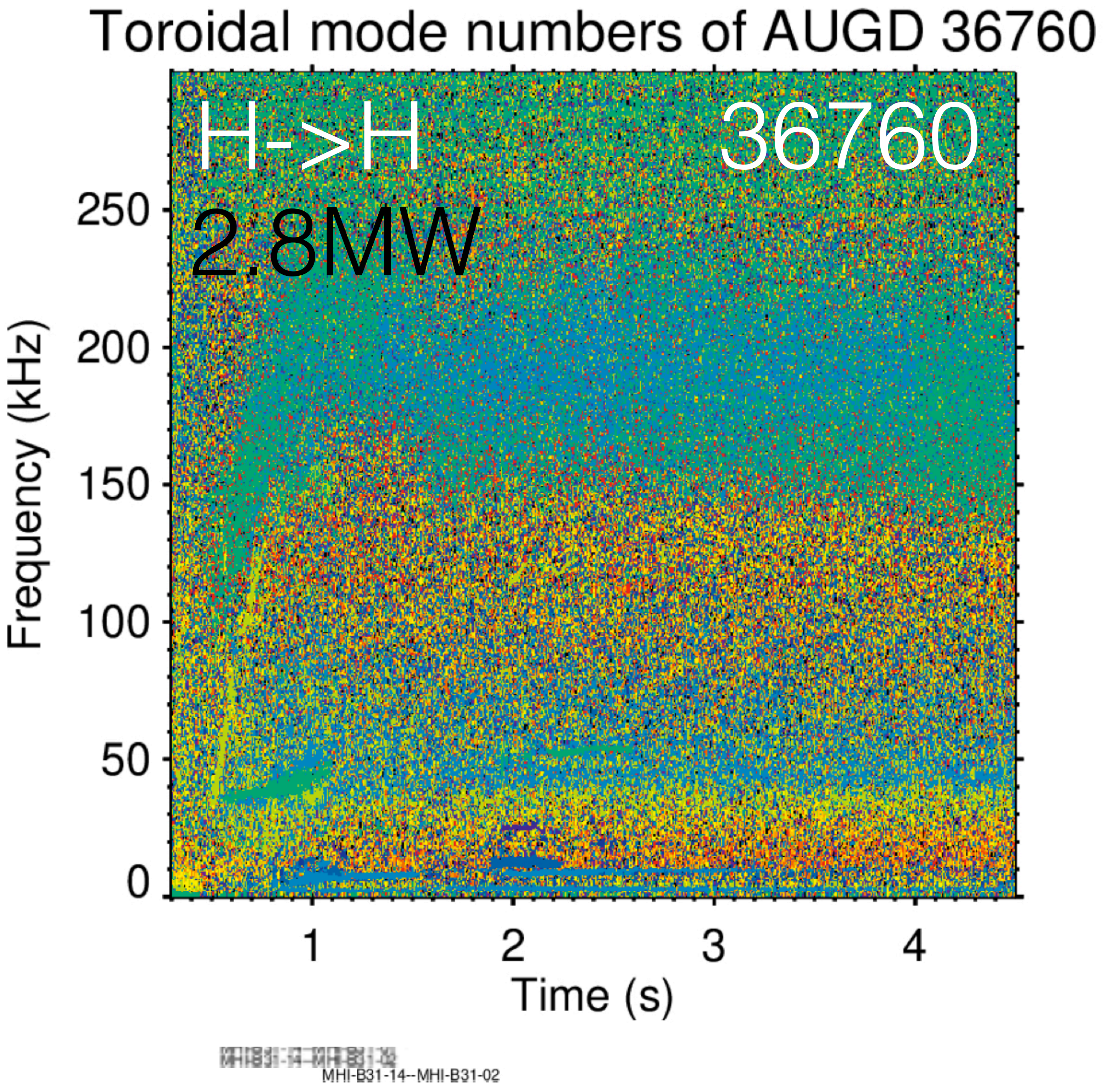


ideal n=2 kink mode

L-mode

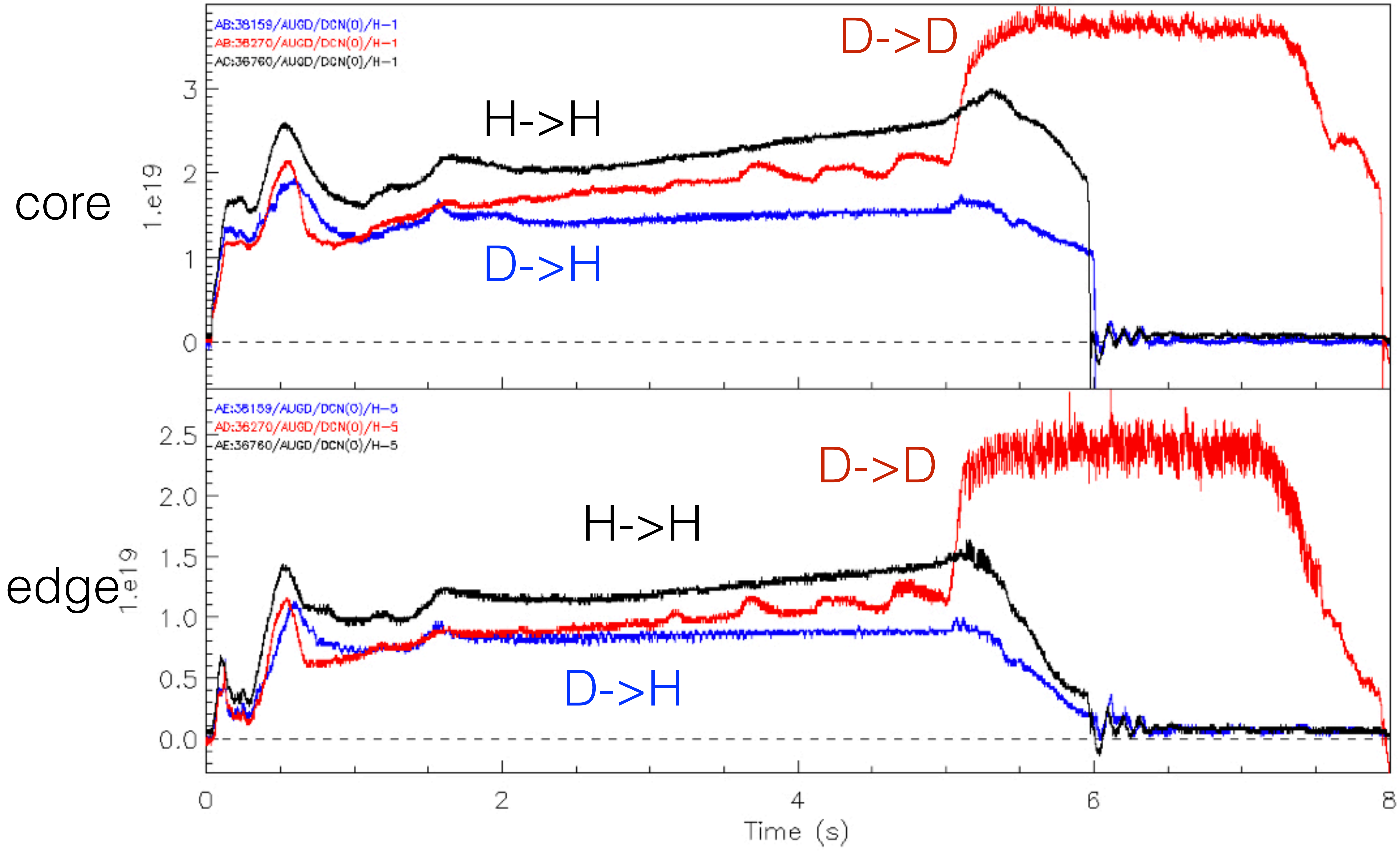


L-mode



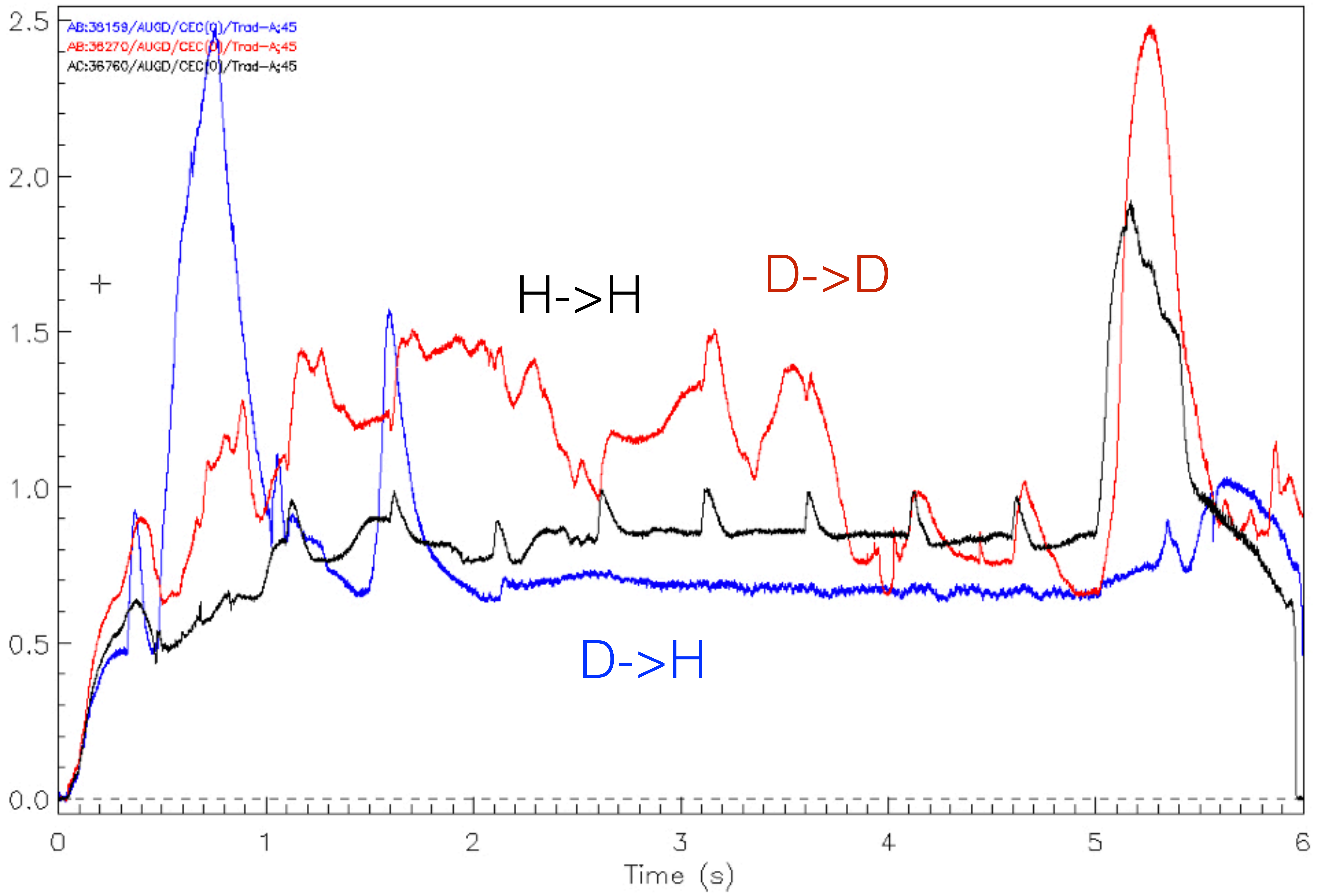
all shots have EGAMs, all except H->H have also TAEs,BAEs
modes in both ion (blueish) and el. diamagnetic (yellowish) directions observed

