EUROfusion

On the development of advanced energetic particle transport models

3rd Trilateral International Workshop on EP physics, 10.11.2022

Ph. Lauber, V.-A. Popa, T. Hayward-Schneider, G. Meng, M.-V. Falessi

**acknowledgements: ATEP ENR team,
F. Zonca, S.D. Pinches, M. Schneider, O. Hoenen**

ENR ATEP: https://wiki.euro-fusion.org/wiki/Project_No10

https://indico.euro-fusion.org/category/309/

ASDEX Upgrade

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

ENEA ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

Center for Nonlinear Plasma Science CNPS Since 2020

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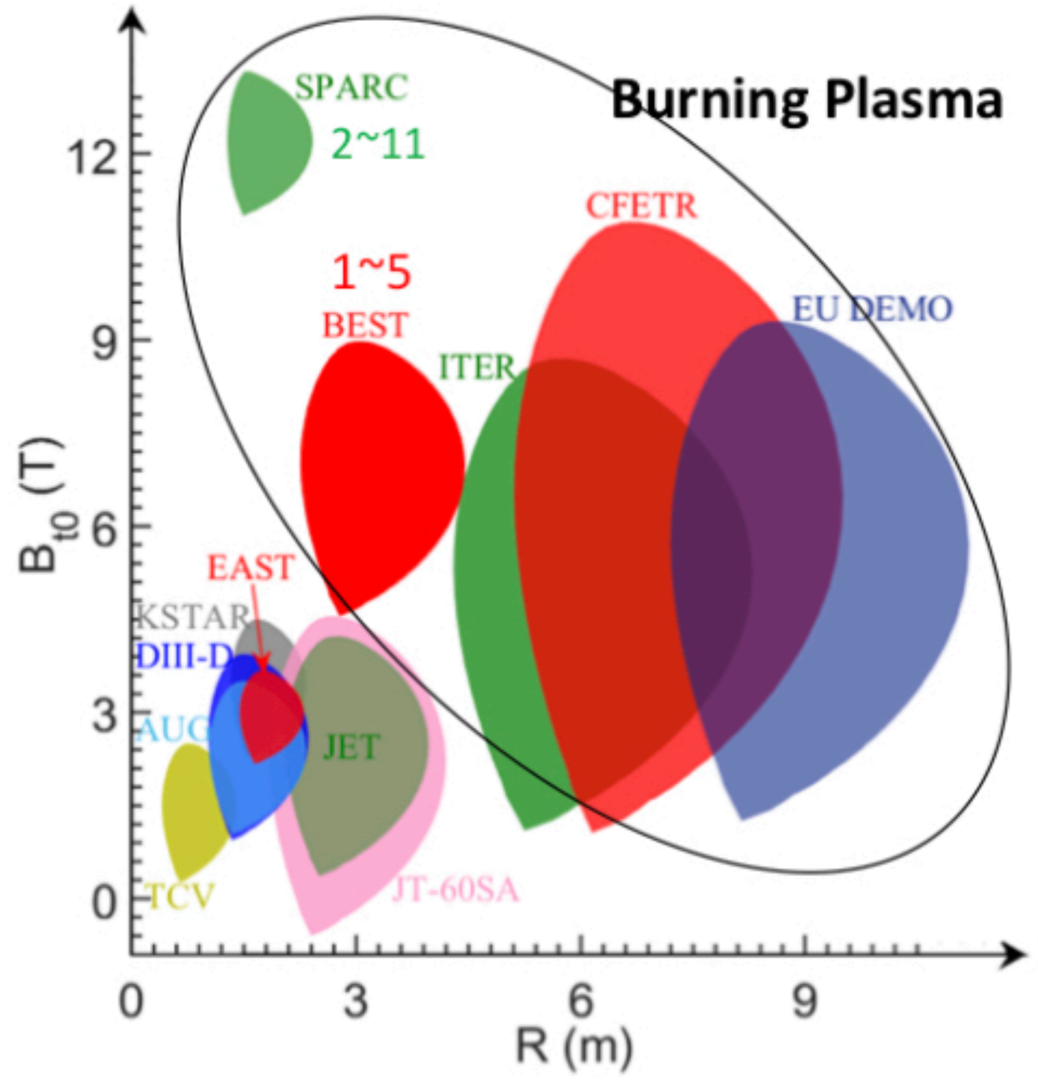
modelling hierarchy for plasmas with significant energetic particle pressure

[Baonian Wan, at this workshop]



for scaling from TCV-AUG-JET,… to JT-60SA-DTT-ITER-DEMO-any other other device, we need:

required model:

4. self-organisation - back reaction of EP transport on profiles and background transport — non-linear/quasi-linear global kinetic + background transport

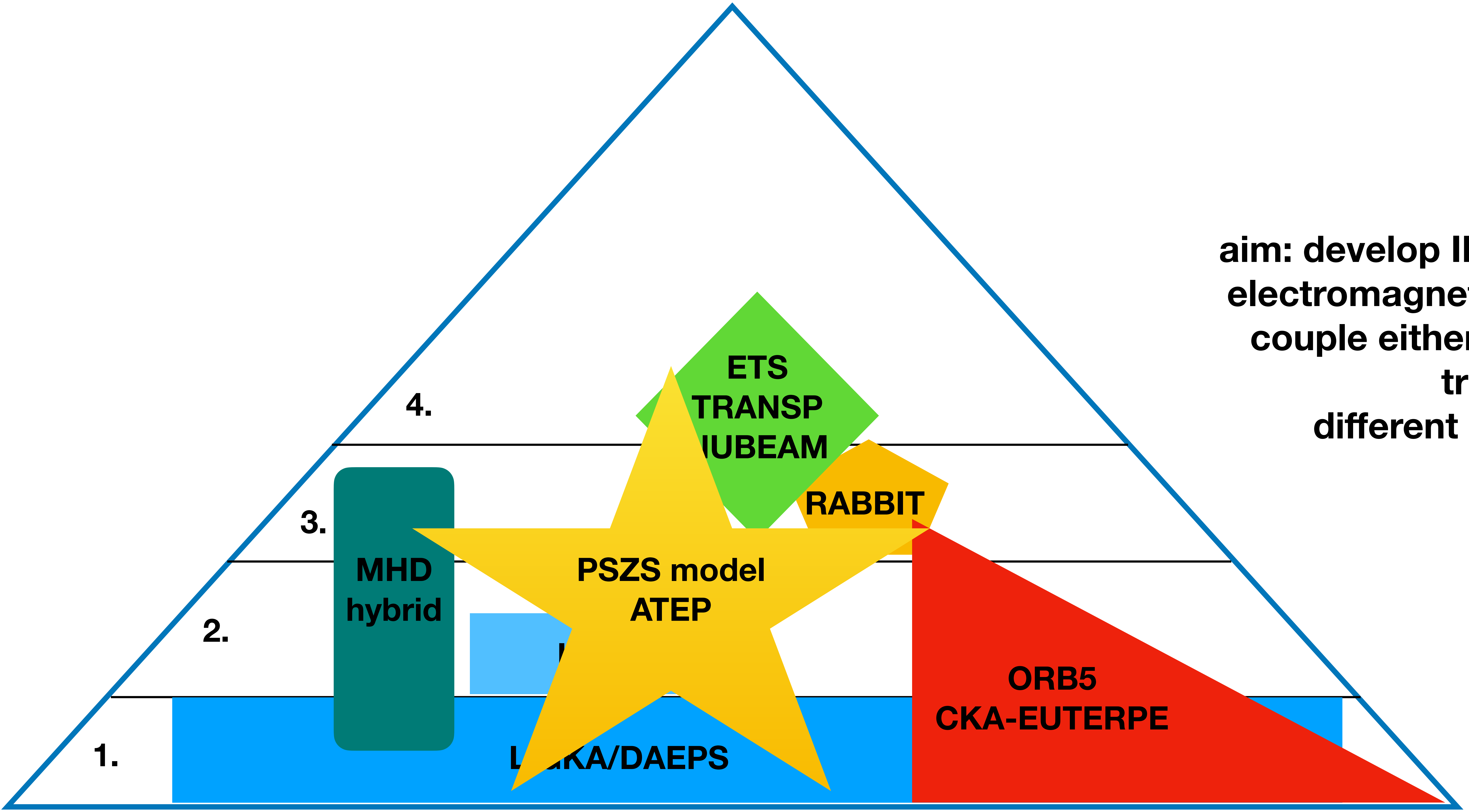
3. EP transport and losses — non-linear/quasi-linear global kinetic + long time scales (source + sink)