aiming for stationary conditions: L mode with 1 beam



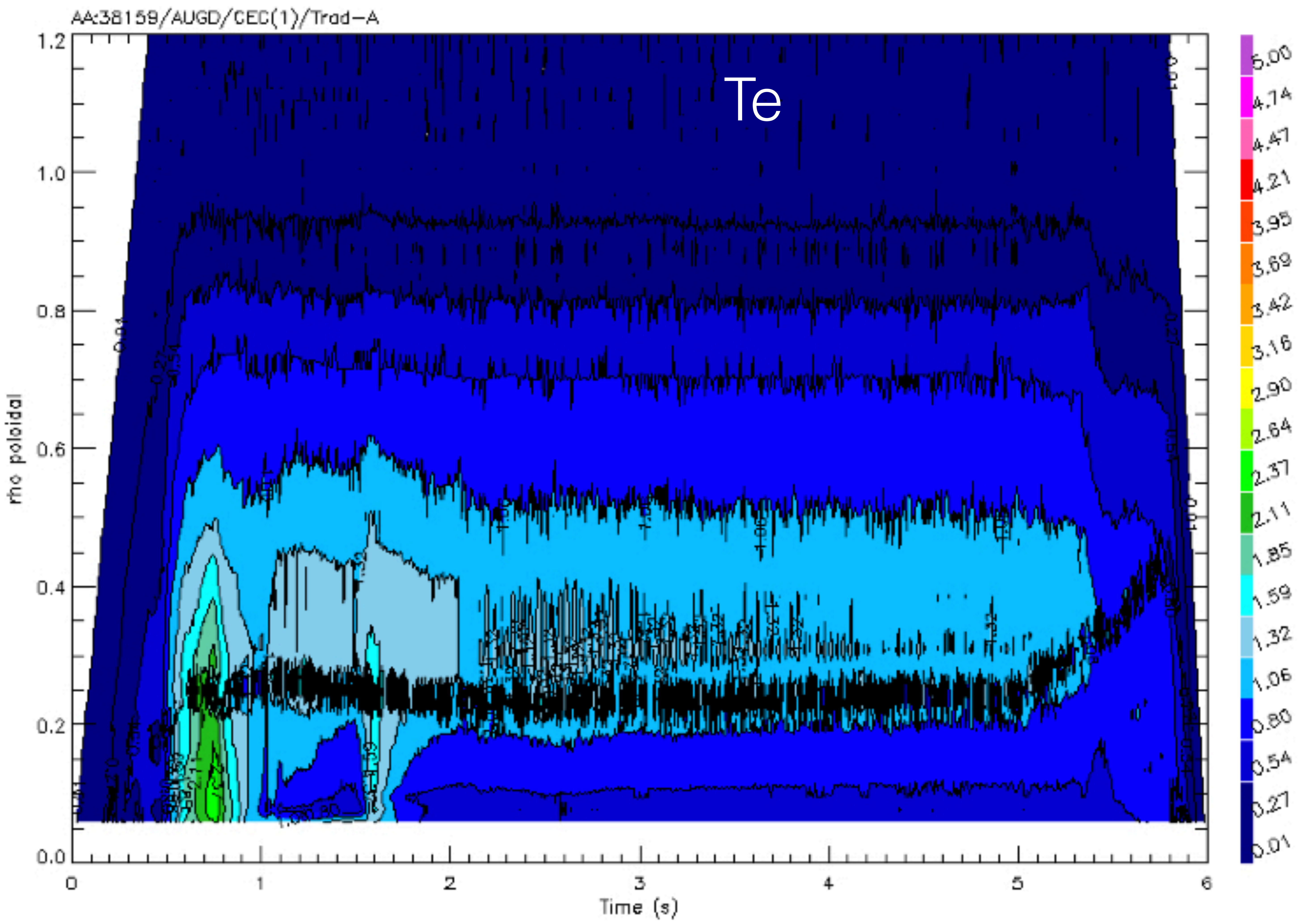
perfect
density control
in D->H

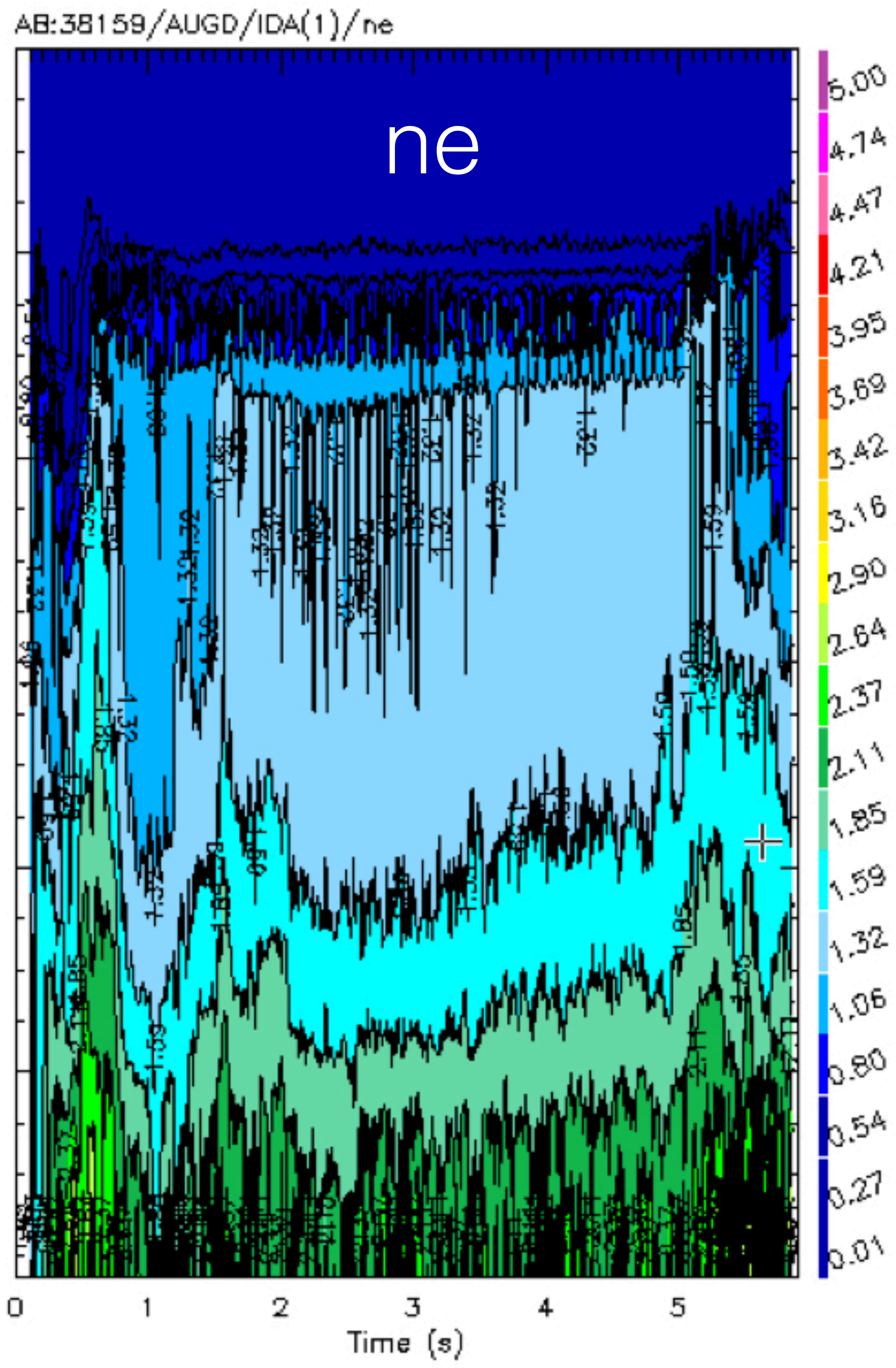
central Te in L mode



most stable conditions in D->H

most stable conditions in D->H, slightly inverted Te



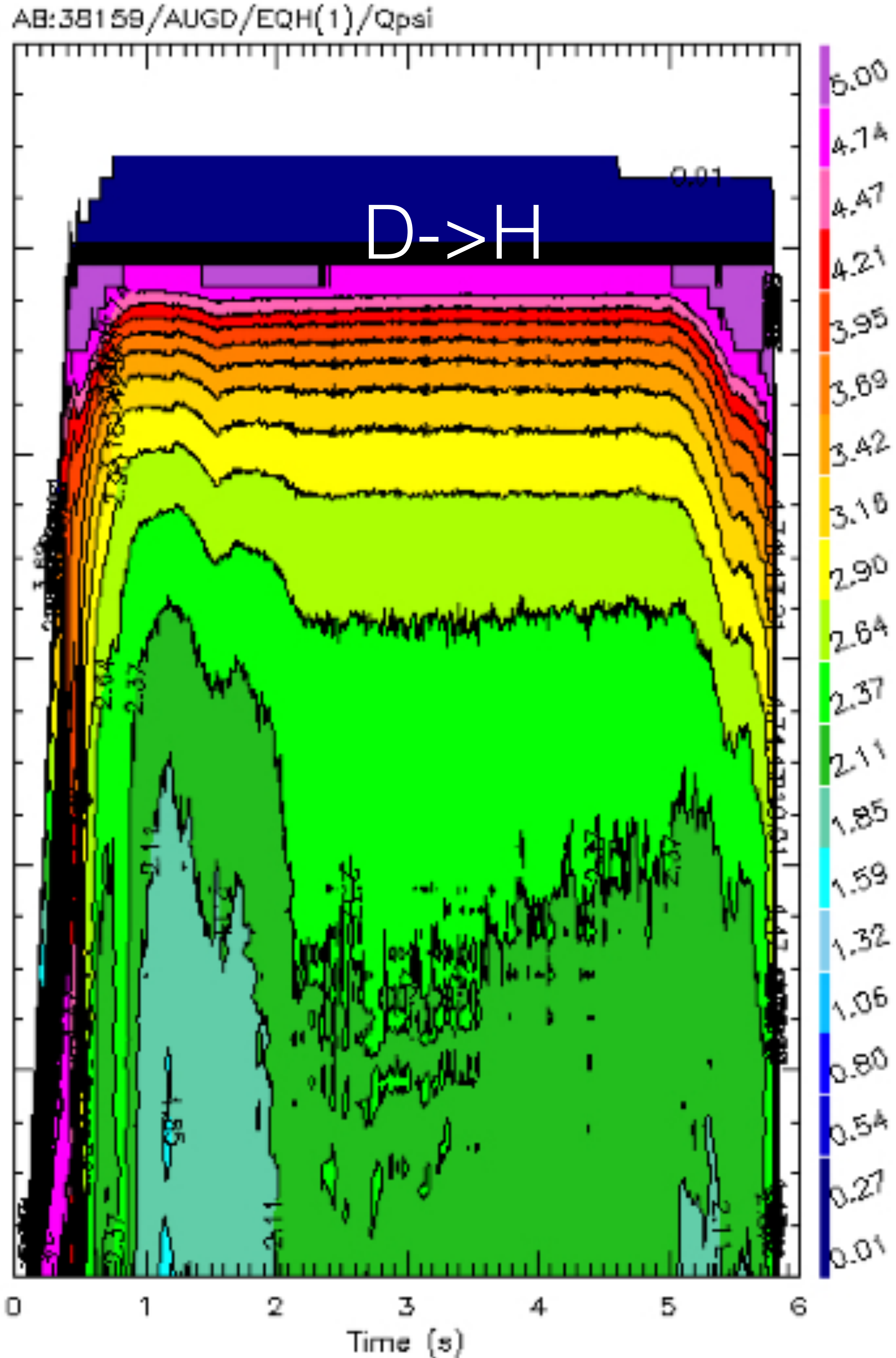


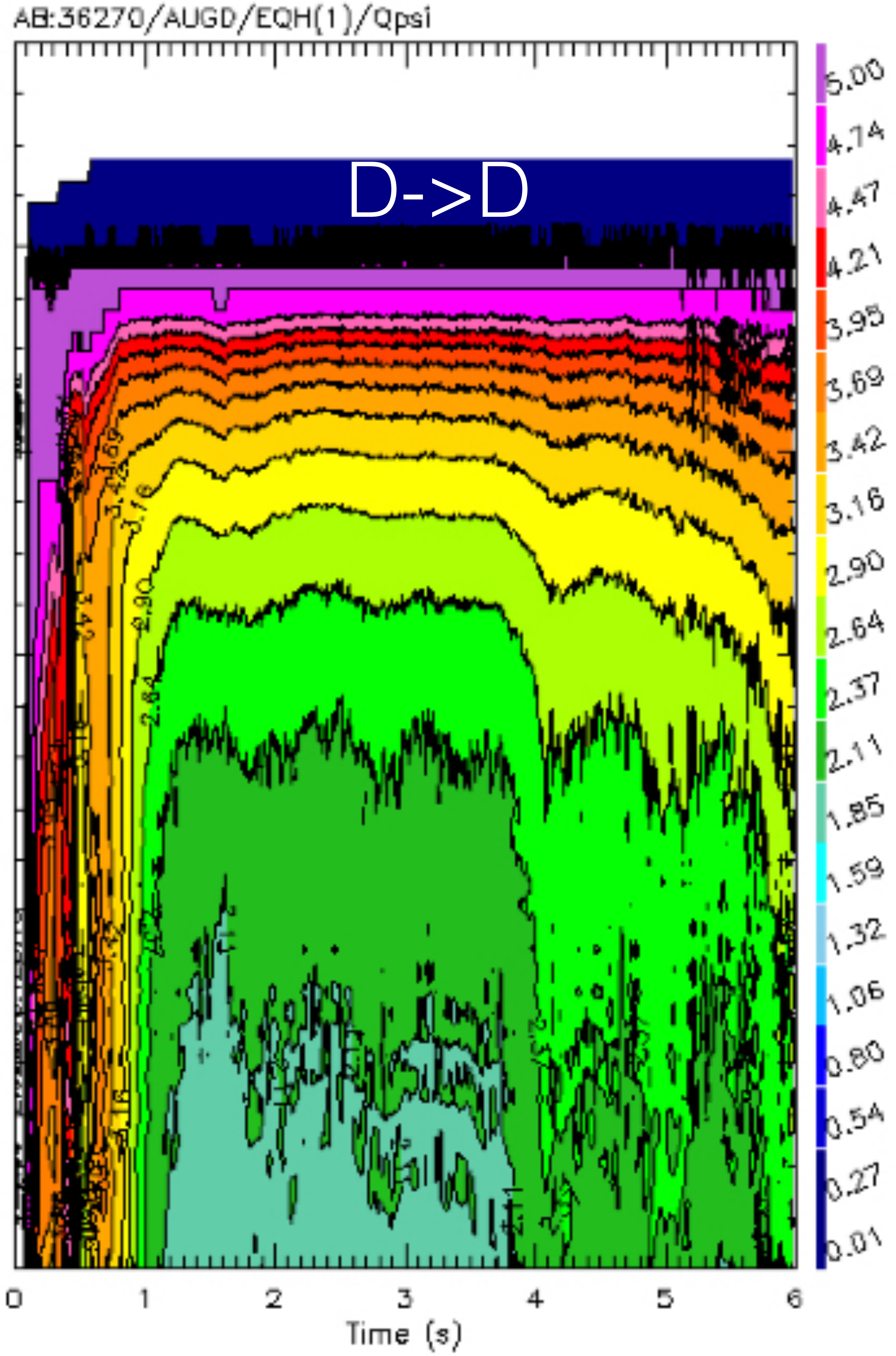
due to staying away from L-H threshold…

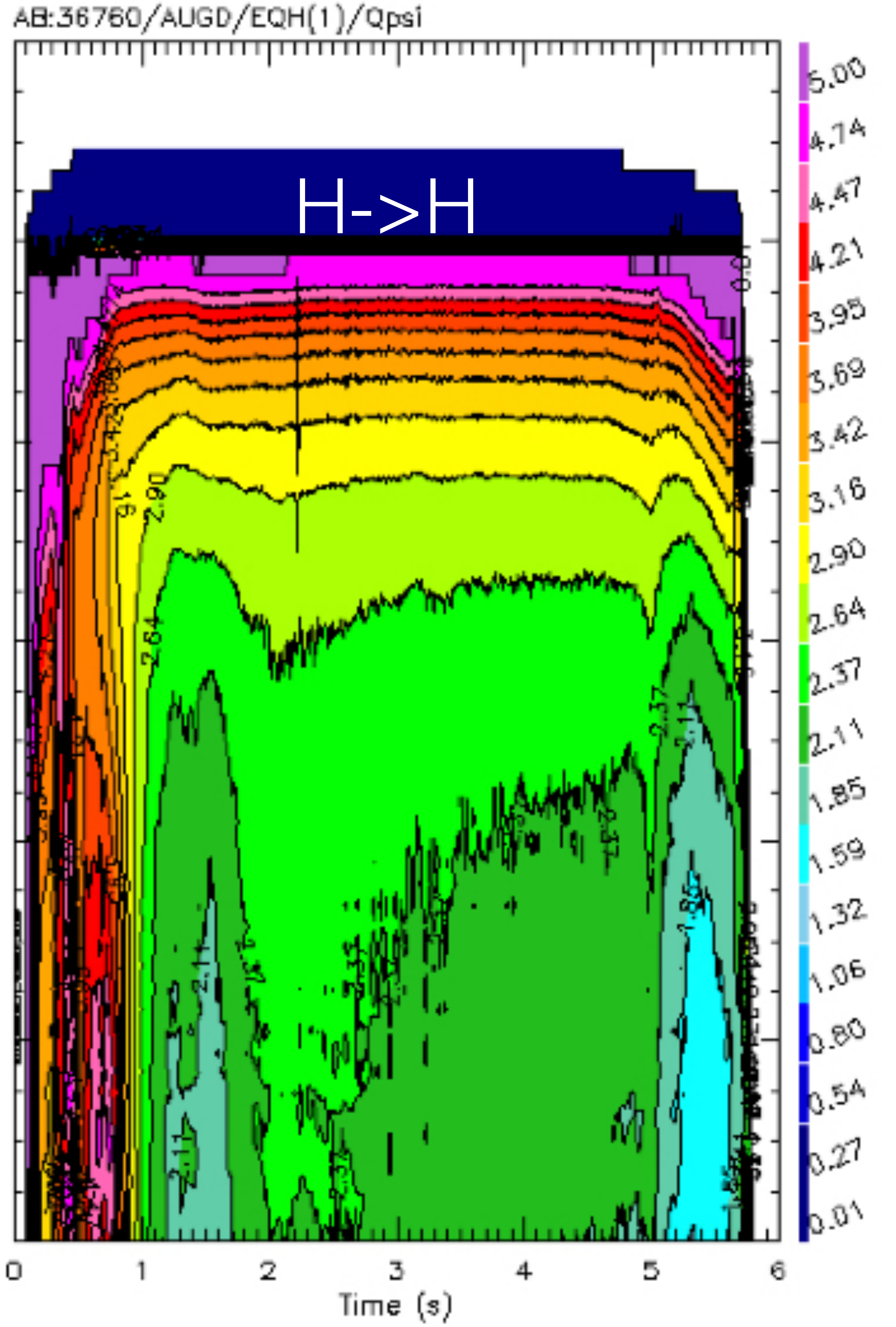
IPP EUROfusion