2. non-linear mode evolution, saturation mechanisms — non-linear global kinetic e.m.

1. mode stability — linear global kinetic e.m.

modelling hierarchy for plasmas with significant energetic particle pressure

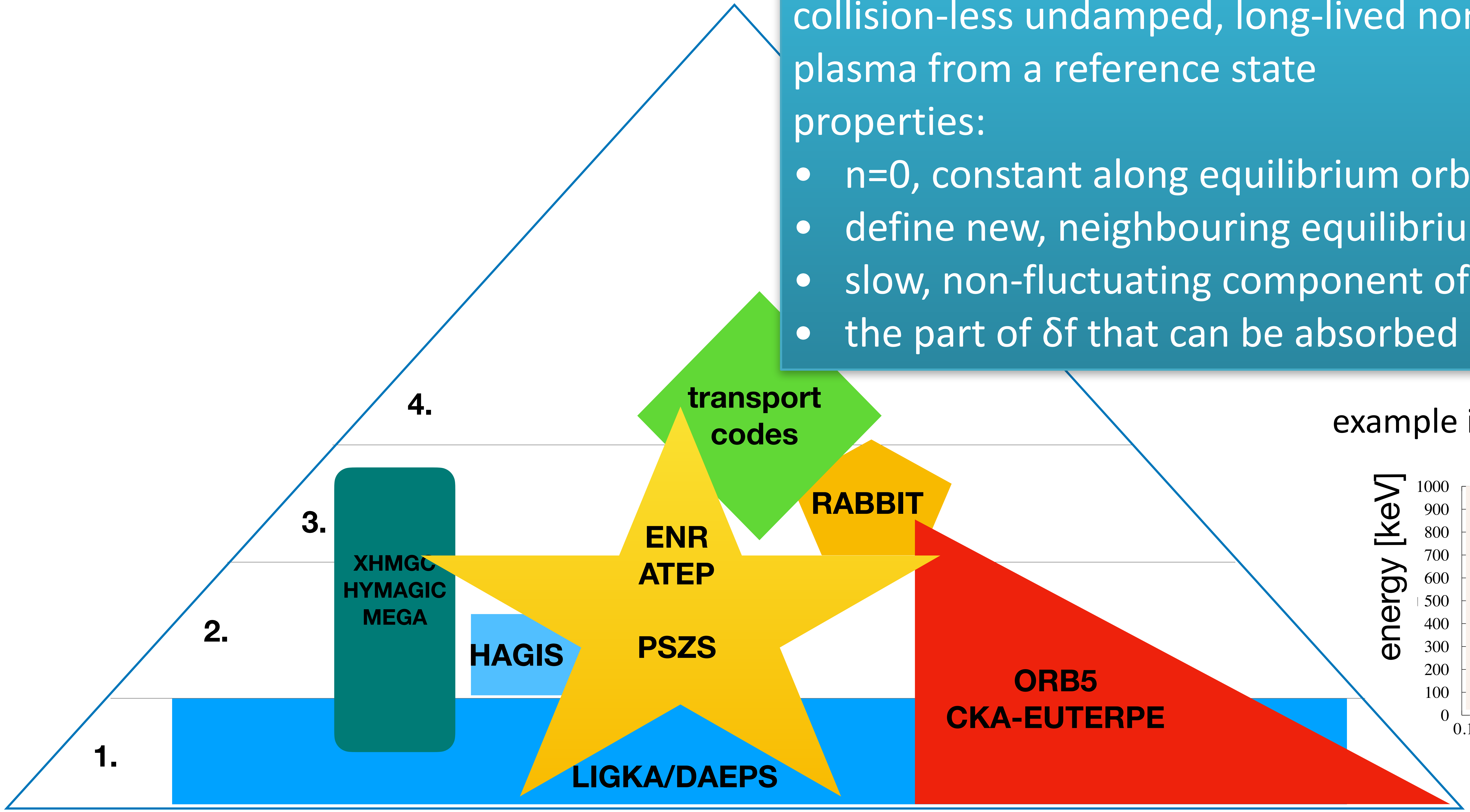
needed for scaling from TCV-AUG-JET,… to JT-60SA-DTT-ITER-DEMO:



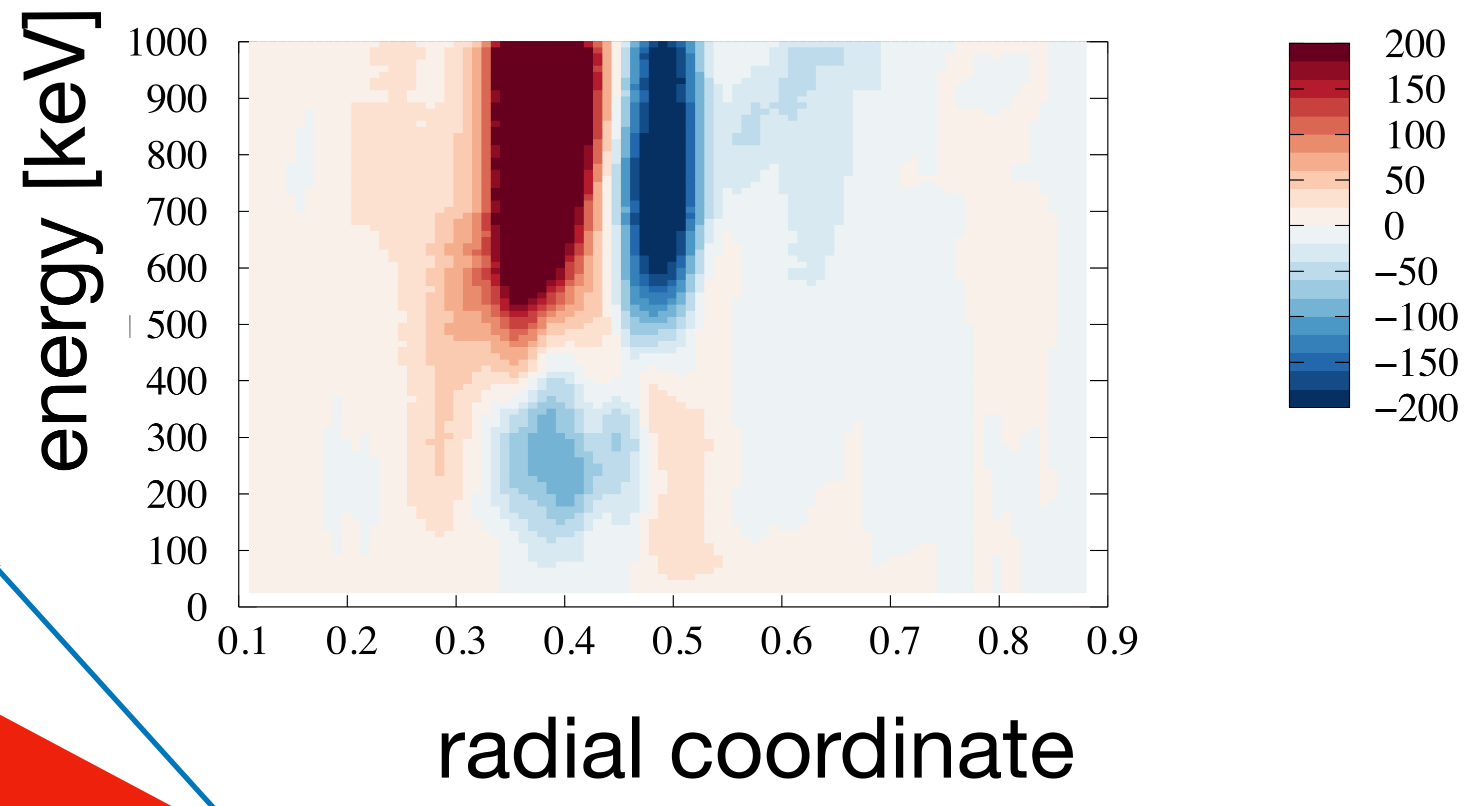
aim: develop IMAS based tool to calculate electromagnetic, global EP transport and couple either via F_{EP} or its moments to transport codes;
different models of fidelity/cost

phase space zonal structures (PSZS) are : [see M. Falessi's talk at this workshop]
collision-less undamped, long-lived nonlinear deviations of the plasma from a reference state
properties:

- n=0, constant along equilibrium orbits
- define new, neighbouring equilibrium reference state
- slow, non-fluctuating component of F_{EP} evolution
- the part of δf that can be absorbed in new F_0



example in COM space representation:



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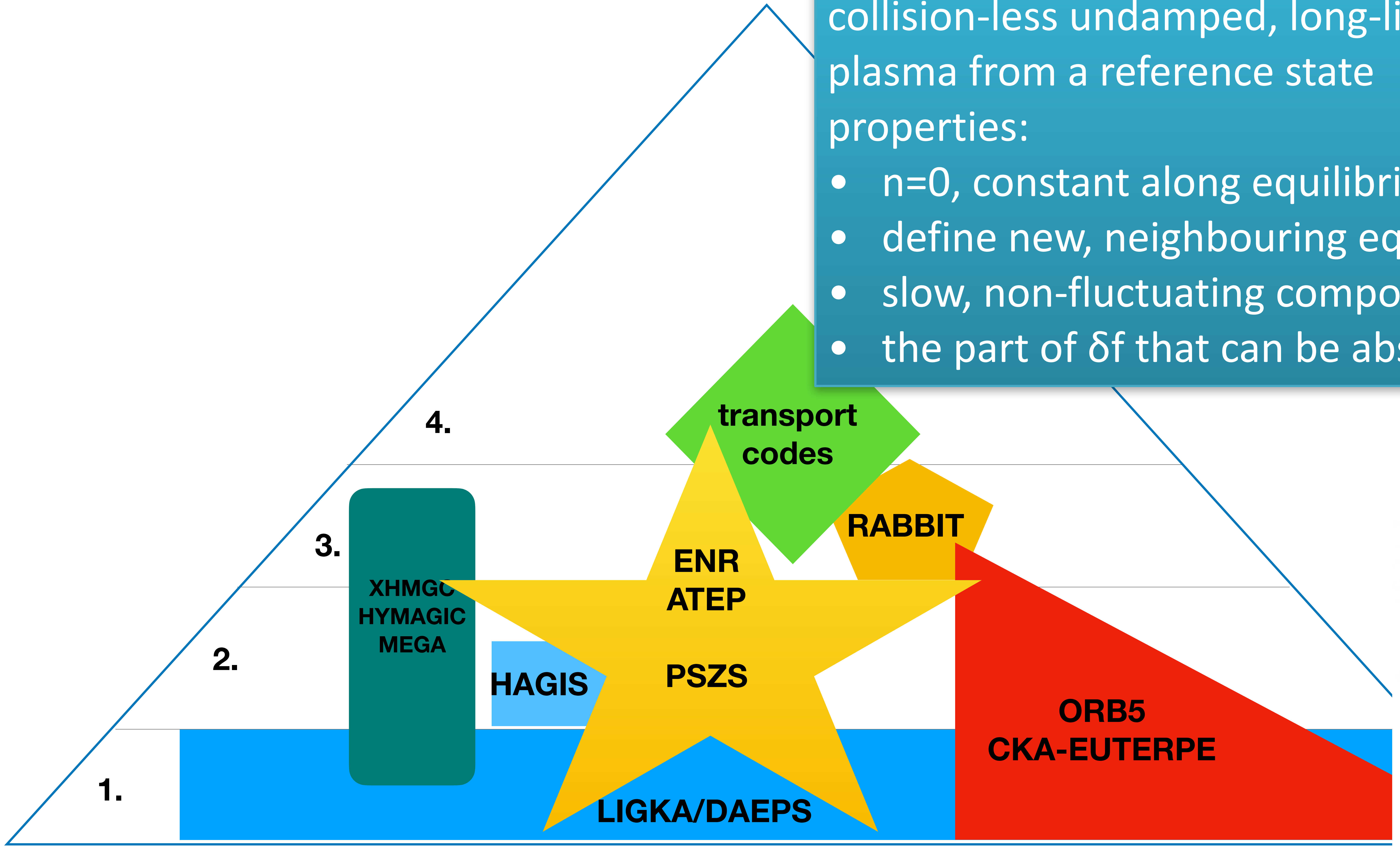
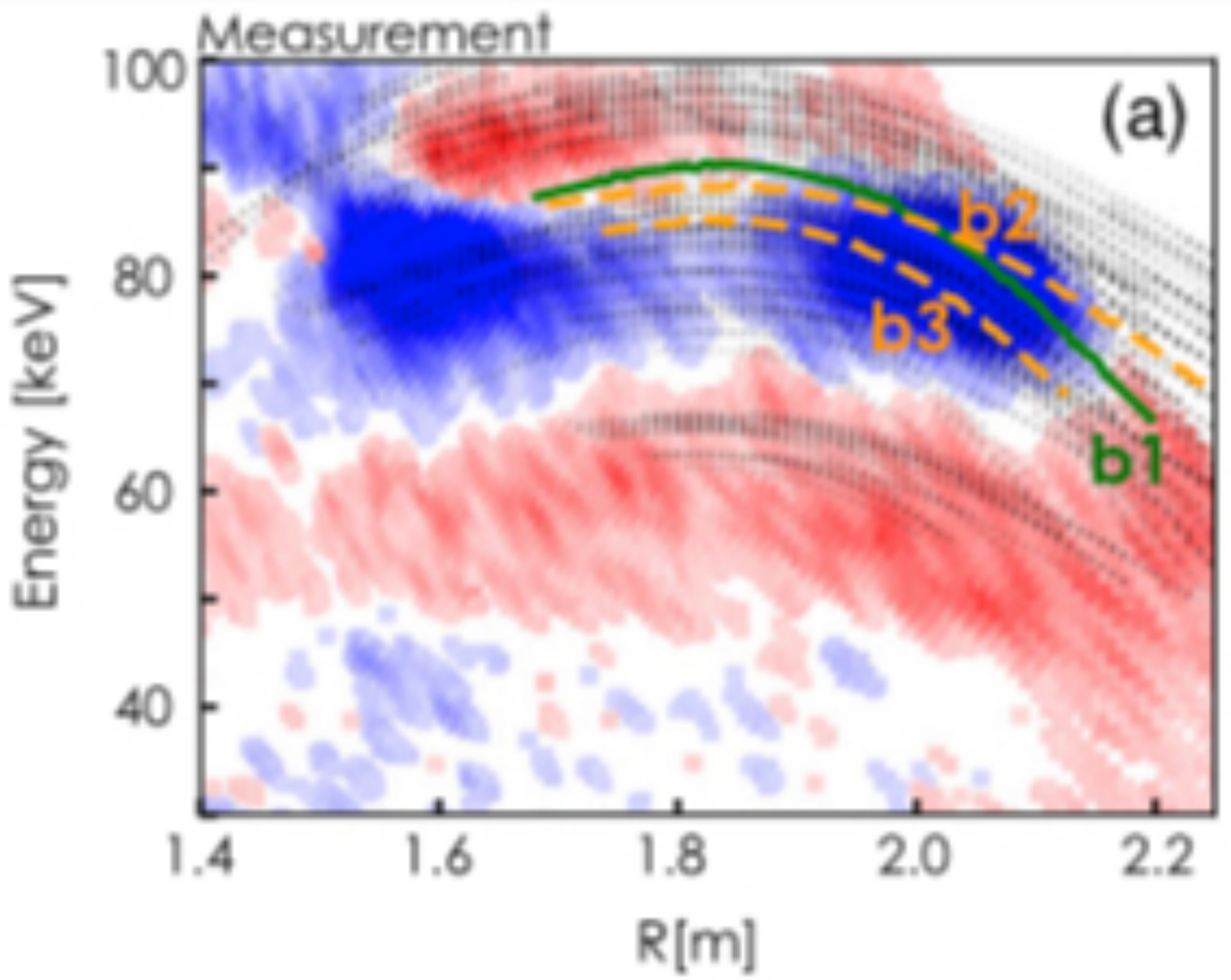