q-profile comparison: L mode discharges

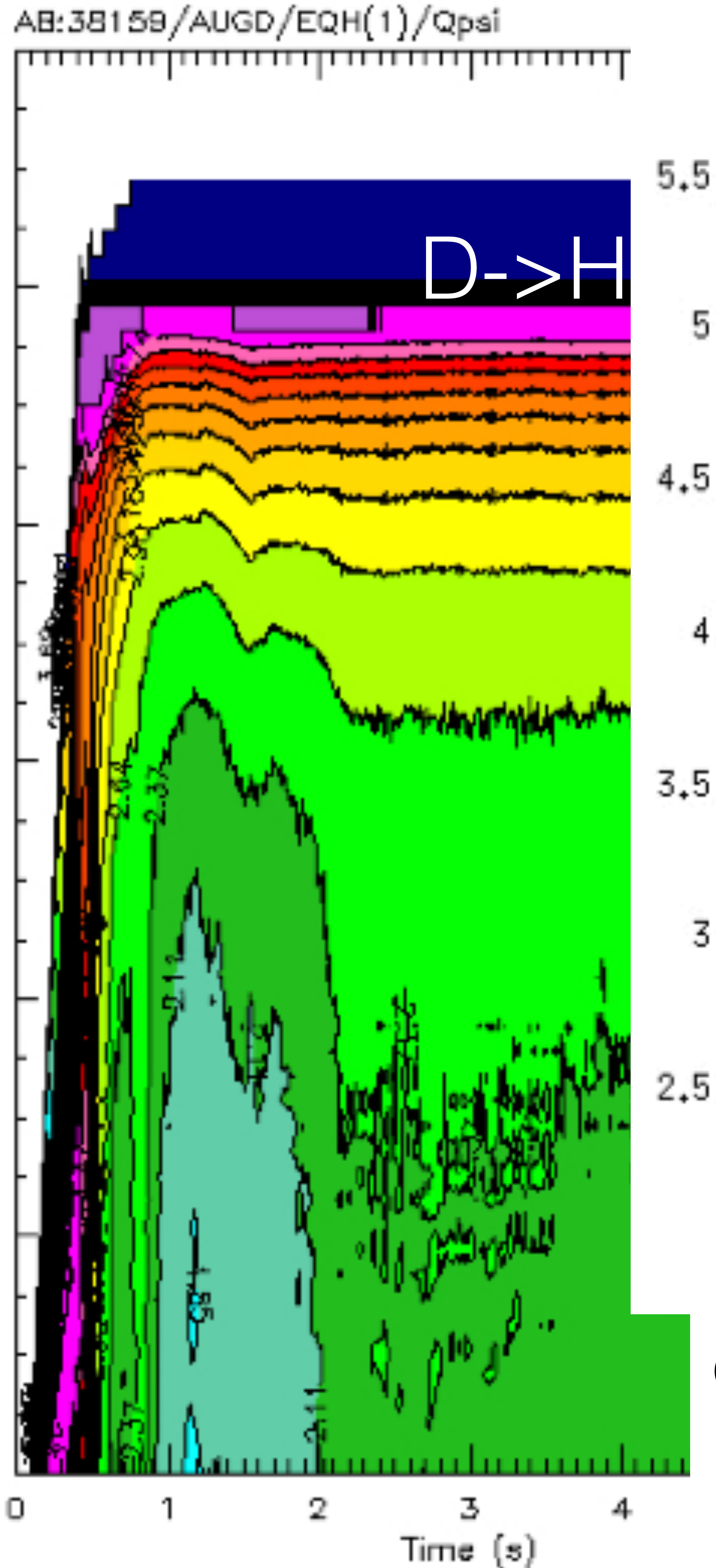
ASDEX Upgrade

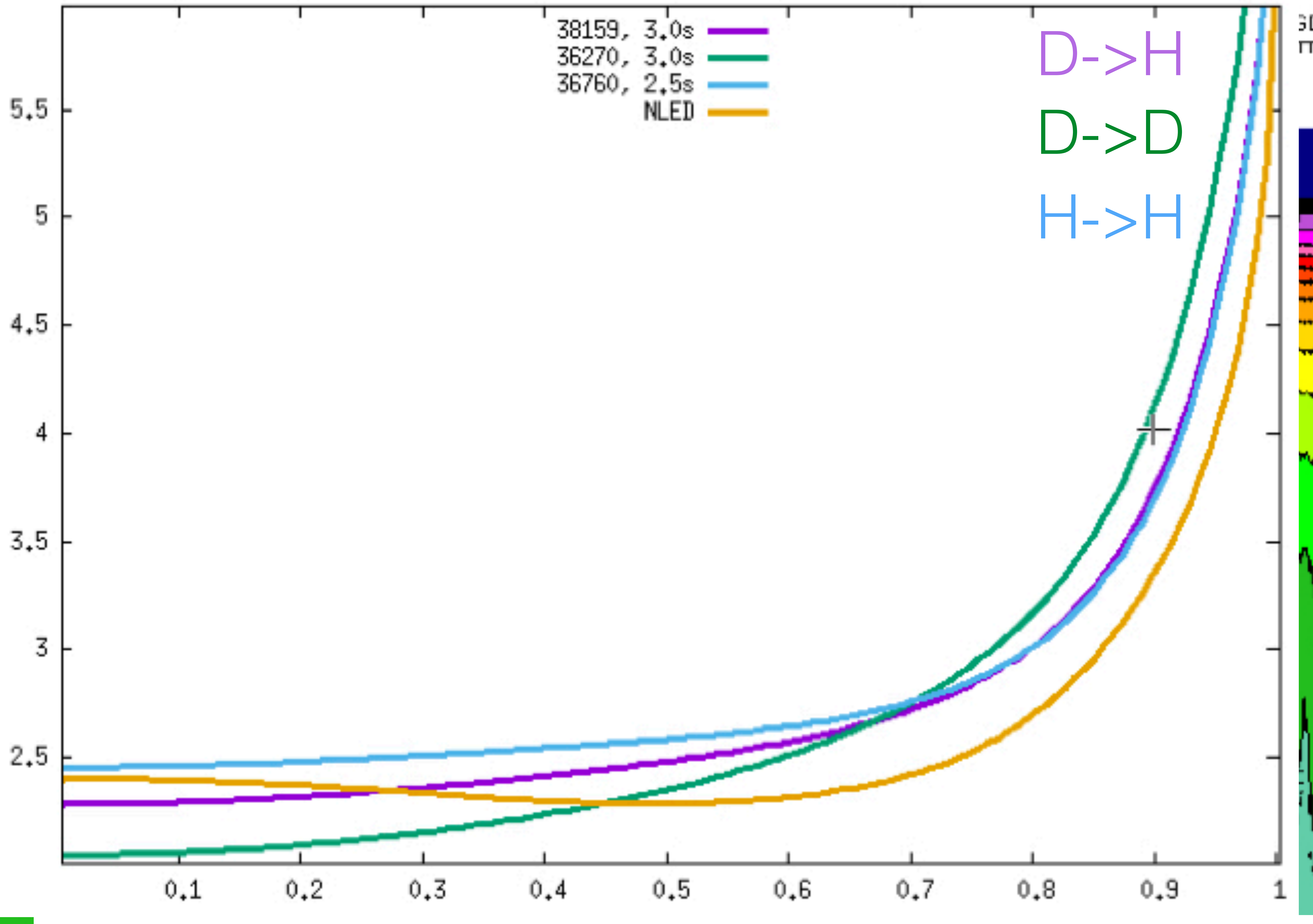


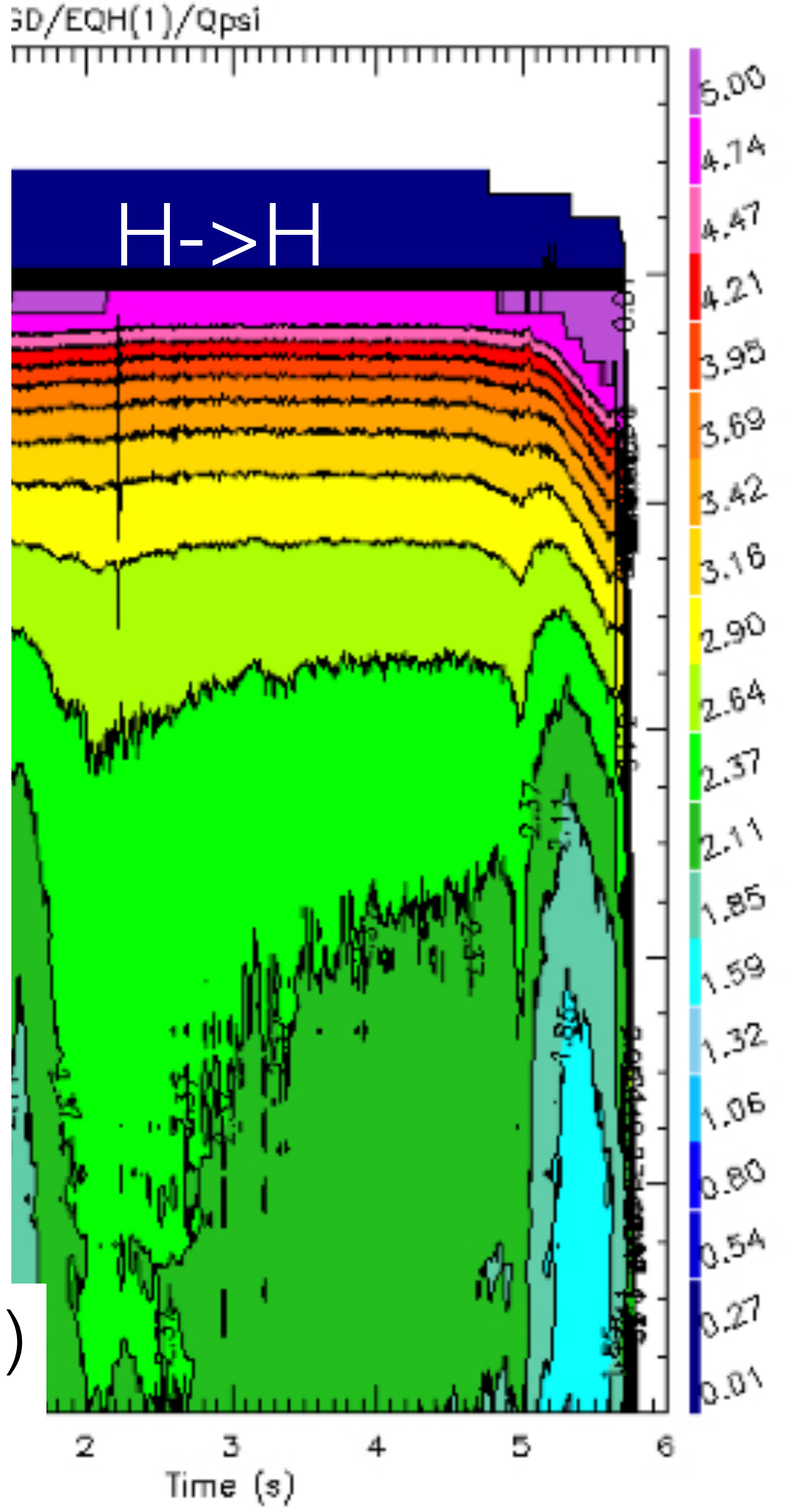




q-profile comparison: L mode discharges



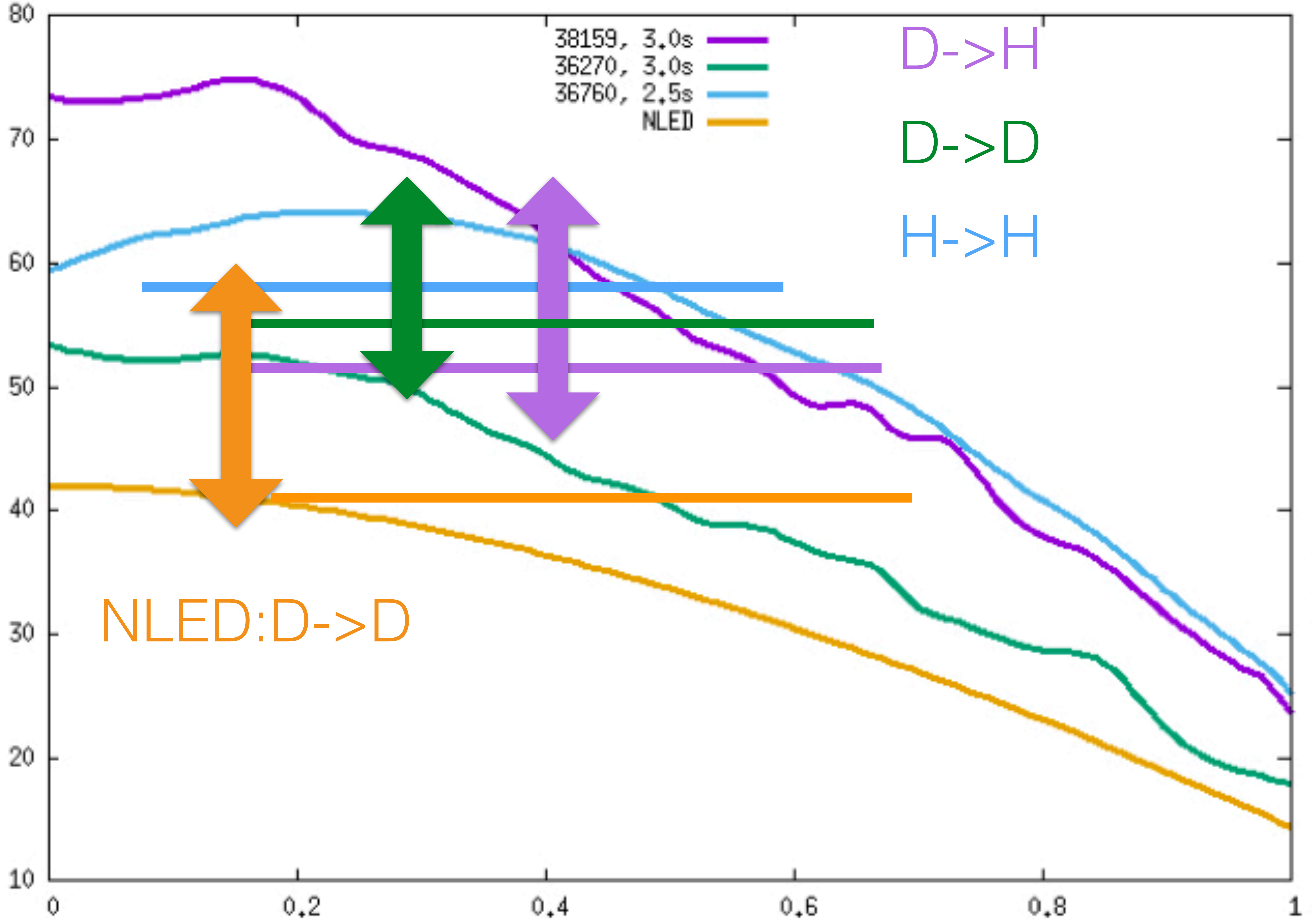


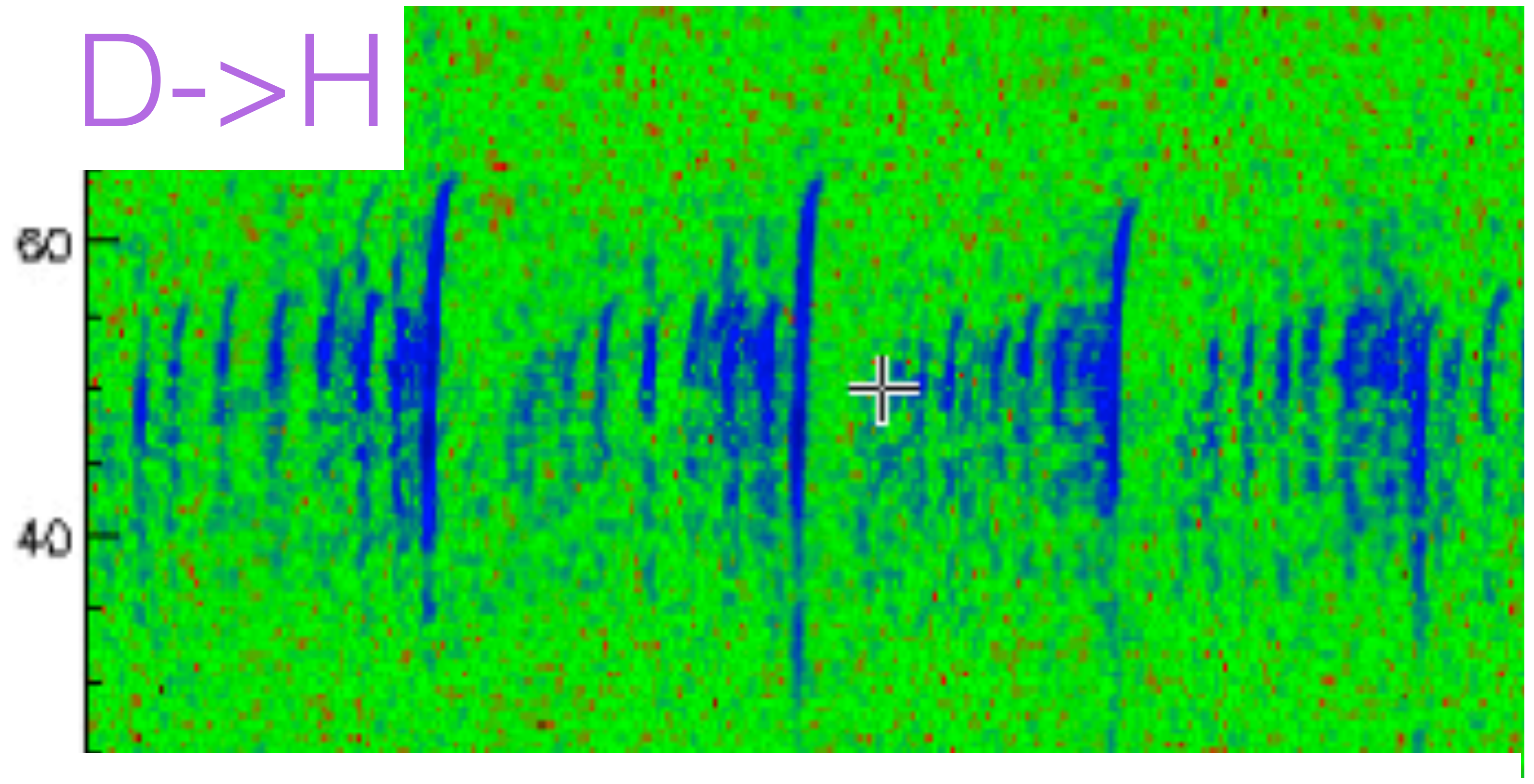


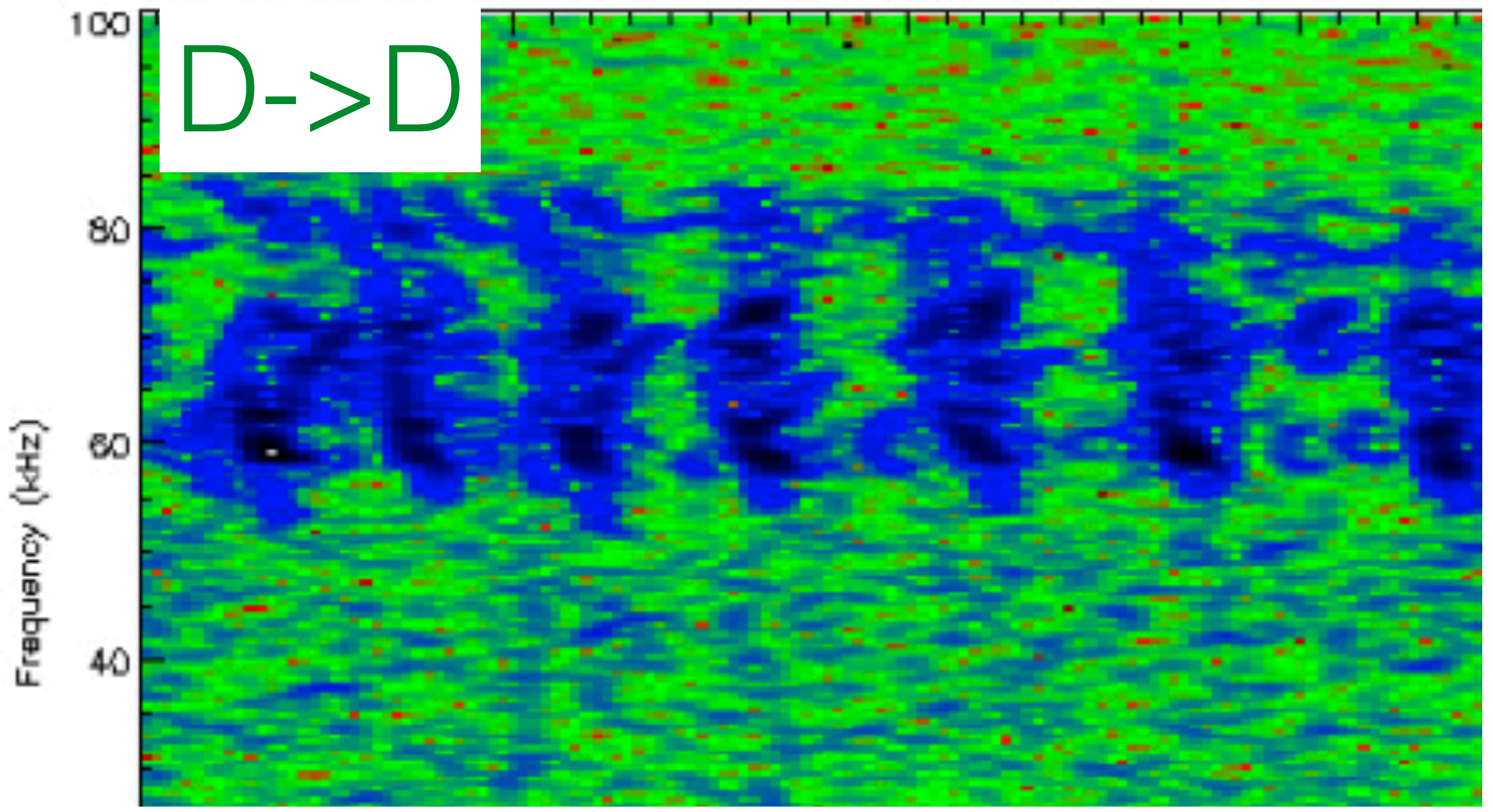
different current drive efficiencies (detailed Zeff needed)

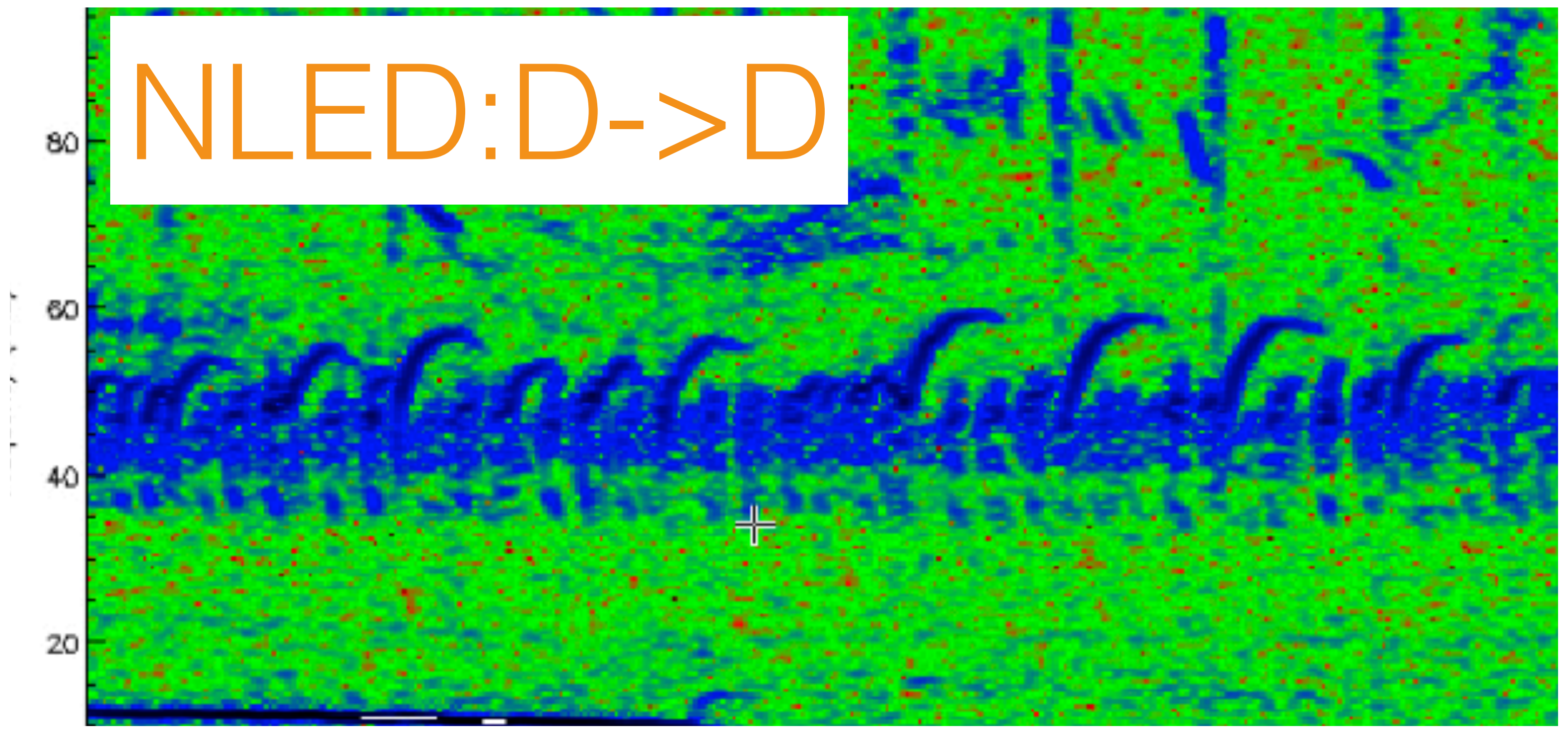
does mode activity influence current drive?