DIII-D, INPA [Du et al PRL 2021]

some existing transport models for EPs

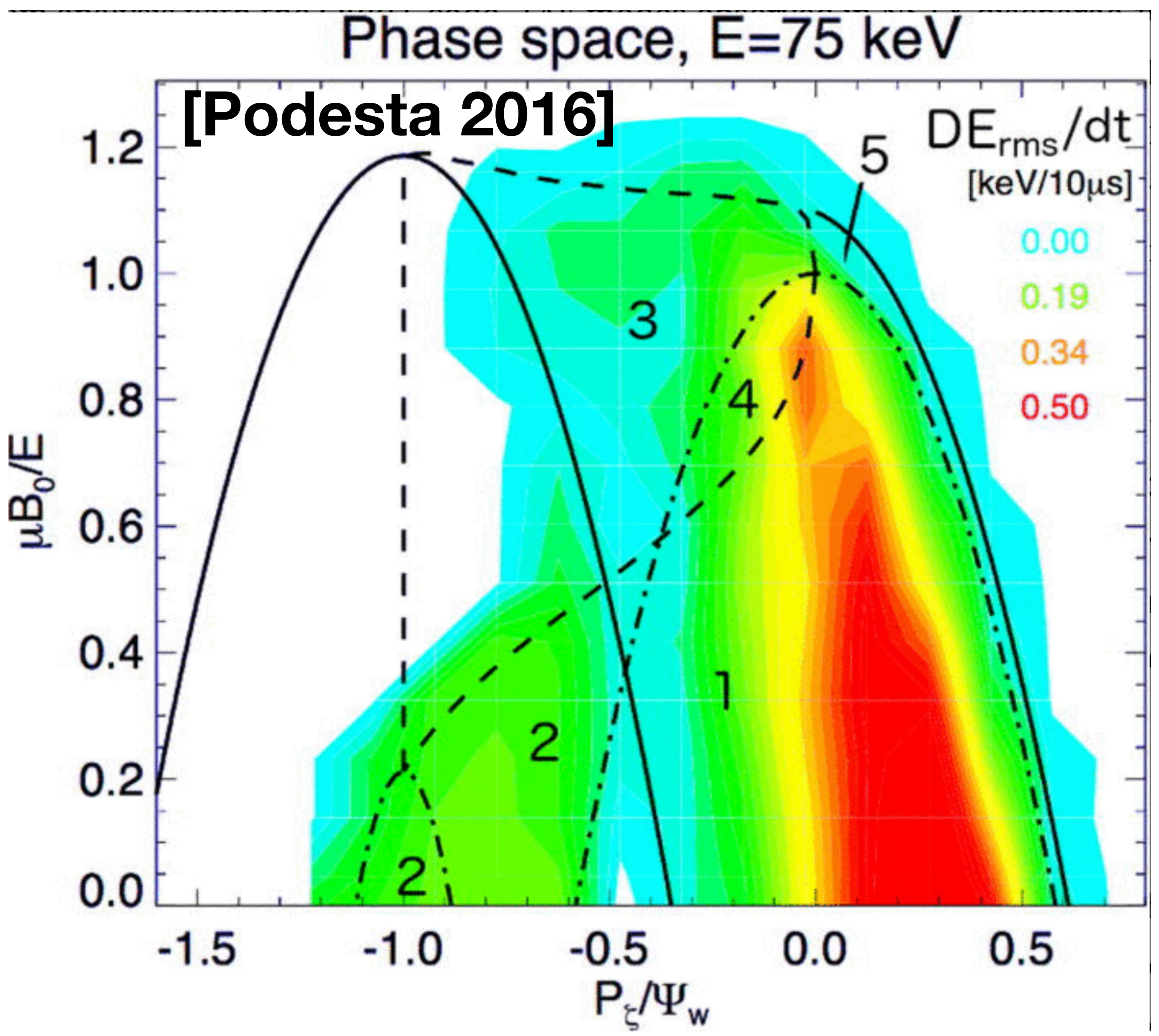
- diffusion coefficients for impurity transport by background turbulence, no e.m. EP-driven modes [Angioni, Püschel, etc]

- critical gradient model [R. Waltz, E. Bass]: use local AE stability threshold, add upshift of transport threshold using $(ExB)_{turb}$ shearing rate; above threshold set DEP to ad hoc values [e.g. $10 m^2/s$] to clamp EP's radial gradient to critical value

- kick model [M. Podesta, 2014-2022]: calculate probability density function of kick in Pz and E for given amplitude

- RBQ model, 1D, 2D [N. Gorelenkov 2015-2022]: use resonance broadening QL theory connected to NOVA-K to evolve mode amplitude consistently with evolution of F_{EP}

- PSZS model [M-V. Falessi, 2017-2022] - consistently embedded in general NL GK theory [see e.g. talk F. Zonca PPPL EP Seminar May 2022]
  gives clear guidance on validity and limitations of reduced models by monitoring simplification conditions



phase space zonal structure transport theory

[M.-V. Falessi, 2017-2021]
[L. Chen JGR, 1999]

start from NL GK equation,
and derive evolution equation of
toroidally symmetric component due to
fluctuations and sources/collisions:

$$\frac{\partial}{\partial t}\overline{F_{z0}} + \frac{1}{\tau_b}\left[\frac{\partial}{\partial P_\phi}\overline{\left(\tau_b \delta \dot{P}_\phi \delta F\right)}_z + \frac{\partial}{\partial \mathcal{E}}\overline{\left(\tau_b \delta \dot{\mathcal{E}} \delta F\right)}_z\right]_S = \overline{\left(\sum_b C_b^g\left[F, F_b\right] + \mathcal{S}\right)}_{zS}$$

splitting micro and meso/macro scales -
describes evolution of non-linear equilibrium
including long-lived n=0 structures from
perturbations

use connection to QL GK equations to
reconcile with QL transport theory, e.g. in
[L. Chen JGR, 1999]

$$\frac{\partial}{\partial t}(B_\parallel^* F_o) + \bar{\nabla}\cdot(B_\parallel^* \dot{\mathbf{X}}_o F_o) + \frac{\partial}{\partial w}(B_\parallel^* w_o F_o) + \bar{\nabla}\cdot(B_\parallel^* \overline{\delta\dot{\mathbf{X}}\delta G_{\text{res}}}) + \frac{\partial}{\partial w}(B_\parallel^* \overline{\delta \dot{w} \delta G_{\text{res}}}) = 0 \qquad (12)$$

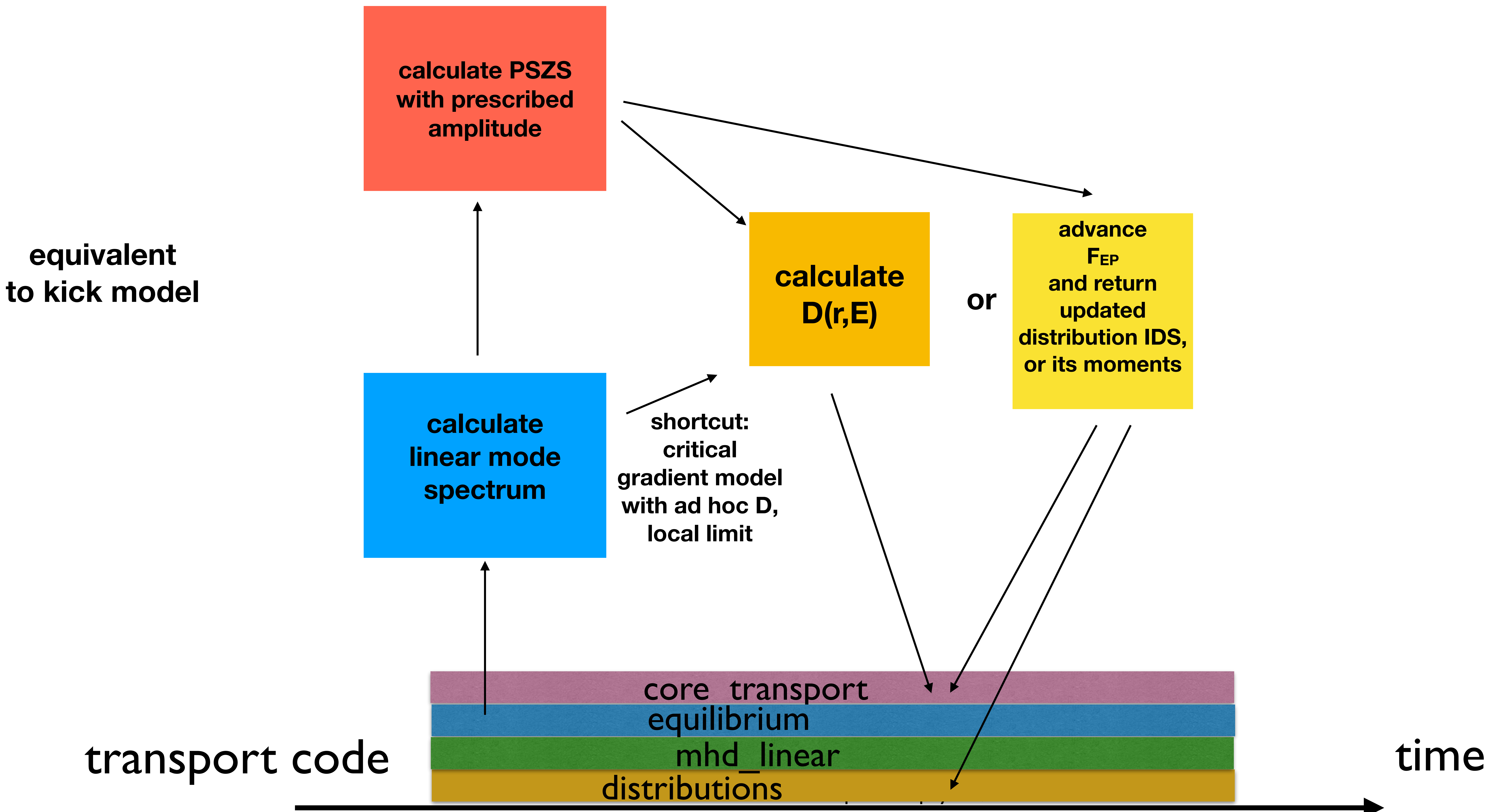
mapping from Pz,E,μ space to real space:

$$D_{\psi\psi} = \overline{\delta\dot{\psi}\delta\dot{\psi}}\tau_{ac} = \frac{1}{2}\sum_{\omega,\mathbf{k}_\perp} c^2 m_\beta^2 |\delta\hat{\Phi}|^2 \tau_{ac} \qquad (45)$$