kinetic GAM continuum (incl. ellipticity [Gao], w/o EPs)



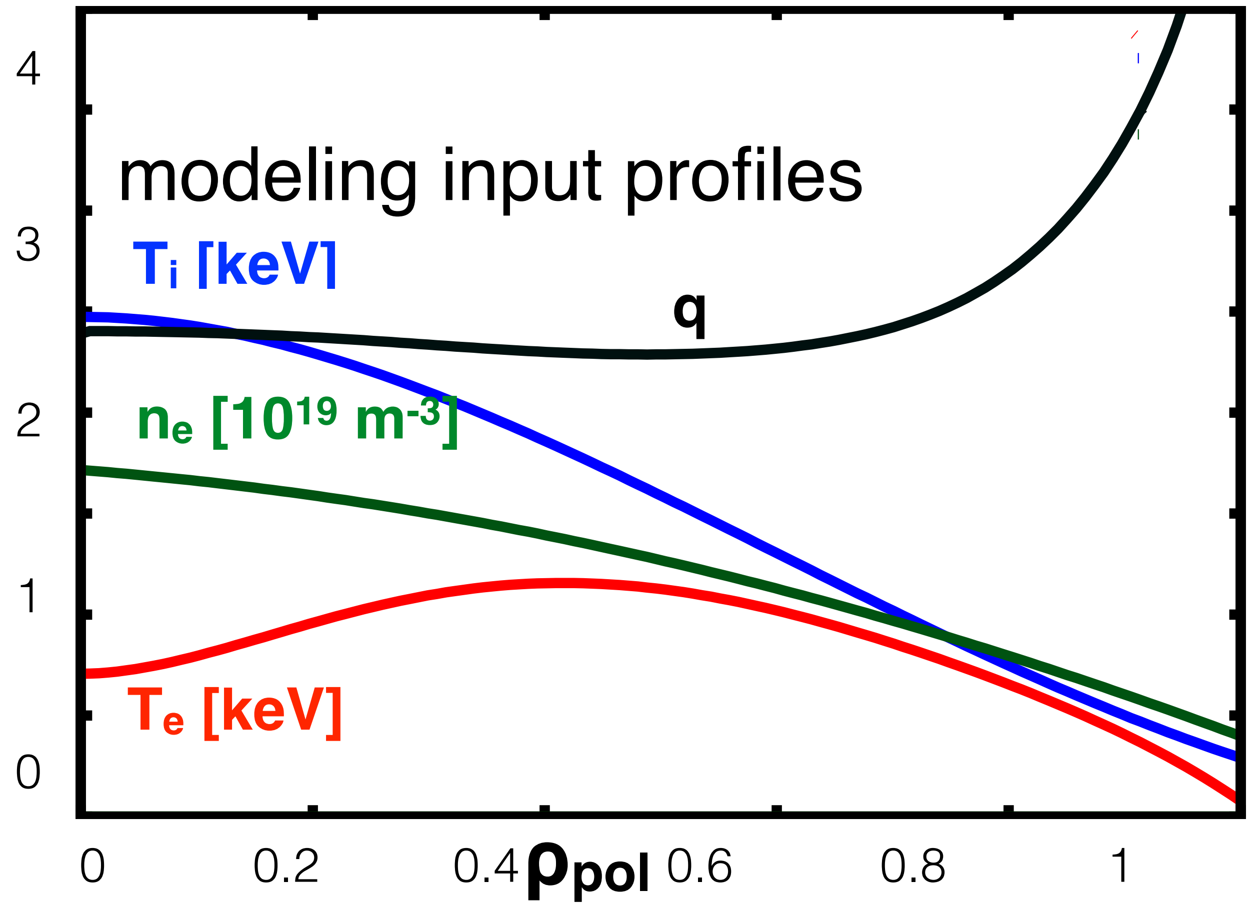






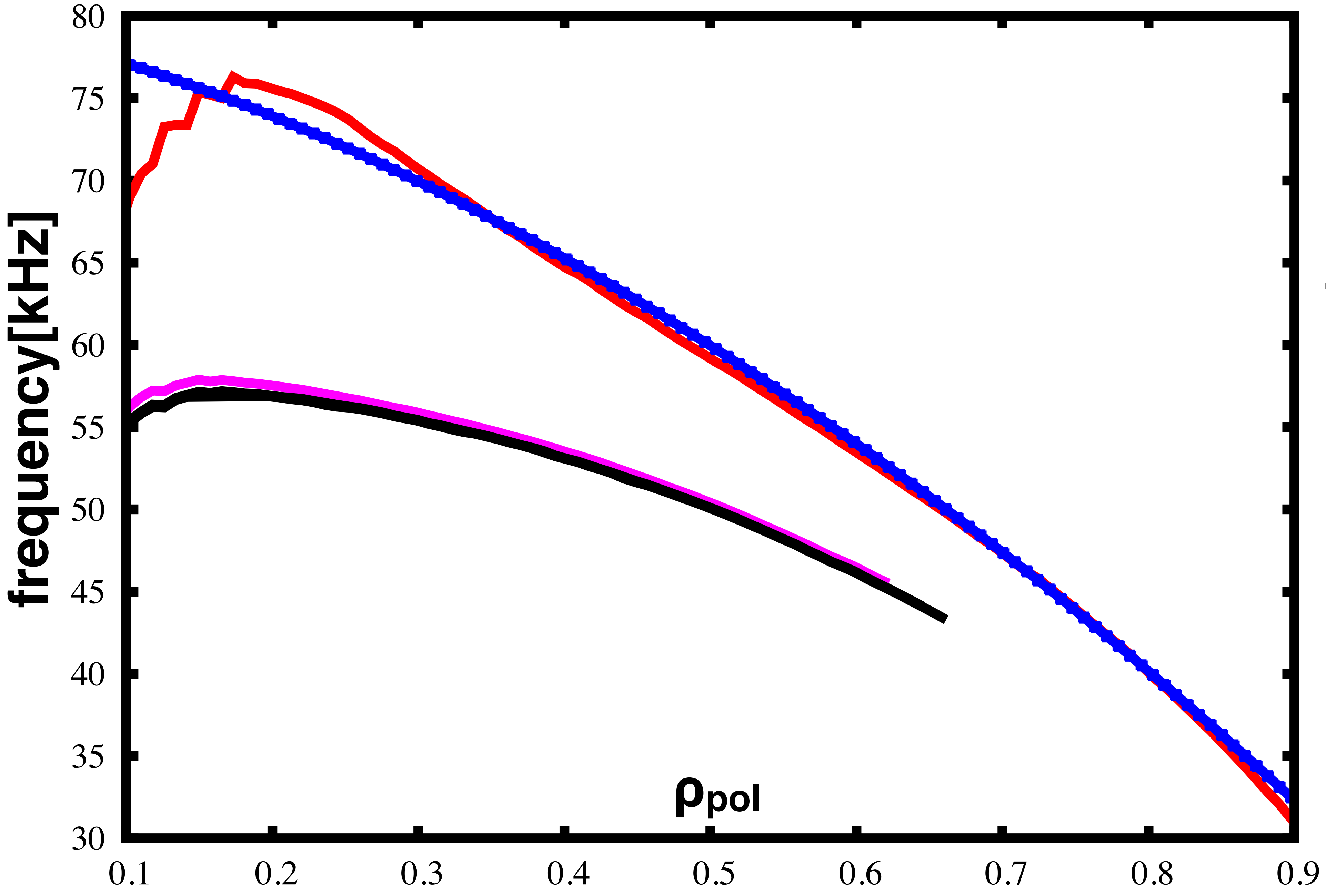
no clear relation between continuum and chirping/onset f_{EGAM}

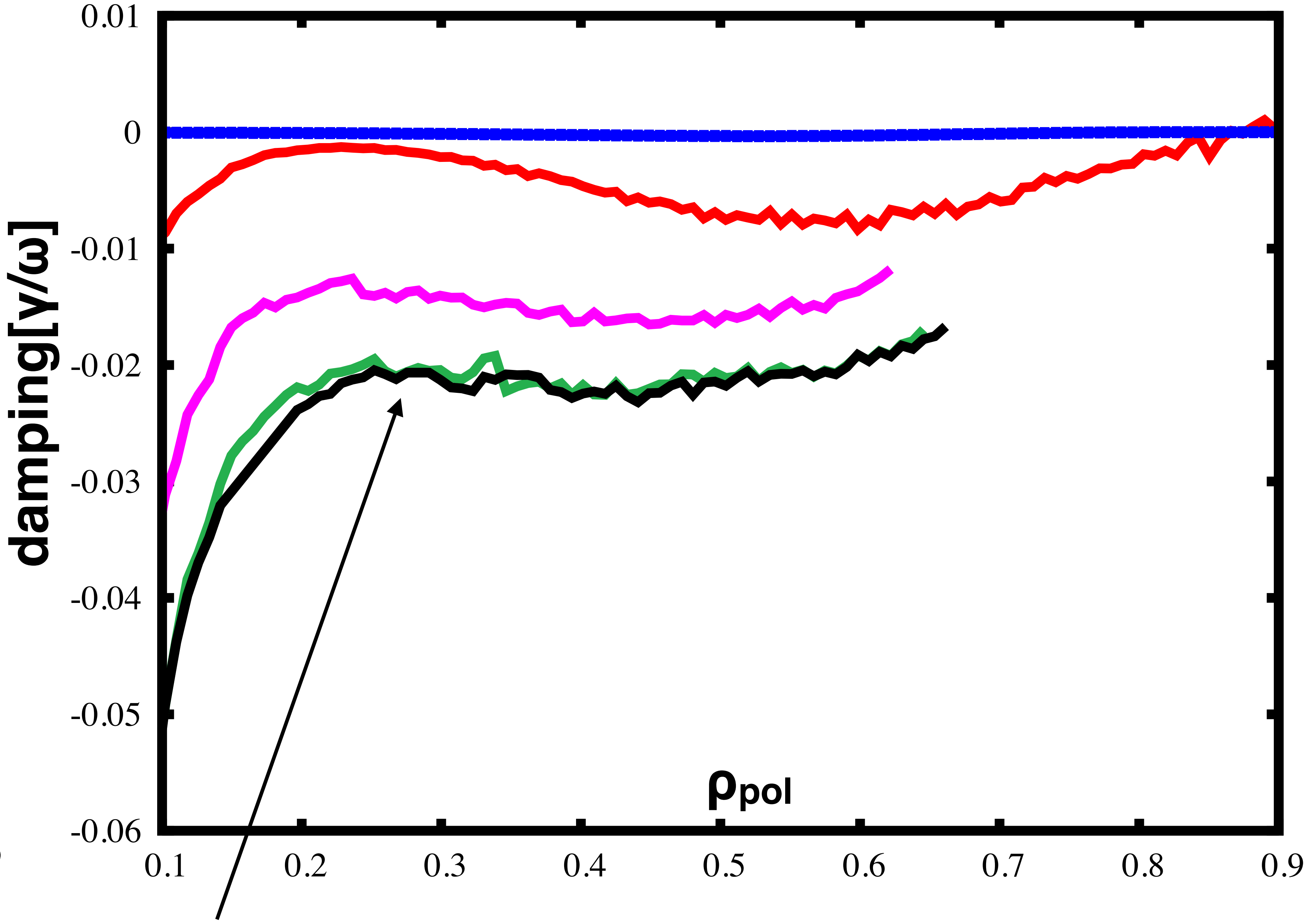
maybe imaginary part needs to be analysed as for NLED case…



at each radial position, solve linear dispersion relation:

- analytical, circular equilibrium
- numerical, circular eq., all ion resonances
- numerical, shaped equilibrium κ~1.6 ; $\omega \sim \sqrt{2/(1+\kappa^2)}$
- numerical, add trapped electrons
- numerical, trapped + circulating electrons





profiles (q,Ti,Te) create (flat) minimum in GAM damping rate

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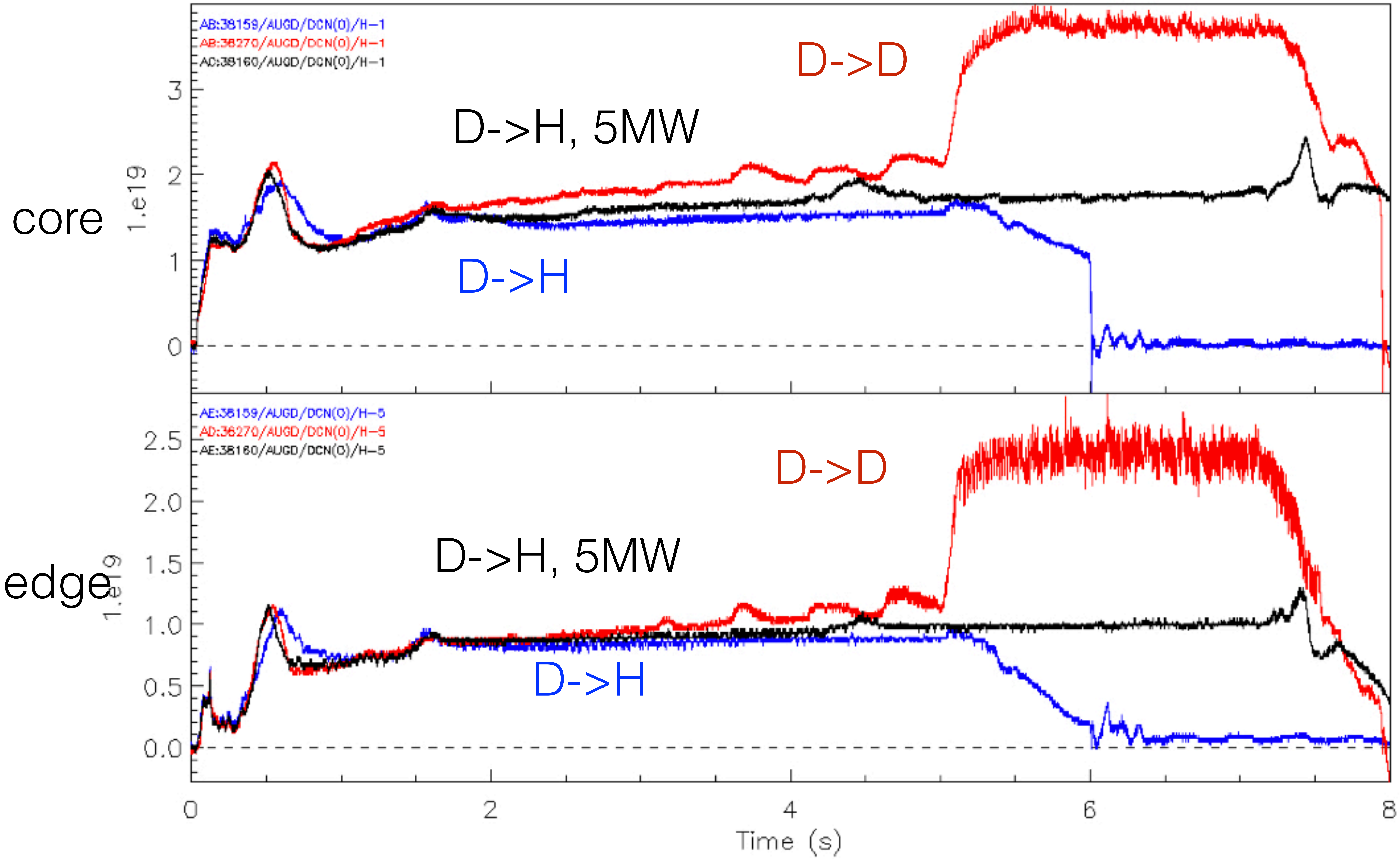
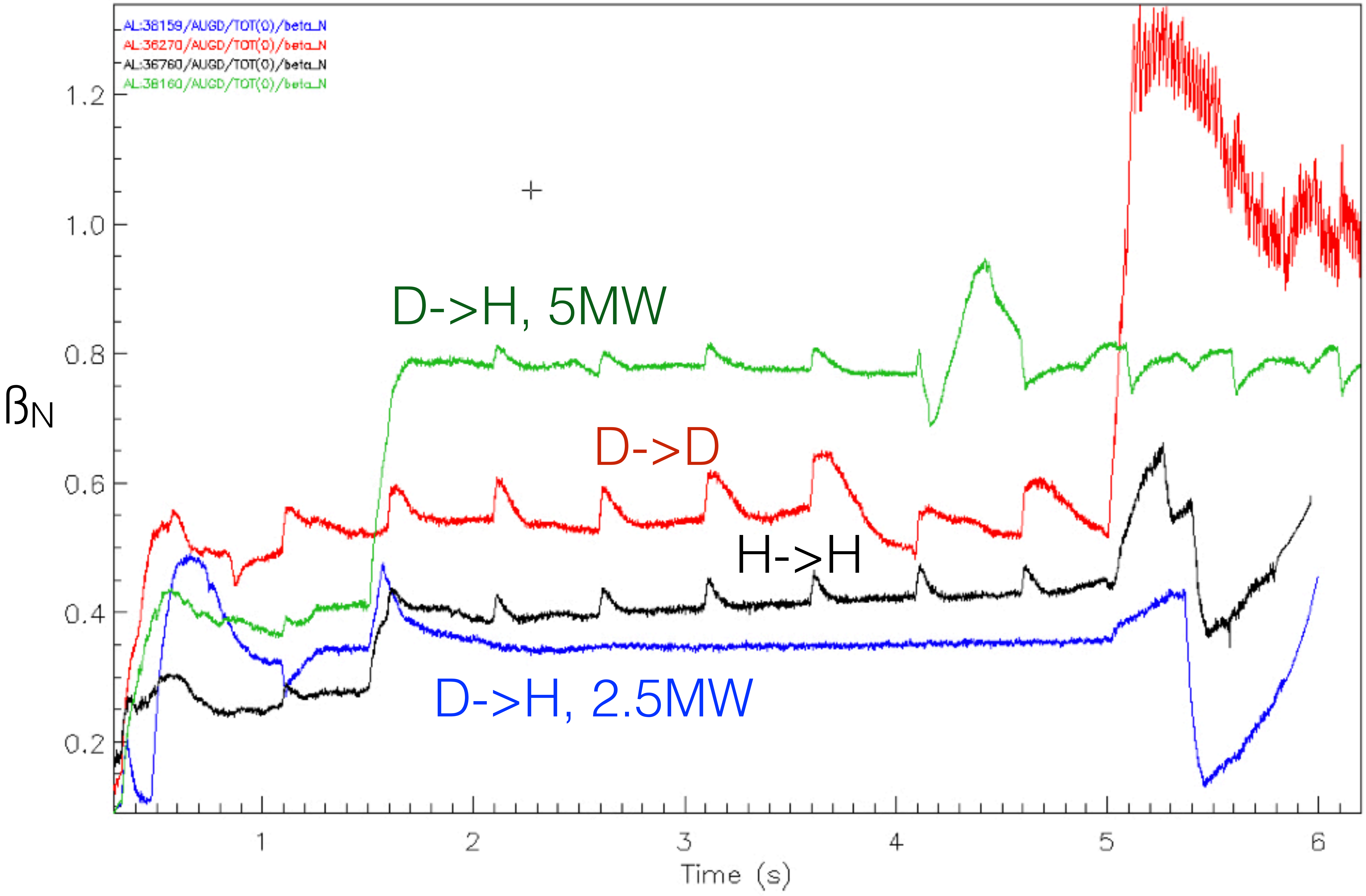
D->H stays in L mode even with 2 beams:



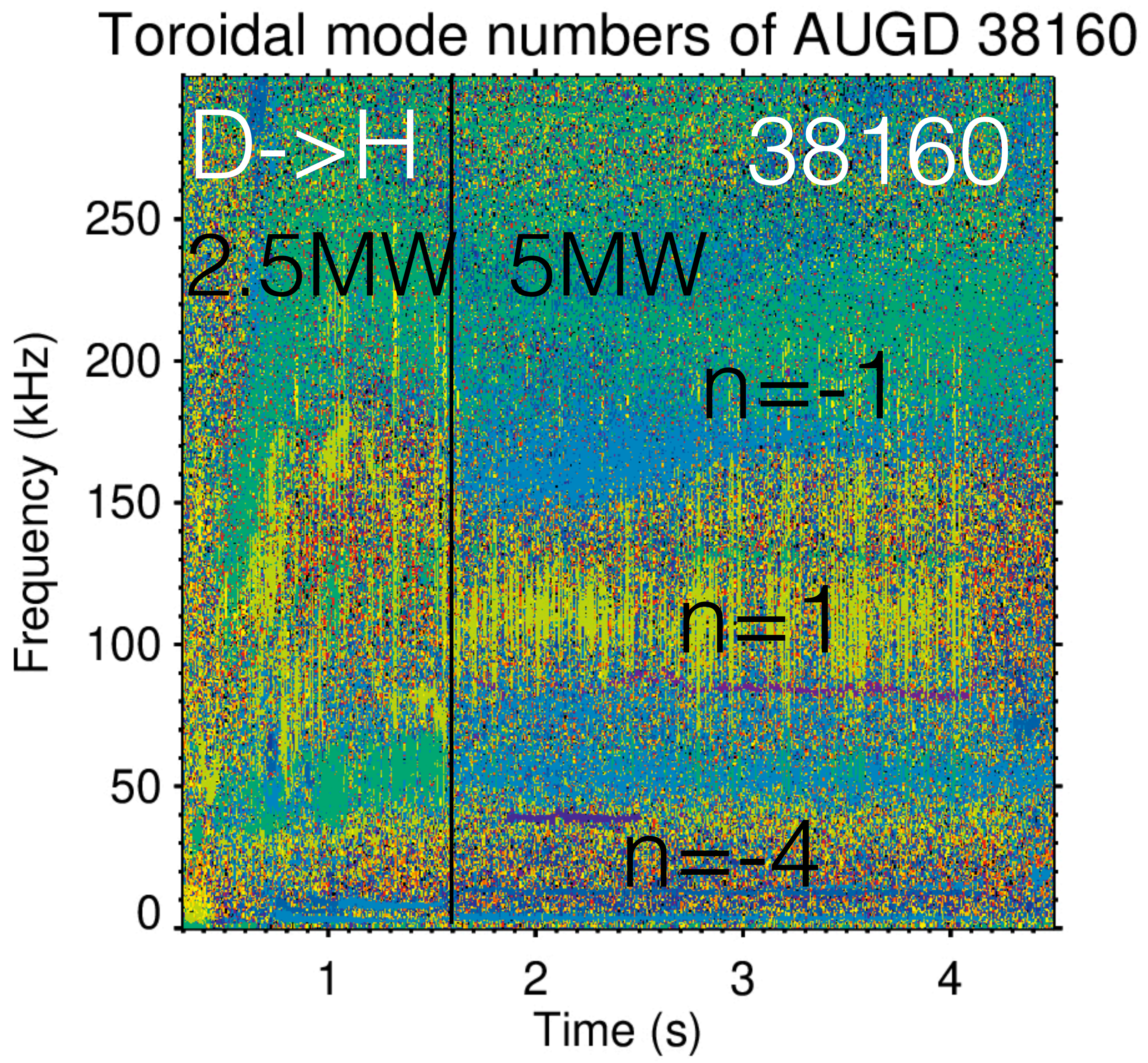
perfect density control in D->H with 2.5 and 5MW

this concludes data set on different betaN:



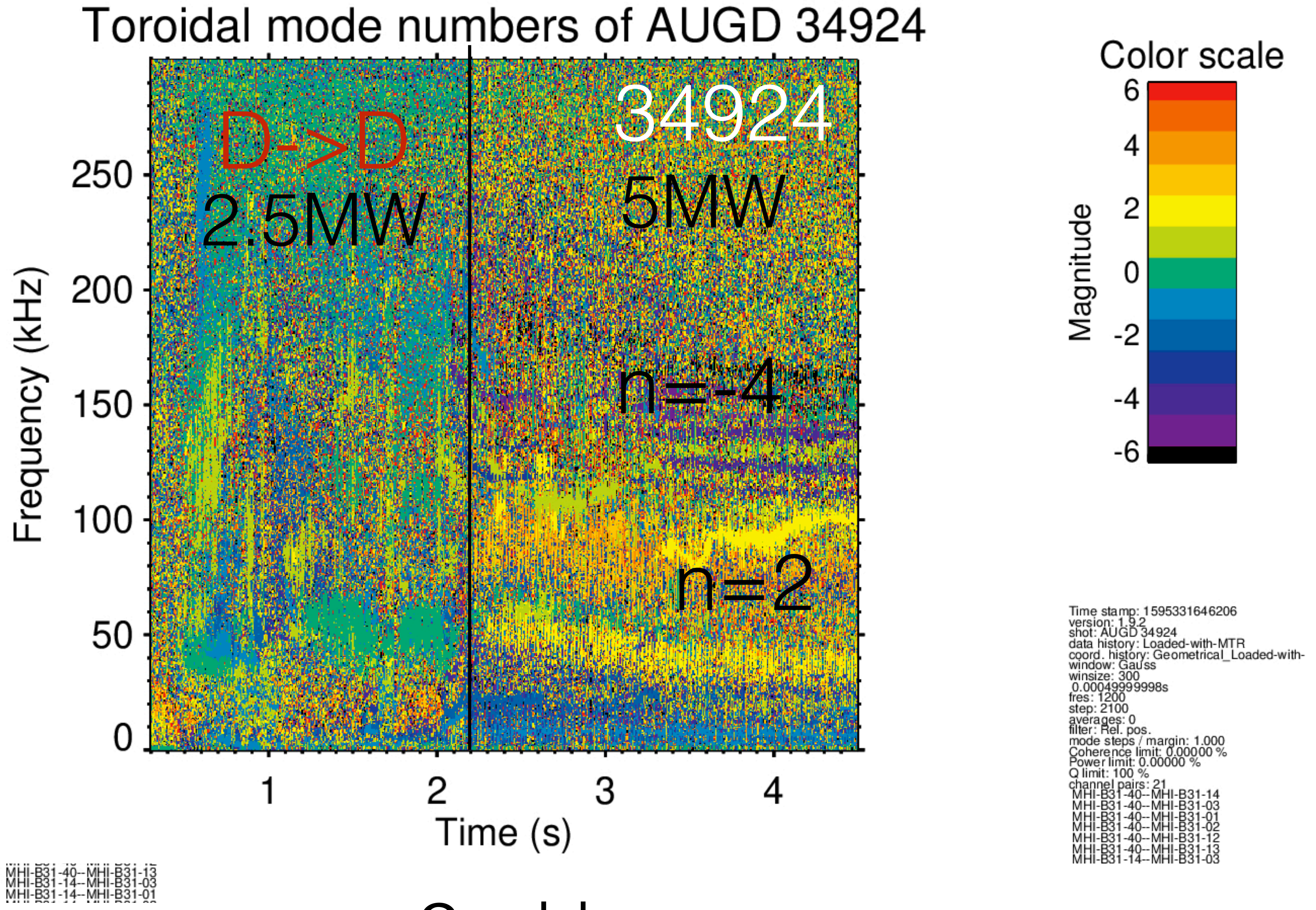
mode spectrum comparison (III)

L-mode L-mode



2nd beam

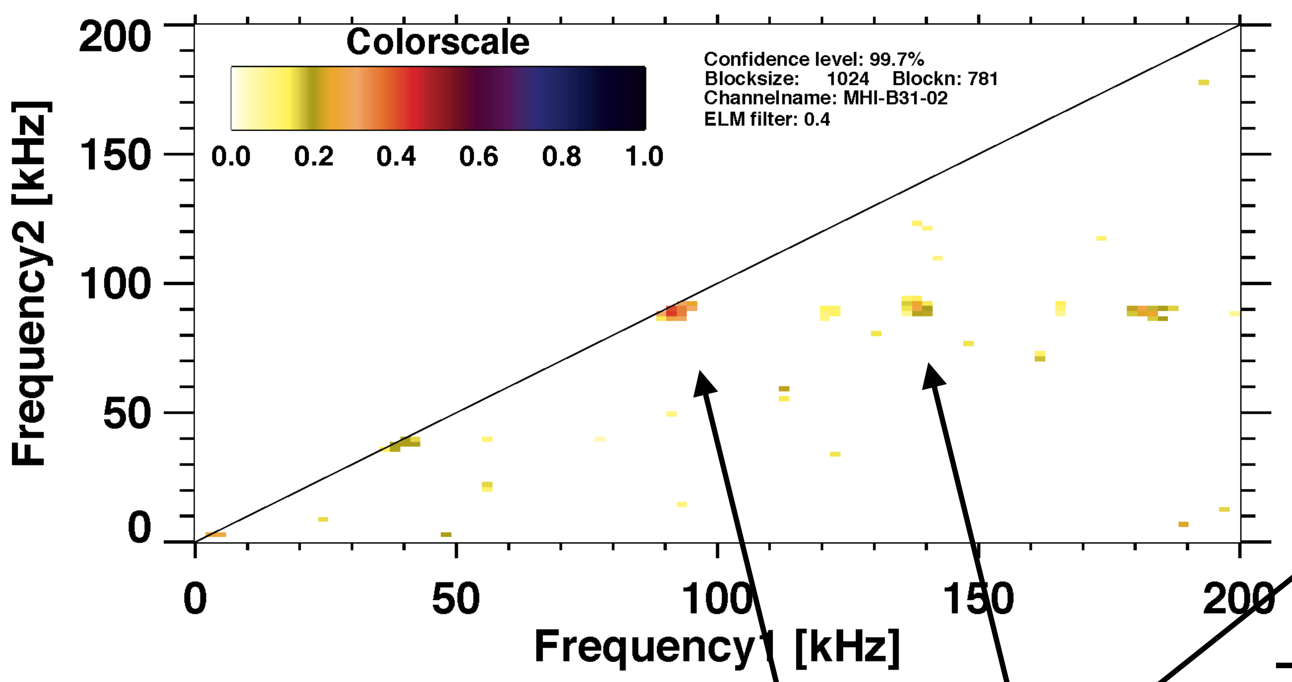
L-mode H-mode



2nd beam

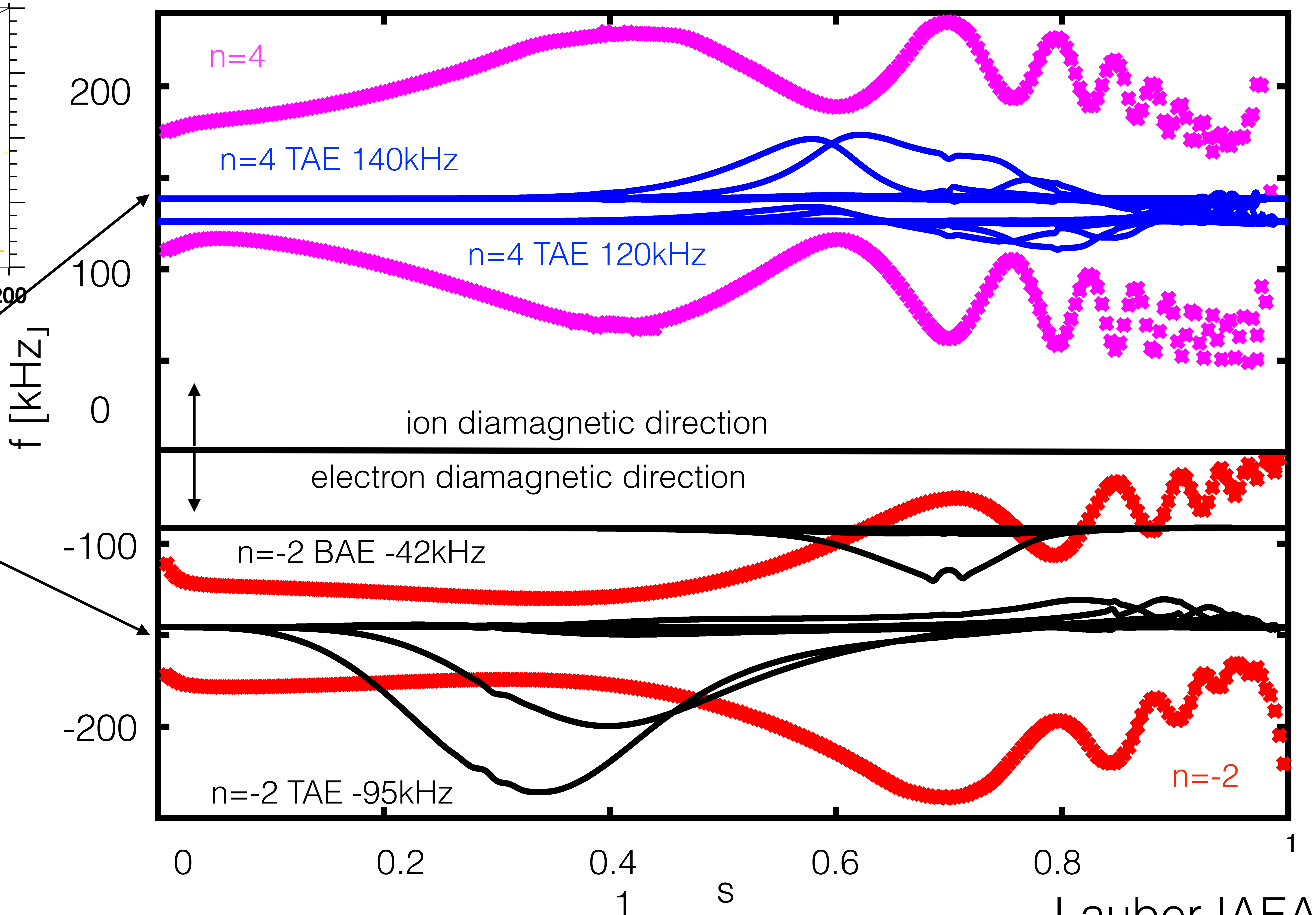
different SAW spectra and gap alignments
also non-linear behaviour/chirping strongly modified