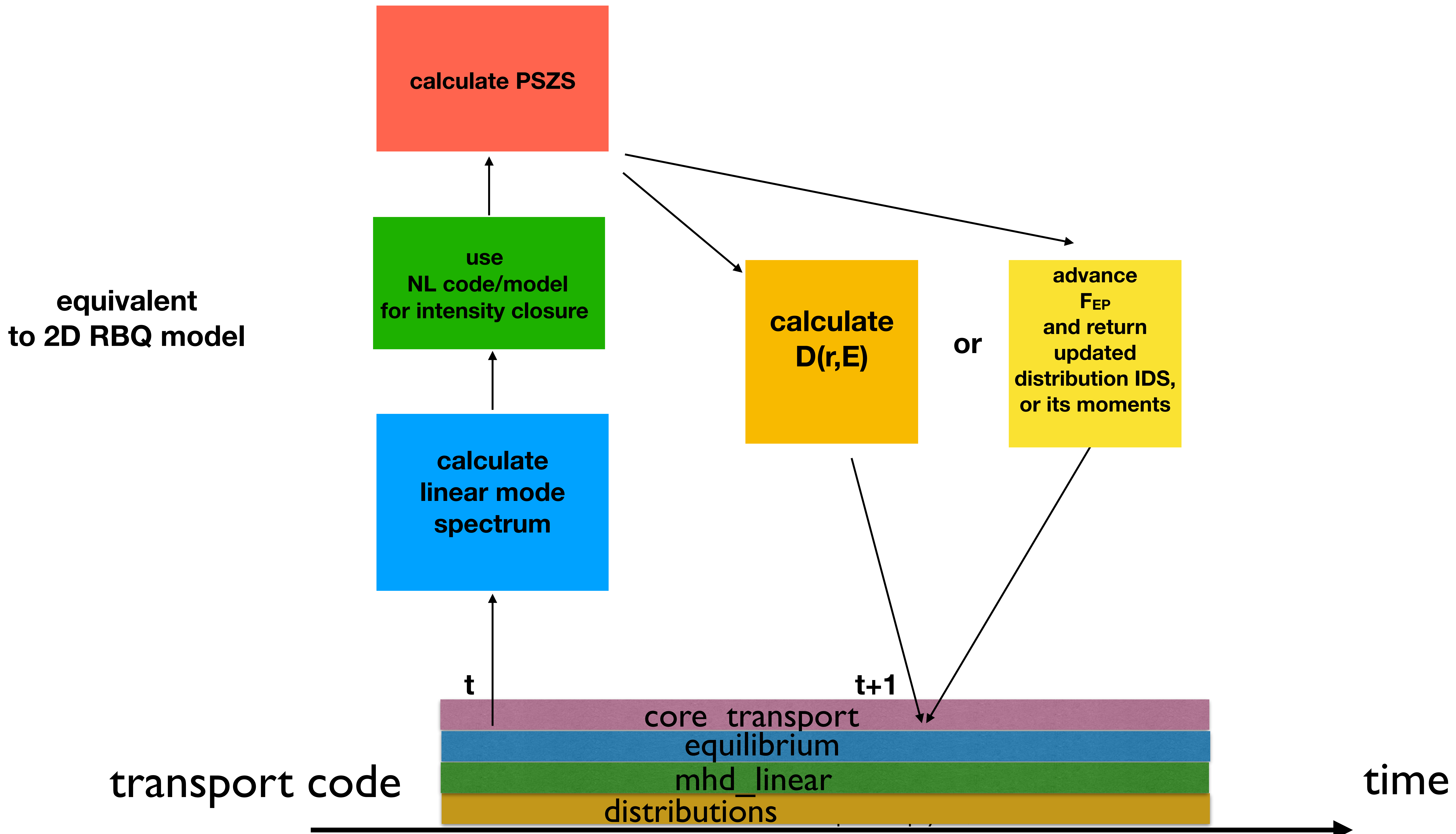
$$D_{\psi\varepsilon} = D_{\varepsilon\psi} = \overline{\delta\dot{\psi}\delta\dot{\varepsilon}}\tau_{ac} = \frac{1}{2}\sum_{\omega,\mathbf{k}_\perp} c m_\beta \frac{\omega e}{m} |\delta\hat{\Phi}|^2 \tau_{ac} \qquad (46)$$

$$D_{\varepsilon\varepsilon} = \overline{\delta\dot{\varepsilon}\delta\dot{\varepsilon}}\tau_{ac} = \frac{1}{2}\sum_{\omega,\mathbf{k}_\perp} \left(\frac{\omega e}{m}\right)^2 |\delta\hat{\Phi}|^2 \tau_{ac} \qquad (47)$$