reminder: unstable modes, 3 wave coupling analysis



exp. bicoherence analysis

TAE_{-2} TAE_{+4}



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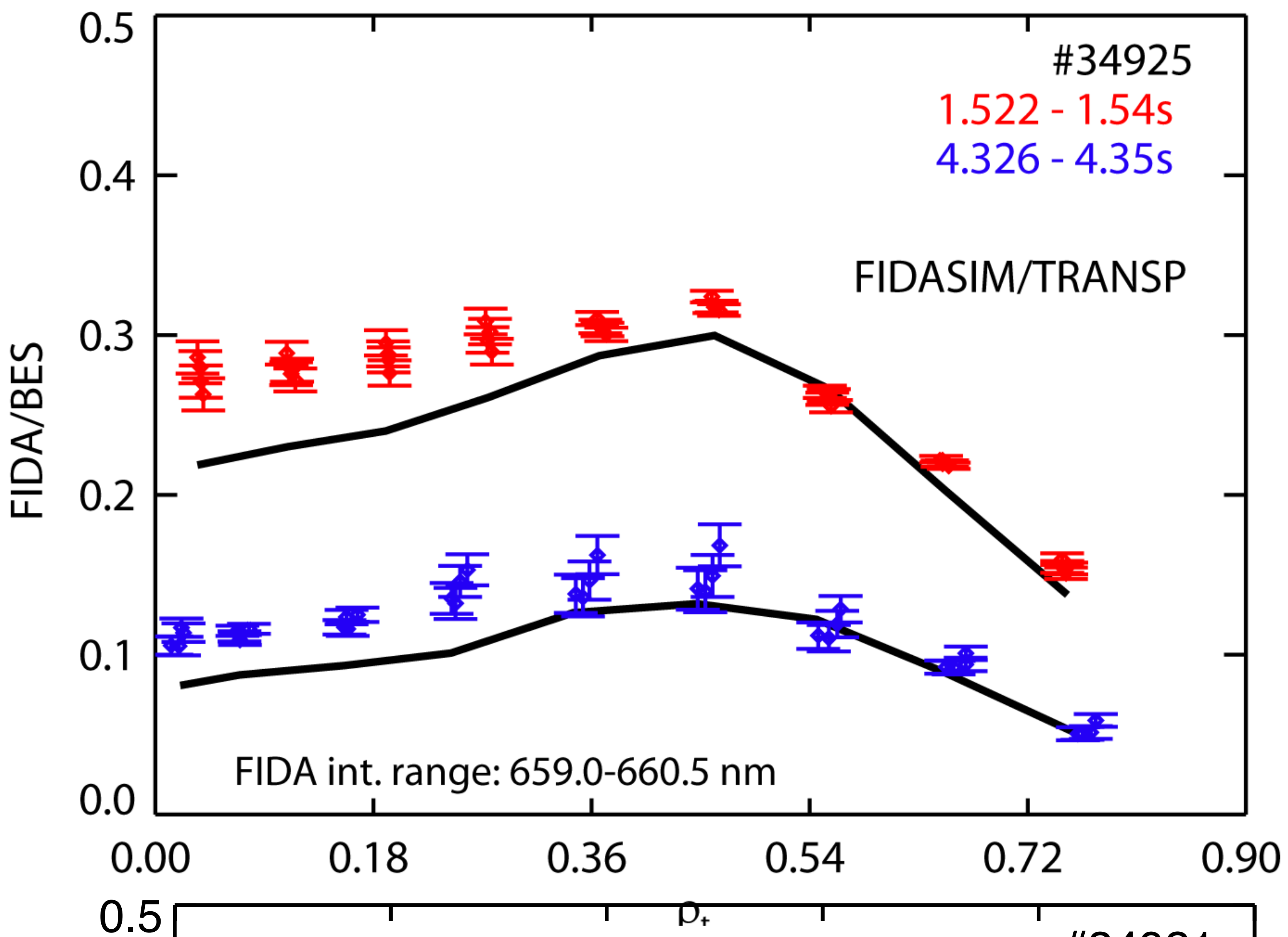
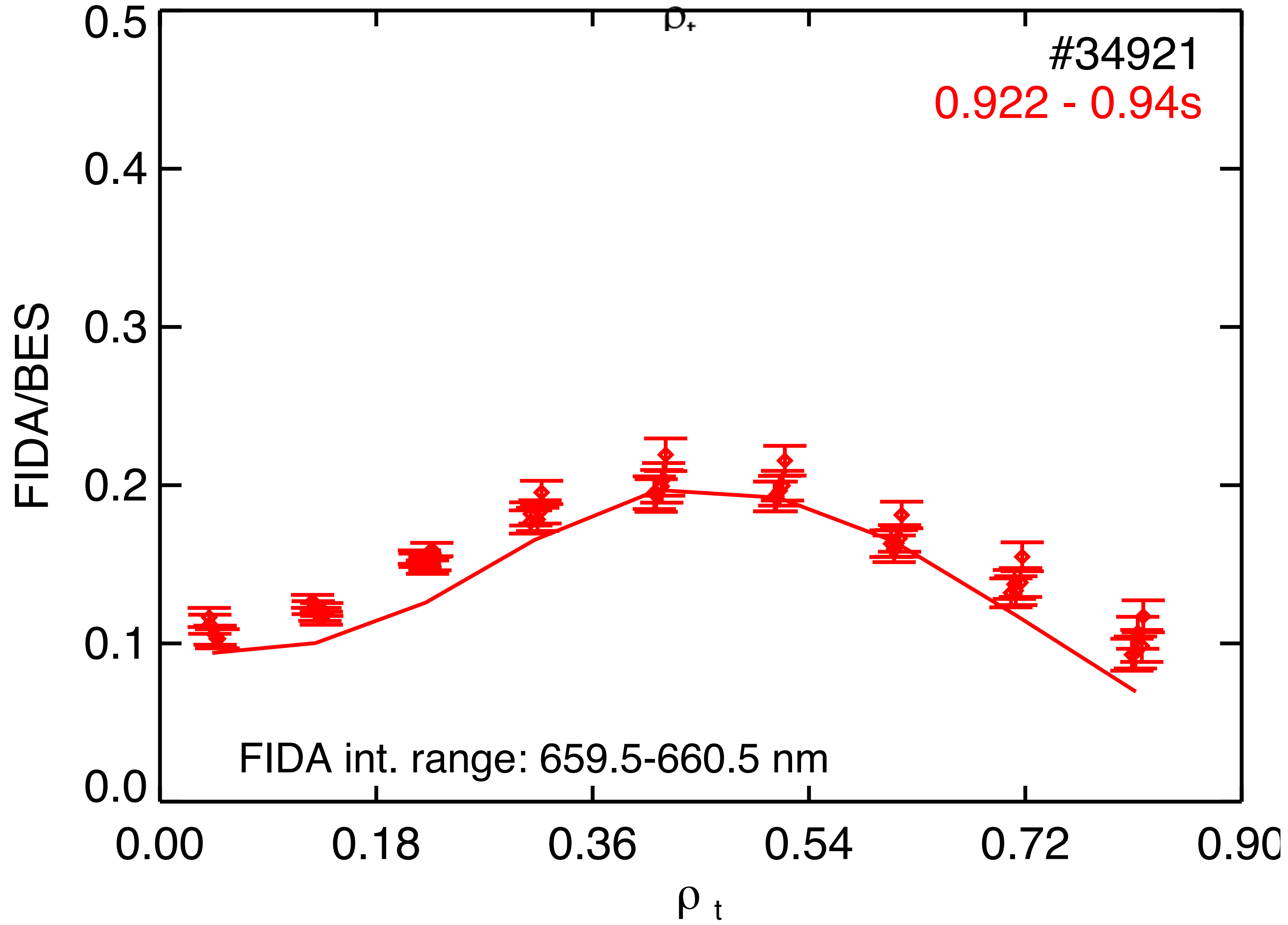
- after subtracting/adding rotation (7kHz): $\omega_{TAE-2}-\omega_{TAE+4}=0$
- also: $k_{\parallel TAE-2}+k_{\parallel TAE+4}= 1/(2\ q_{TAE-2}\ R)-1/(2\ q_{TAE+4}\ R)=0.222-0.211\approx 0$
- fulfil matching conditions with zero frequency zonal structure: modified parametric decay constellation

radial flattening of EP gradient observed - inwards transport

TAE and BAE redistribute particles radially: FIDA measurements in comparison to neoclassical TRANSP/NUBEAM calculations

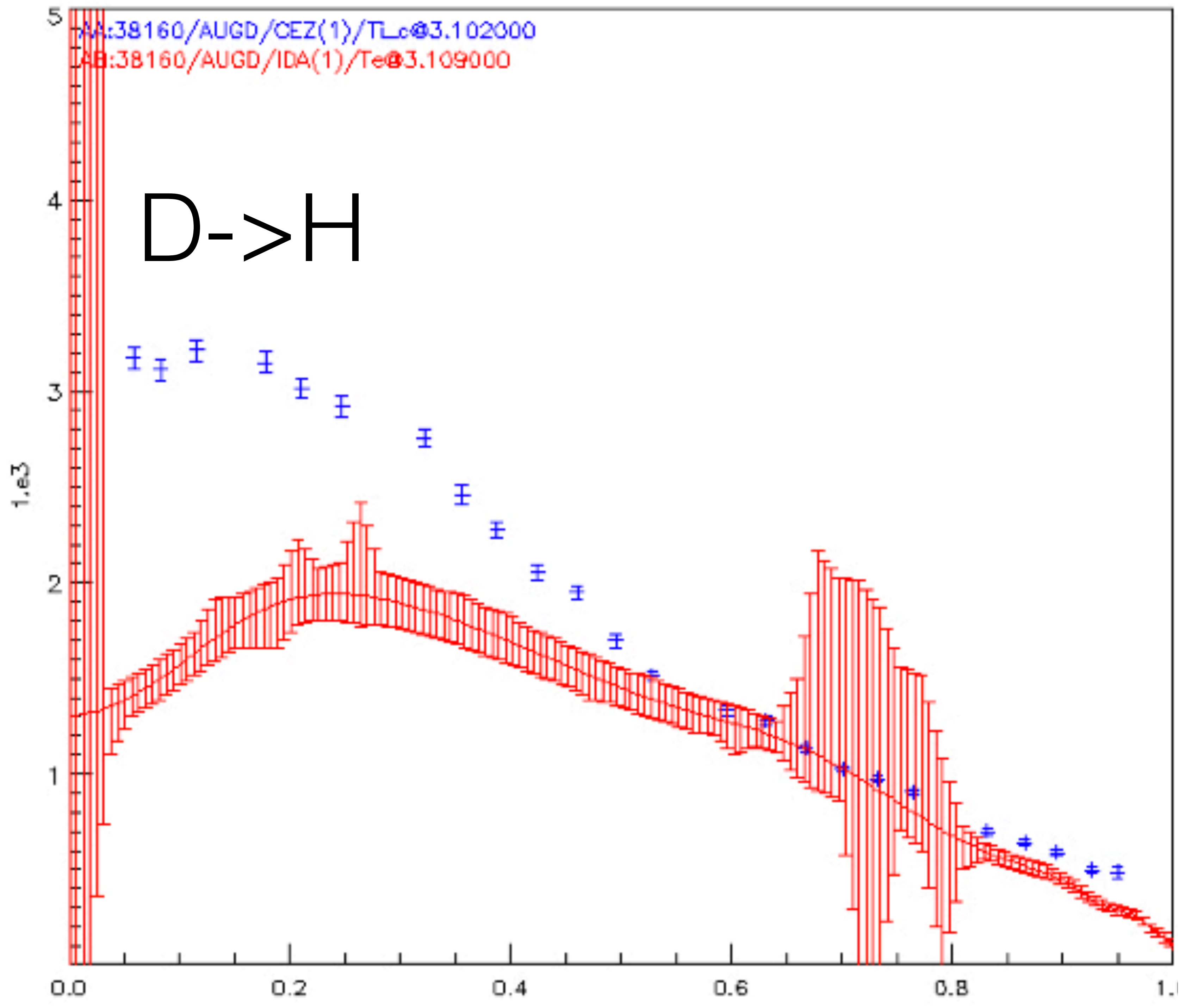


control case, where no strong Alfvénic mode activity is observed (#34921): strongly inverted EP gradient, small EP transport



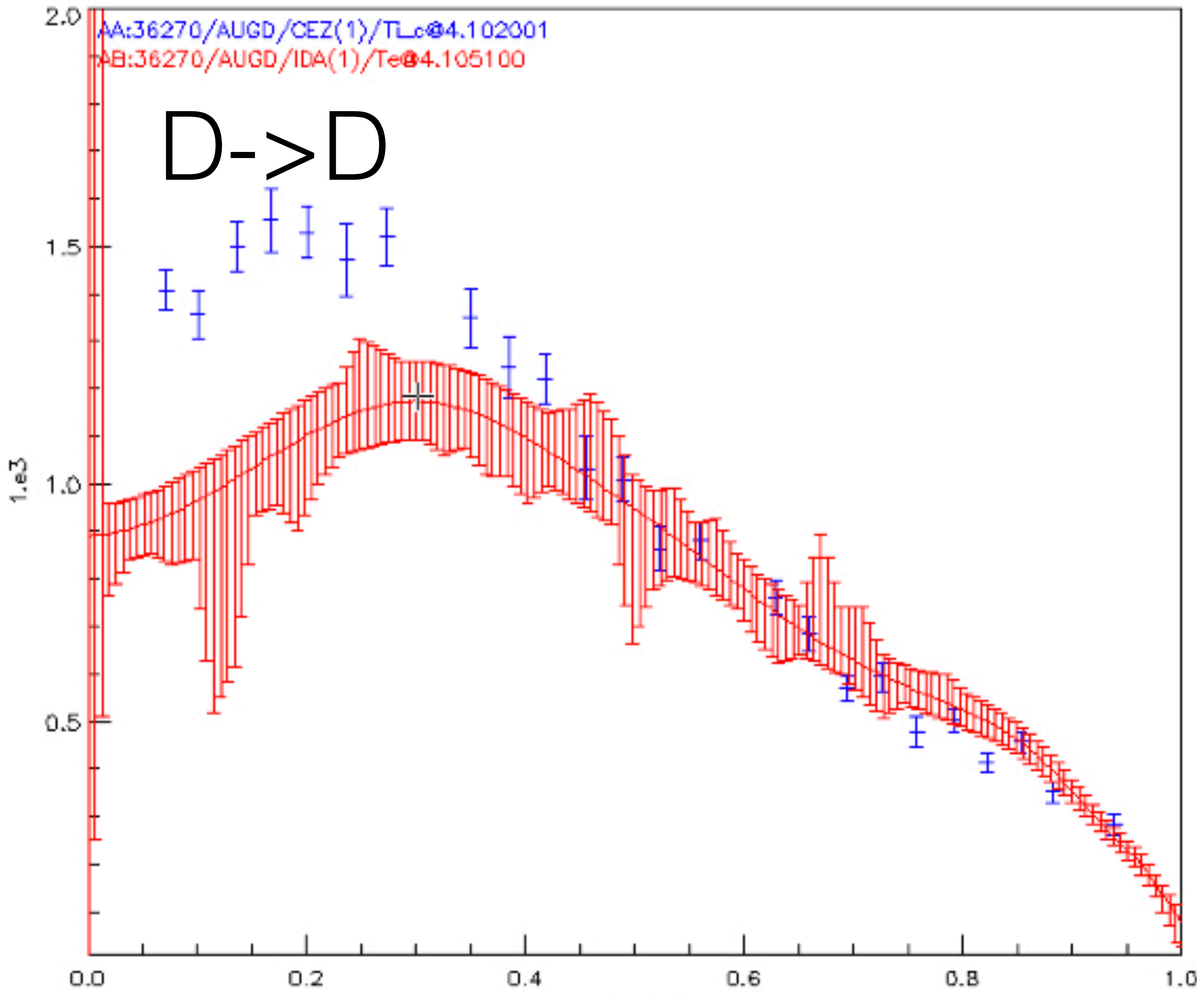
background ion temperature profiles show high Ti in core (when many modes are present)

Te,i [keV]



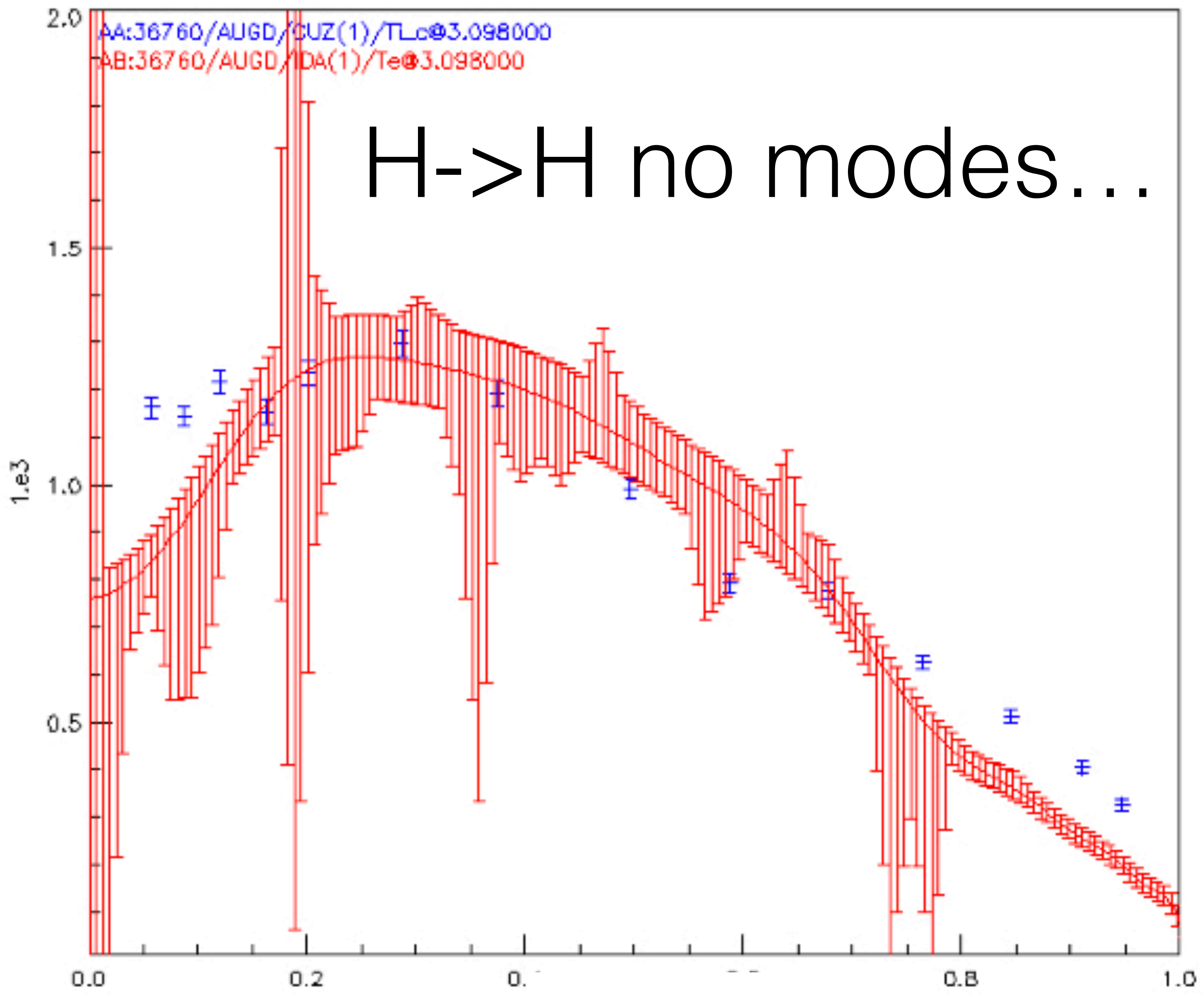
ρpol

Te,i [keV]



ρpol

Te,i [keV]