outline: ATEP framework
EP transport workflow schematics

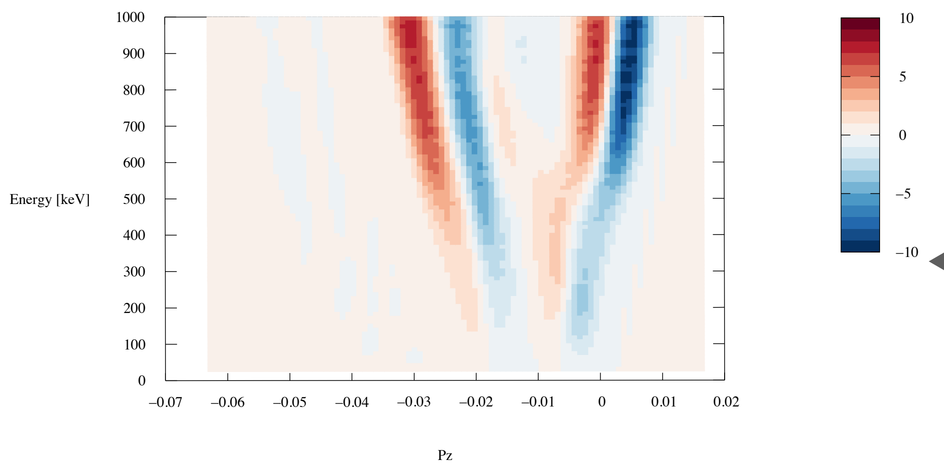


EP transport workflow schematics

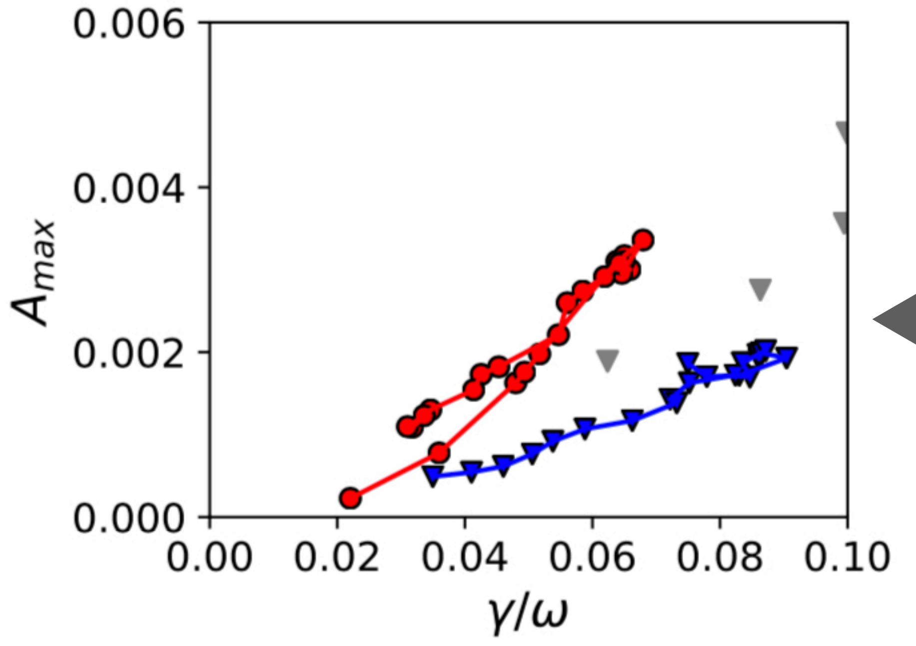


EP transport workflow schematics

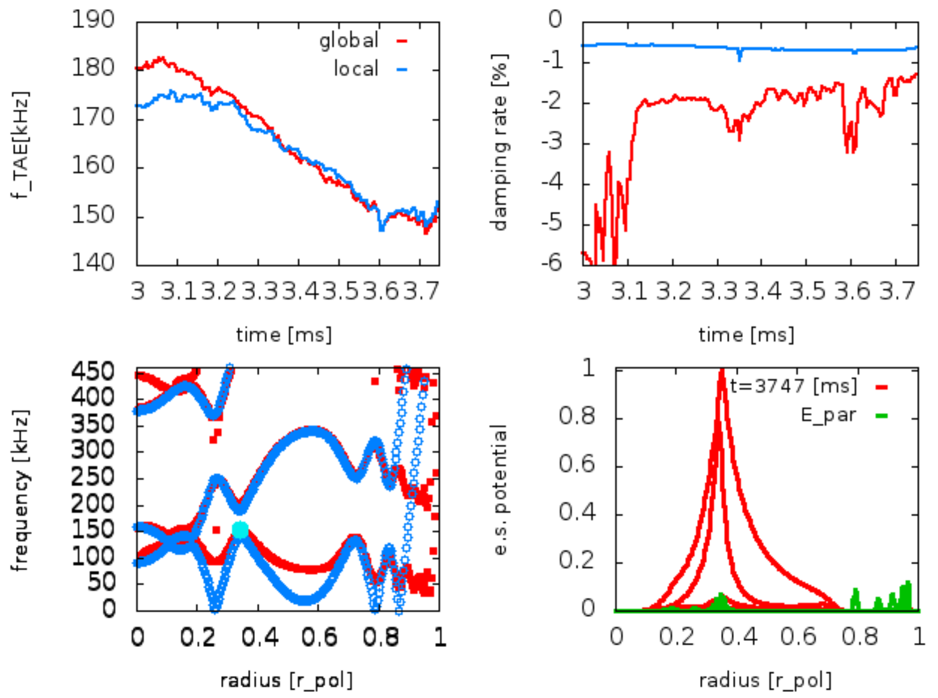
FINDER/HAGIS [Ph. Lauber, 2007,2022]

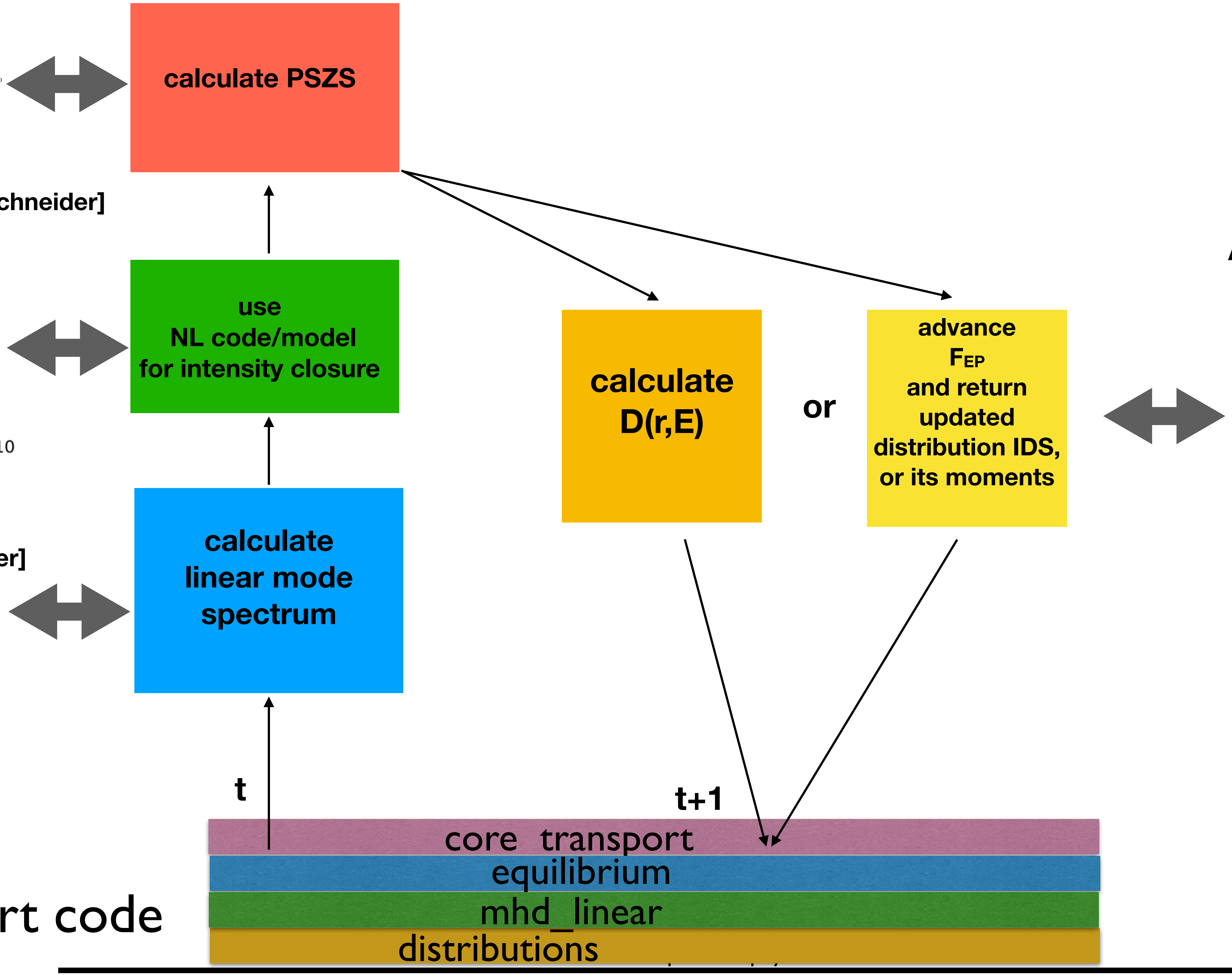


[HAGIS, S.D. Pinches, T Hayward-Schneider]