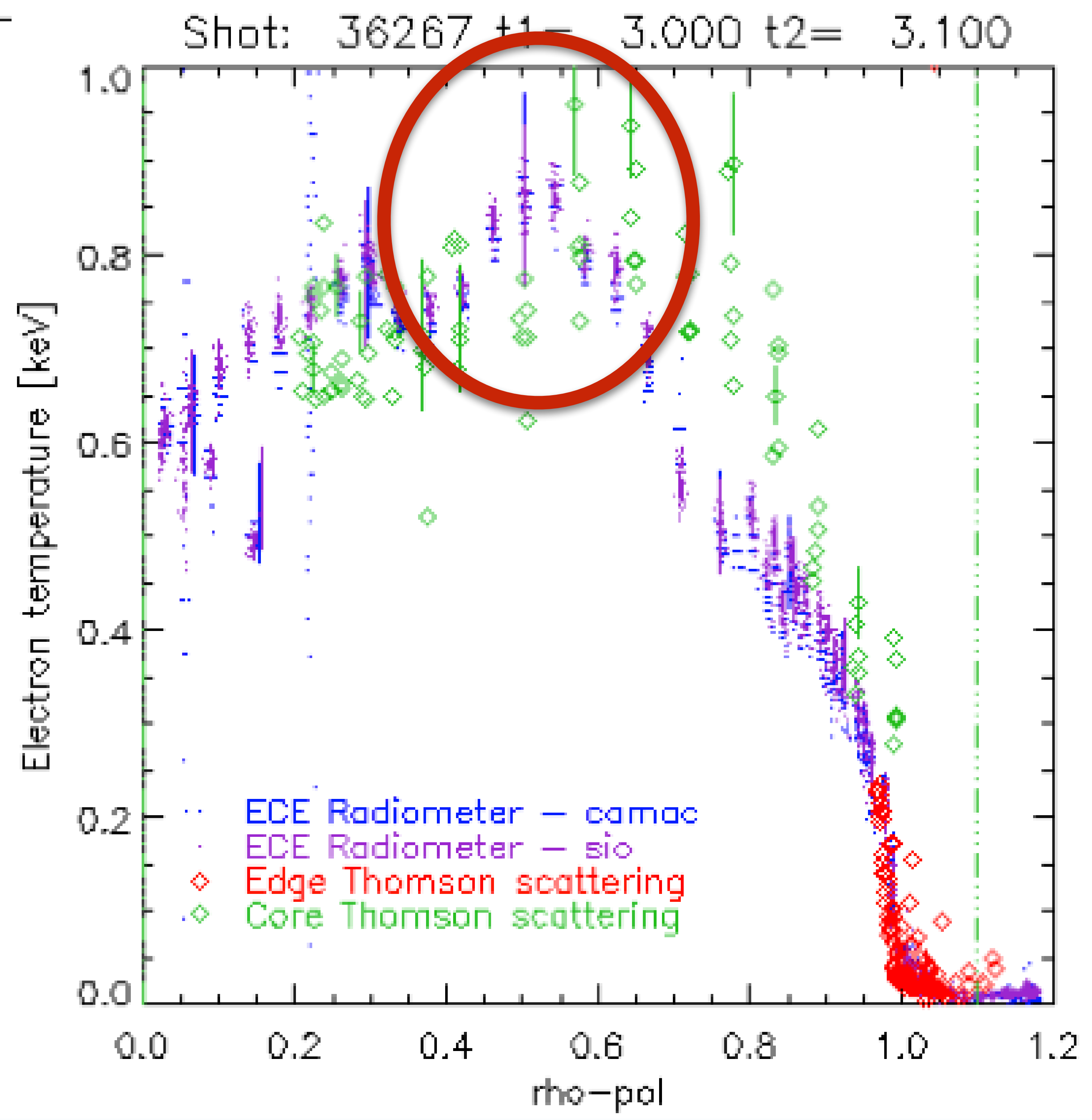


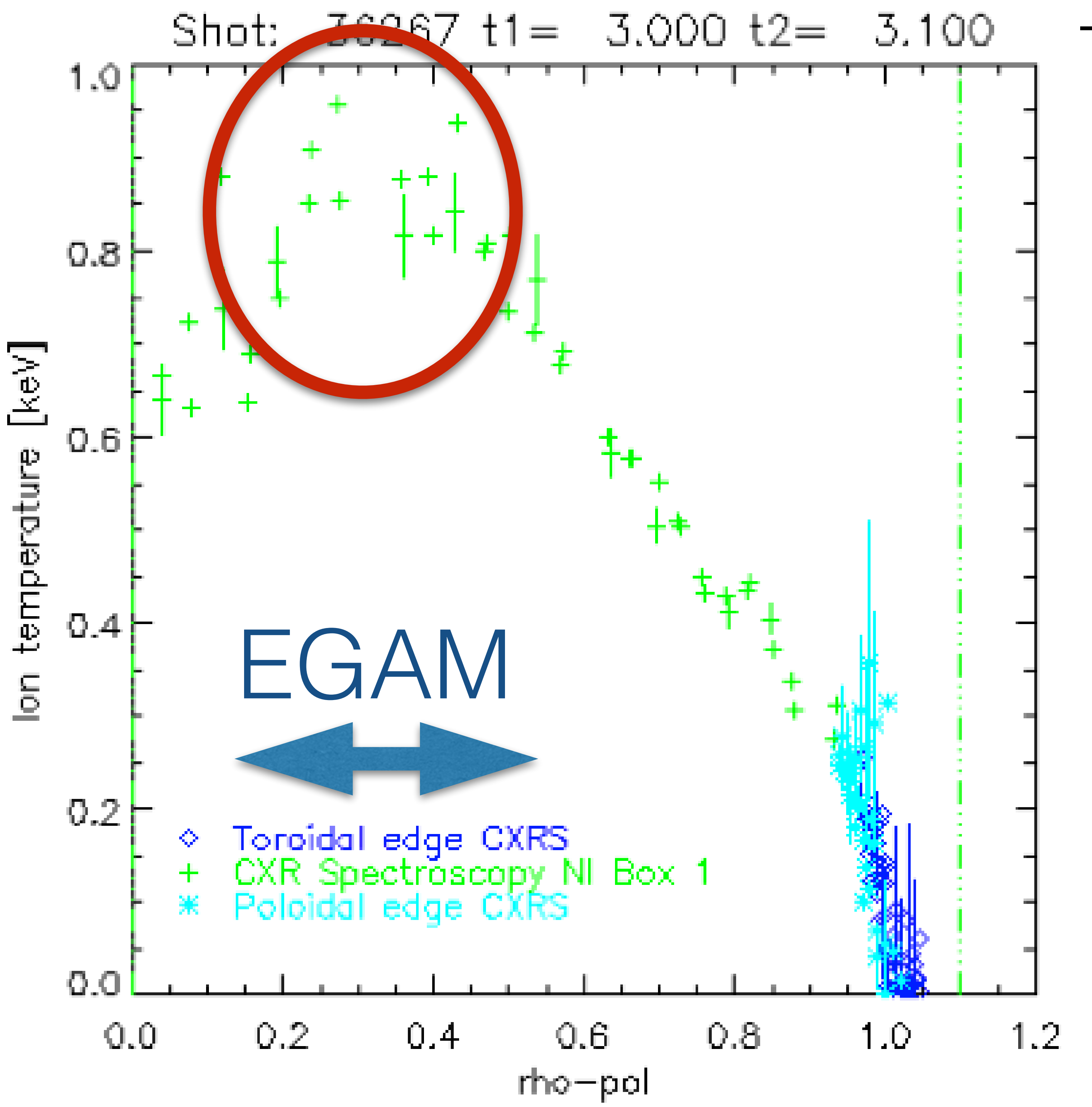
ρpol

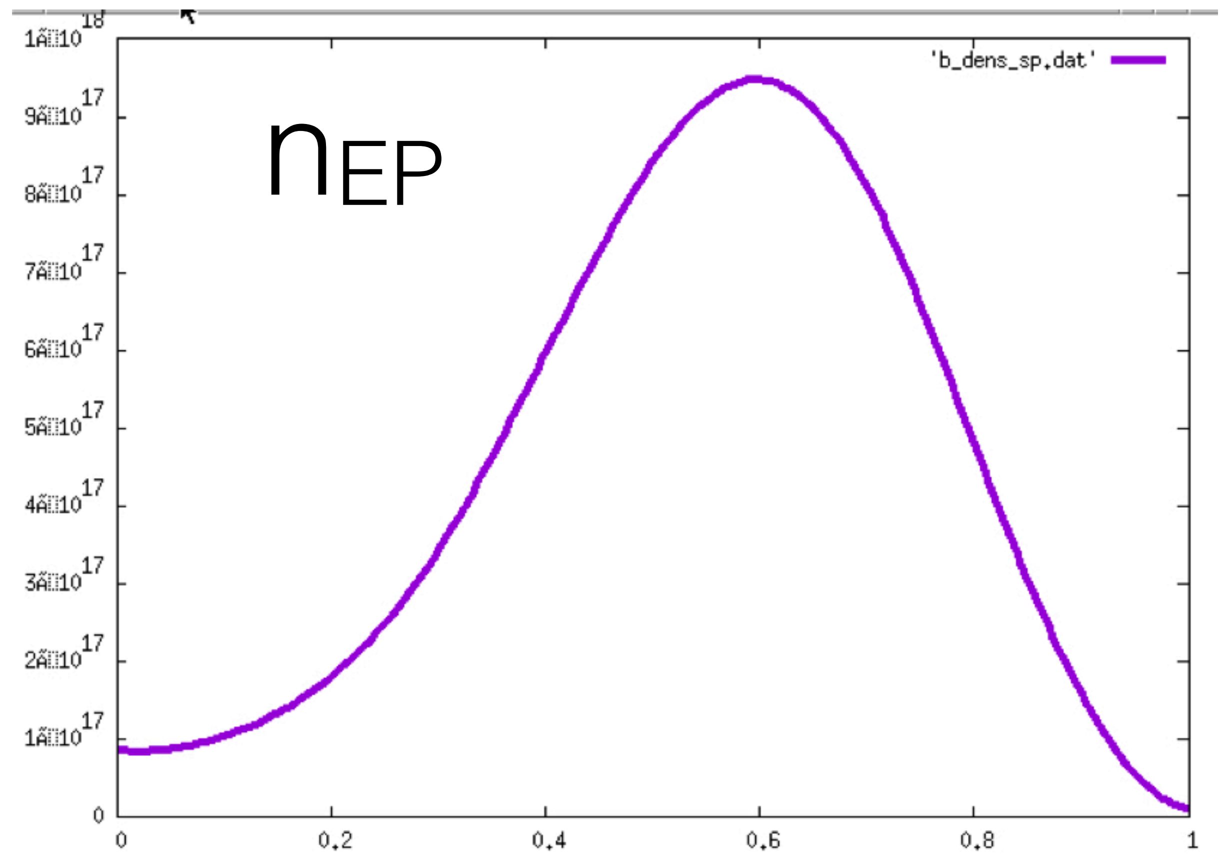
IPP EUROfusion ASDEX Upgrade

also in H-mode

#36267@3s

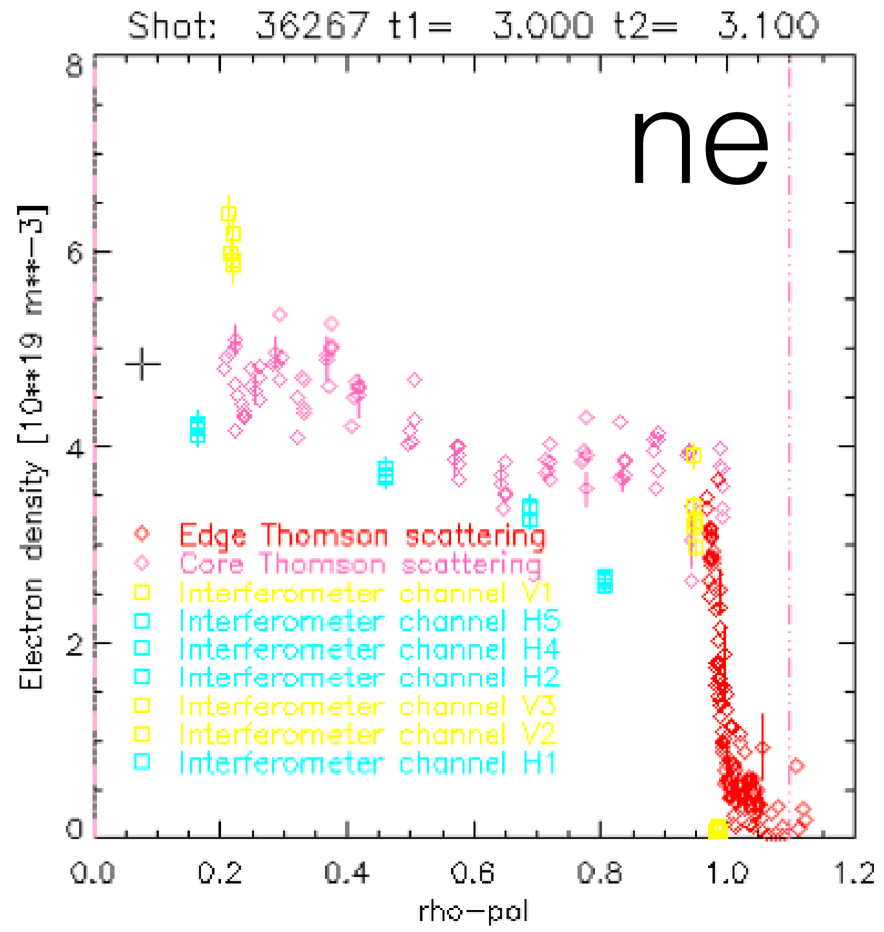






Te,Ti maxima radially shifted

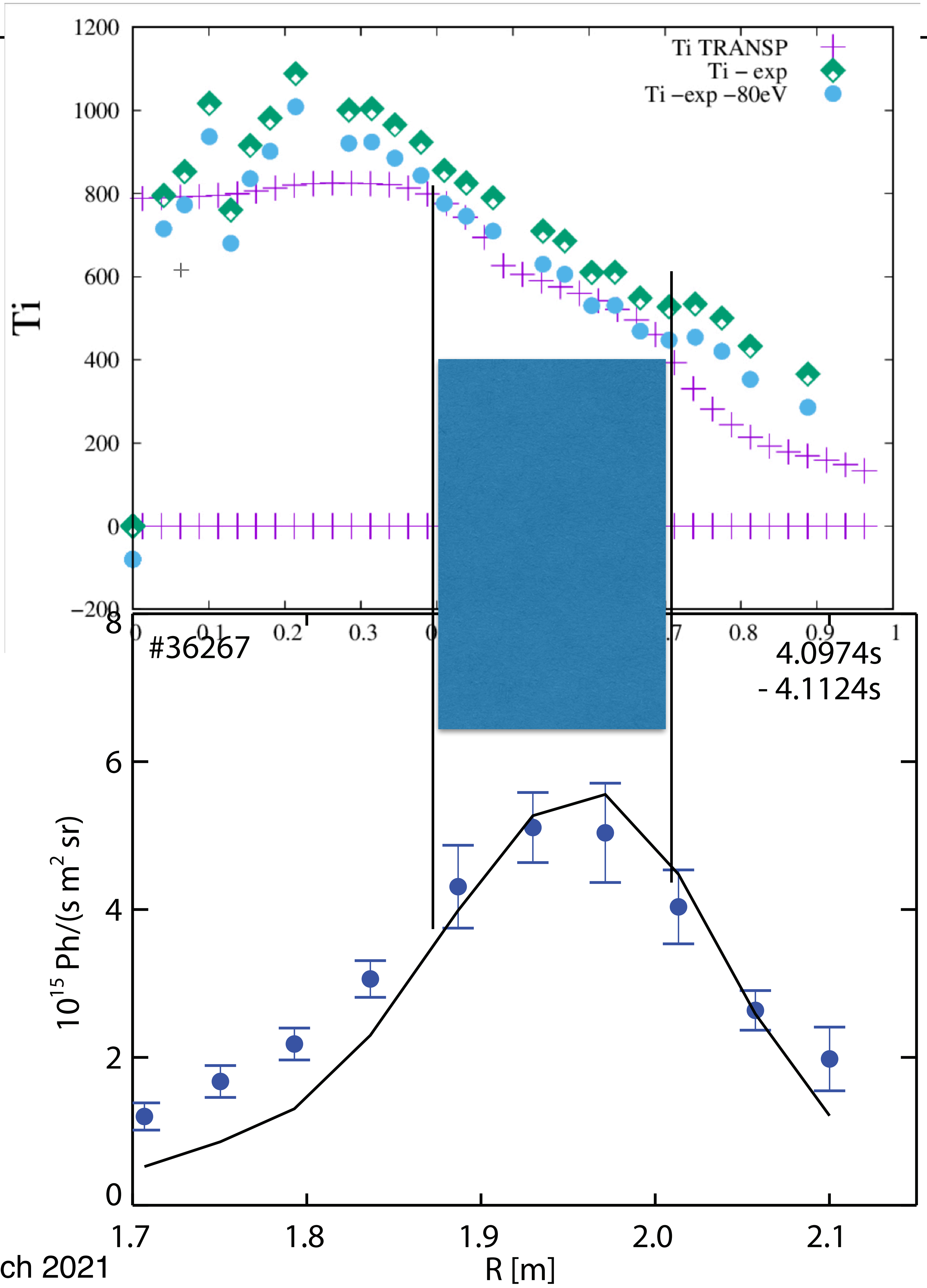
E_{beam}/T_i~120-150! (~3.5MeV/25keV)



EP transport, background ion heating?

TRANSP modelling (with B. Geiger):

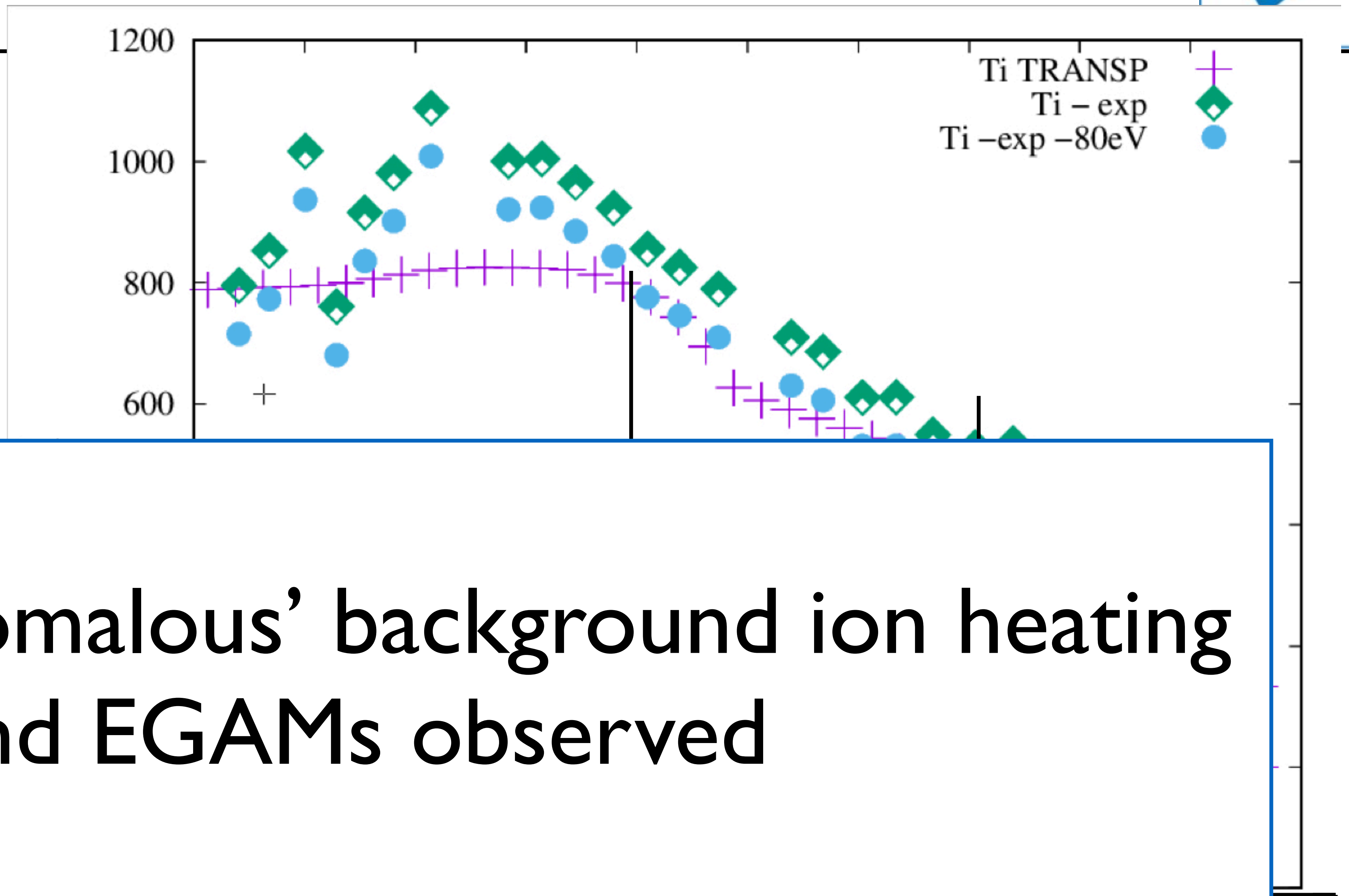
- run in semi-interpretative mode: use profiles, in particular ne, Te, q from exp. measurements
- use gyro-bohm model for chi(ions)
- use Nubeam neoclassical model for calculating EP deposition
- compare T_i and n_{EP} with actually measured profiles to detect 'anomalous' effects
- in shaded region between 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?

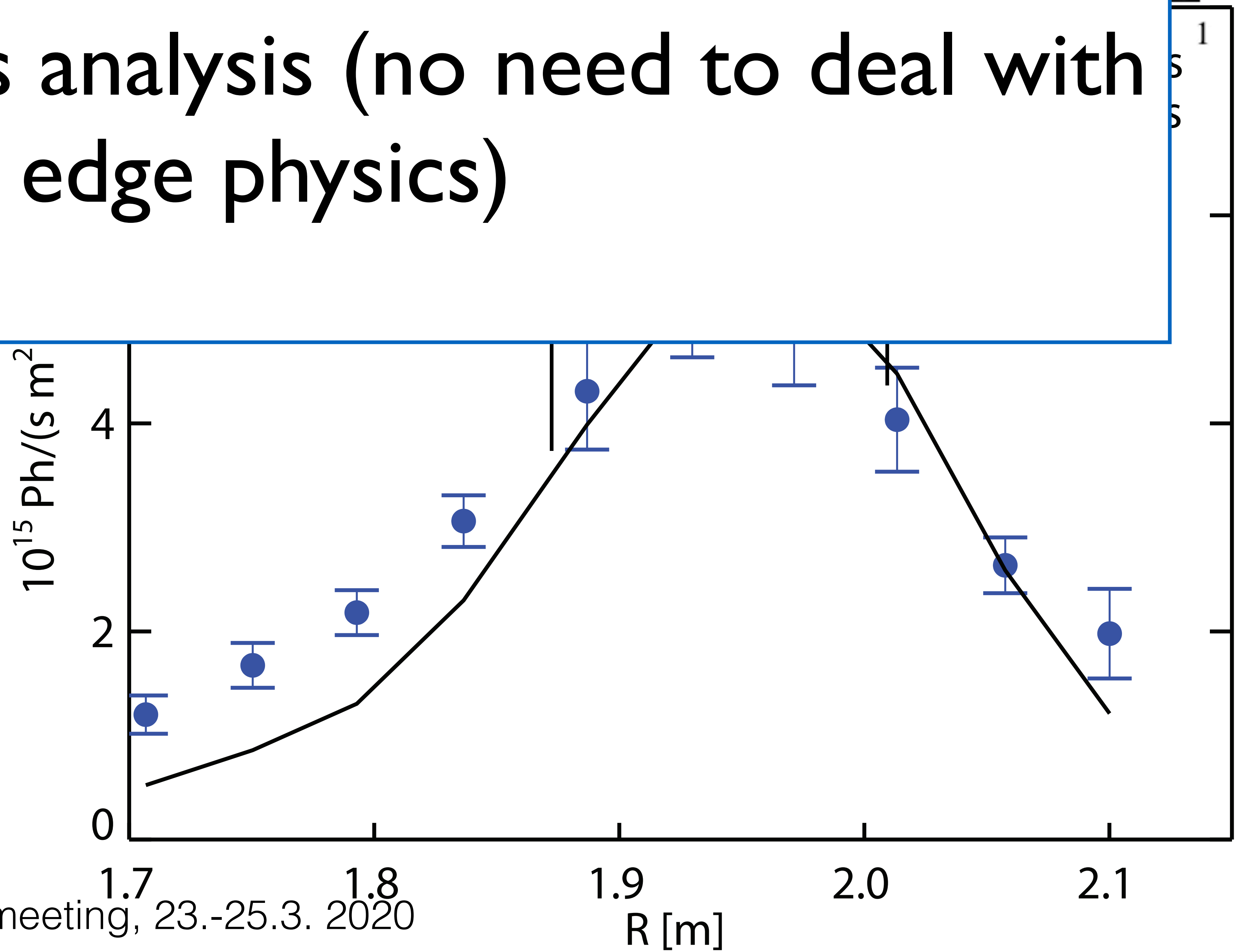
TRANSPORT modelling (with B. Geiger):

- run in semi-interpretative mode: use profiles, in particular ne, Te, q from exp. measu
- use gy
- use Nu calcula
- compa measu effects
- in shac model
- in core s<0.4 and edge s>0.7 Ti 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

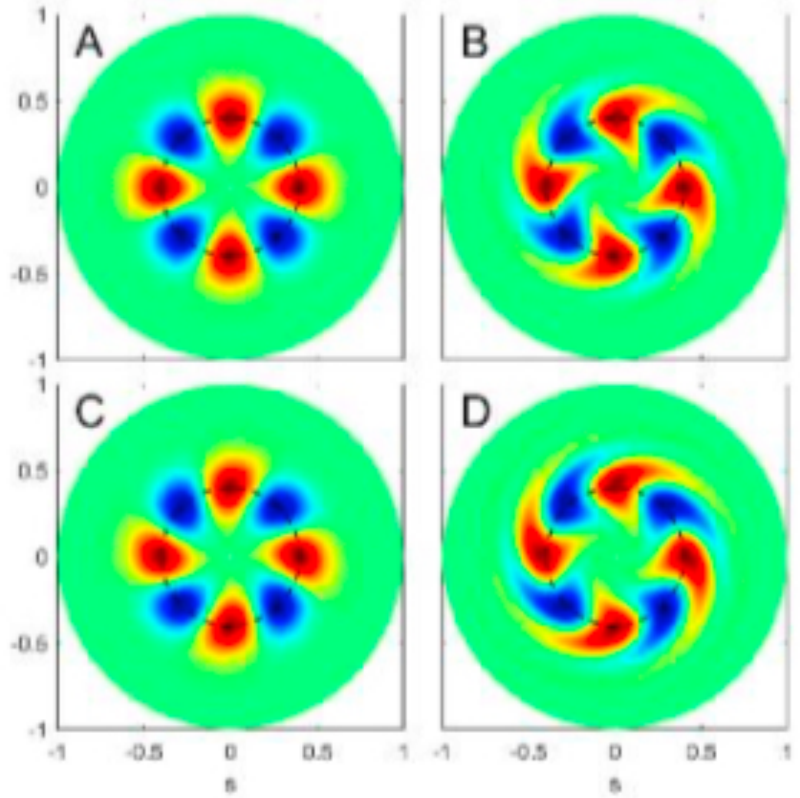


possible signature of 'anomalous' background ion heating due to AEs and EGAMs observed

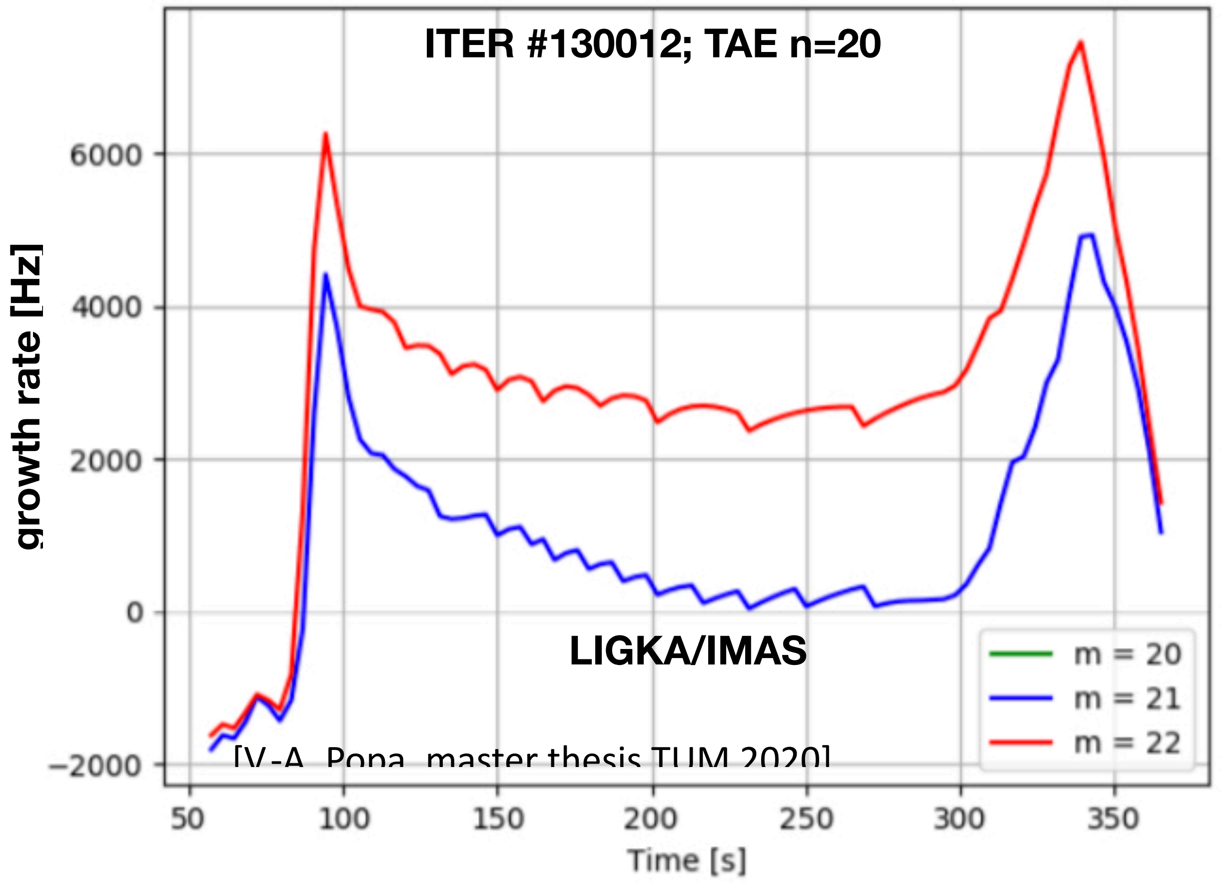
inwards transport simplifies analysis (no need to deal with losses and edge physics)



summary & conclusions

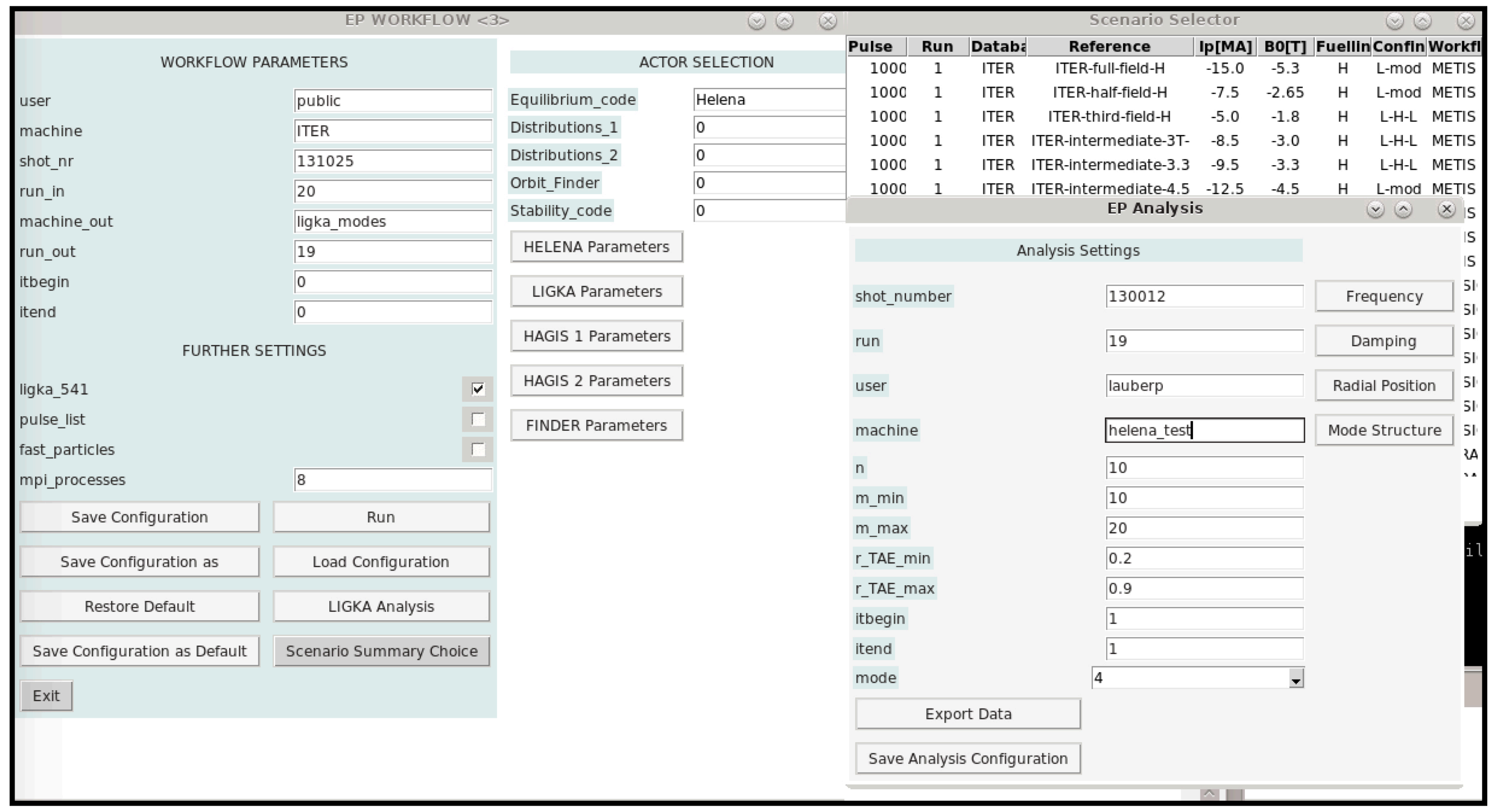


- unique set of data for code validation: EGAMs, BAEs,RSAEs,TAE
- linear, non-linear features, mode-mode interactions and EP transport measured
- NBI distribution is most interesting - and most influential - ingredient
- EP redistribution influences background profiles

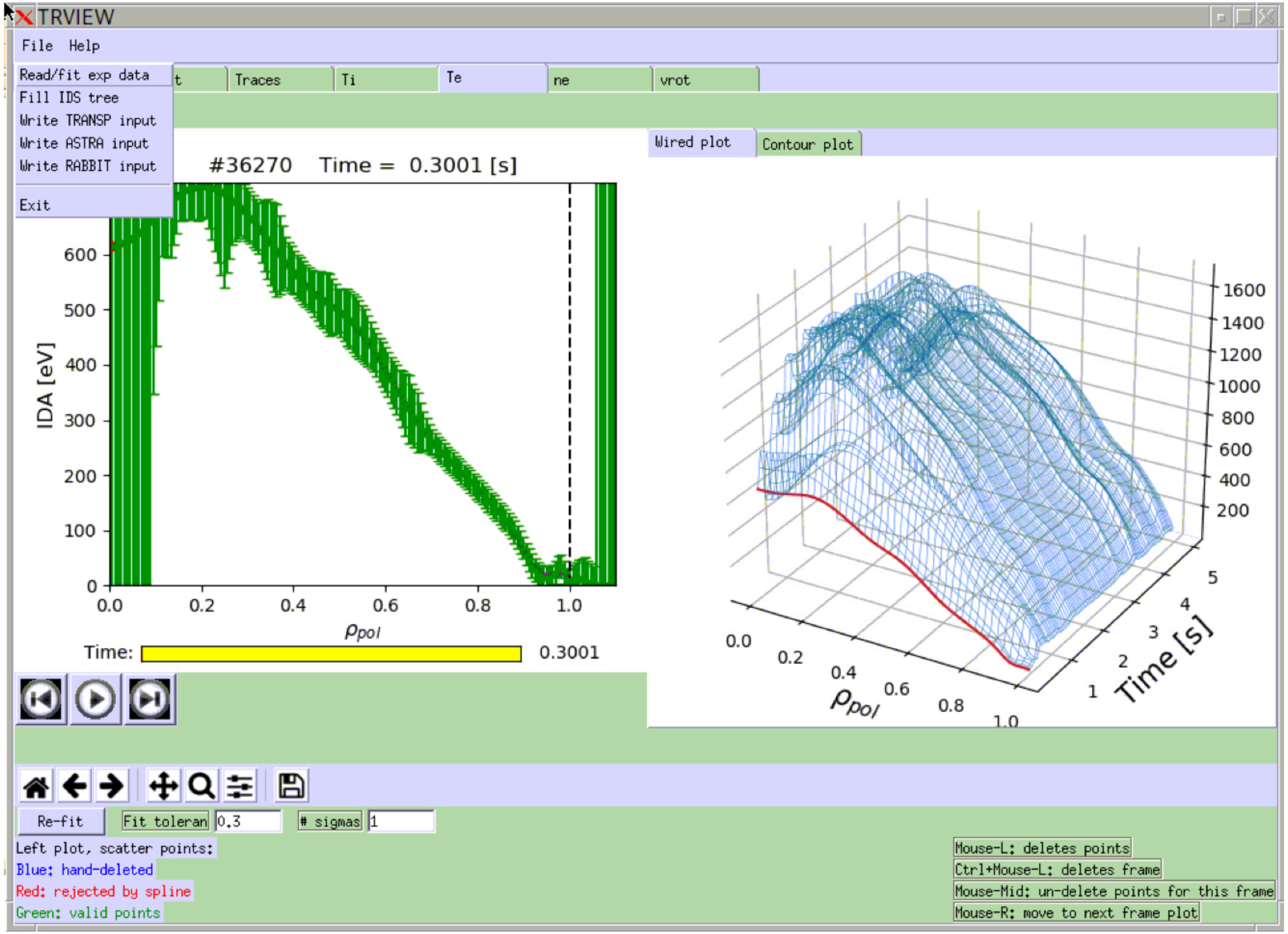


- current redistribution not yet investigated…
- mode symmetry breaking measurements will be attempted again (G. Meng)

- LIGKA/HAGIS package is ready for automated scan (ITER, thx V.A. Popa) - AUG functionality should be available soon (thanks to great work of G Tardini, M. Weiland!):
- run reduced automated analysis for many time slices to find linear stability thresholds, select best cases for expensive codes
- interface LIGKA/ RABBIT started (building on ORB5 tool by T. Hayward-Schneider, B. Rettino) - try ITER H&CD package on AUG?
- implement reduced EP transport models - building blocks are ready!



https://confluence.iter.org/pages/viewpage.action?pageId=289069024



[G. Tardini,M Weiland]