EP WF (LIGKA) [A . Popa, Ph. Lauber]

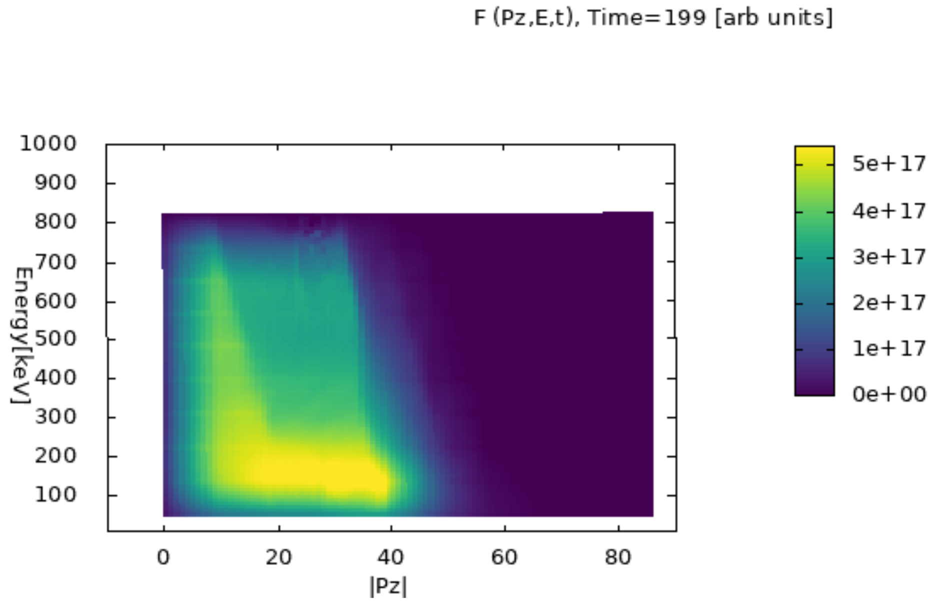




transport code

time

ATEP code [Ph. Lauber, 2022]



$$\frac{\partial F_{EP}}{\partial t} = \frac{\partial Pz}{\partial t}\frac{\partial F_{EP}}{\partial P_z} + \frac{\partial E}{\partial t}\frac{\partial F_{EP}}{\partial E}$$

outline

- **Linear stability: EP stability**
- **calculating PSZSs**
- **progress on implementation of transport model: ATEP code**
- **verification & validation**

LIGKA: hierarchy of linear GK models

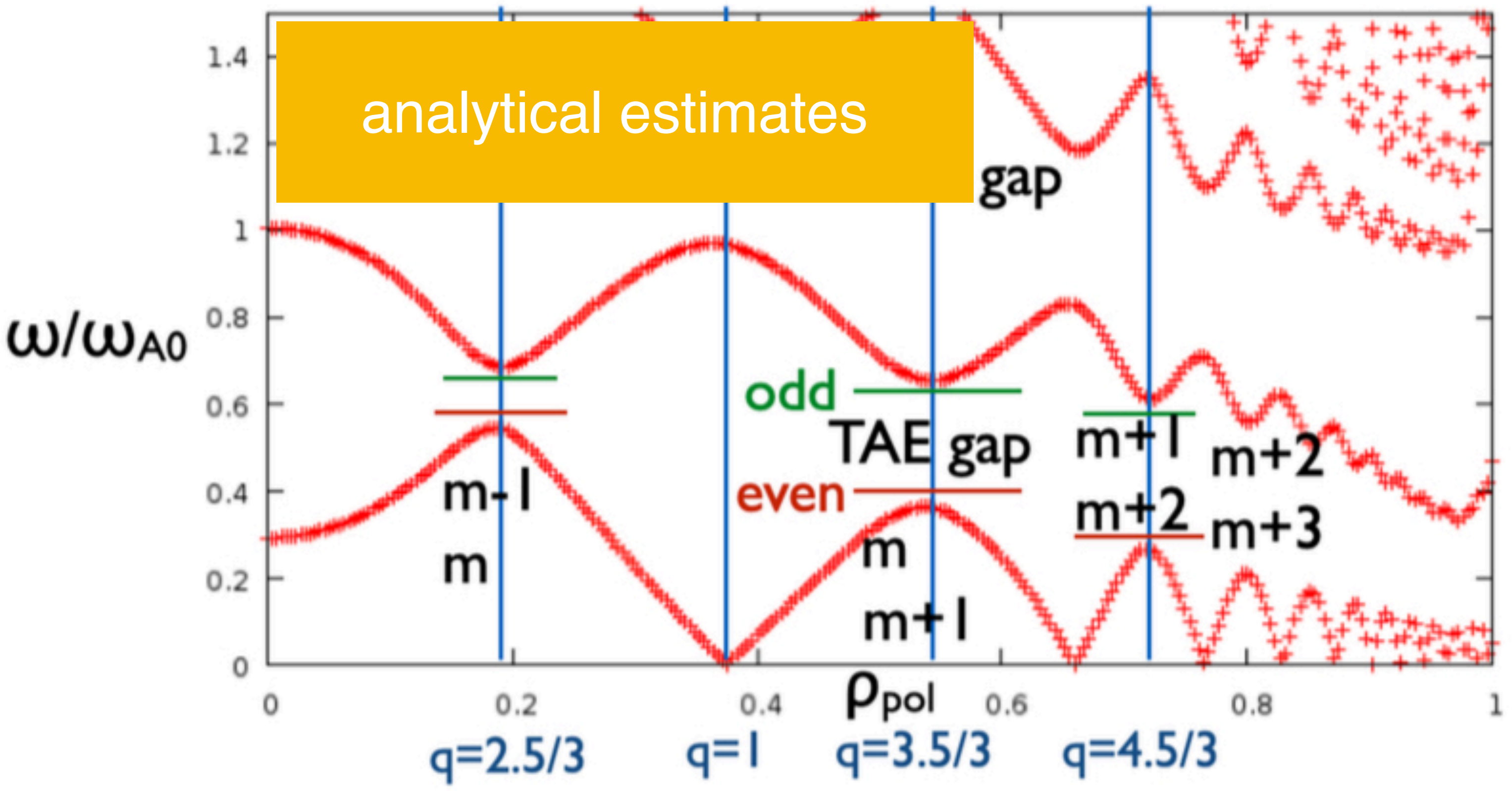
- local, analytical estimates [mode 5]
- local reduced MHD - spectra [mode 6]
- global reduced MHD - MHD eigenfunction [mode 6]
- local kinetic (w/o numerical coefficients) [mode 3/4]
- local kinetic with FLR/FOW (w/o numerical coefficients) [mode 3/4]
- global kinetic (w/o numerical coefficients): two different solvers [mode 1]
- global kinetic track mode (w/o numerical coefficients) [mode 2]

typically modes are called in sequence;
results are stored in unique structure keeping results from various calls in the same format -
adoption to IMAS finished, documentation on https://confluence.iter.org/pages/viewpage.action?pageId=289069024

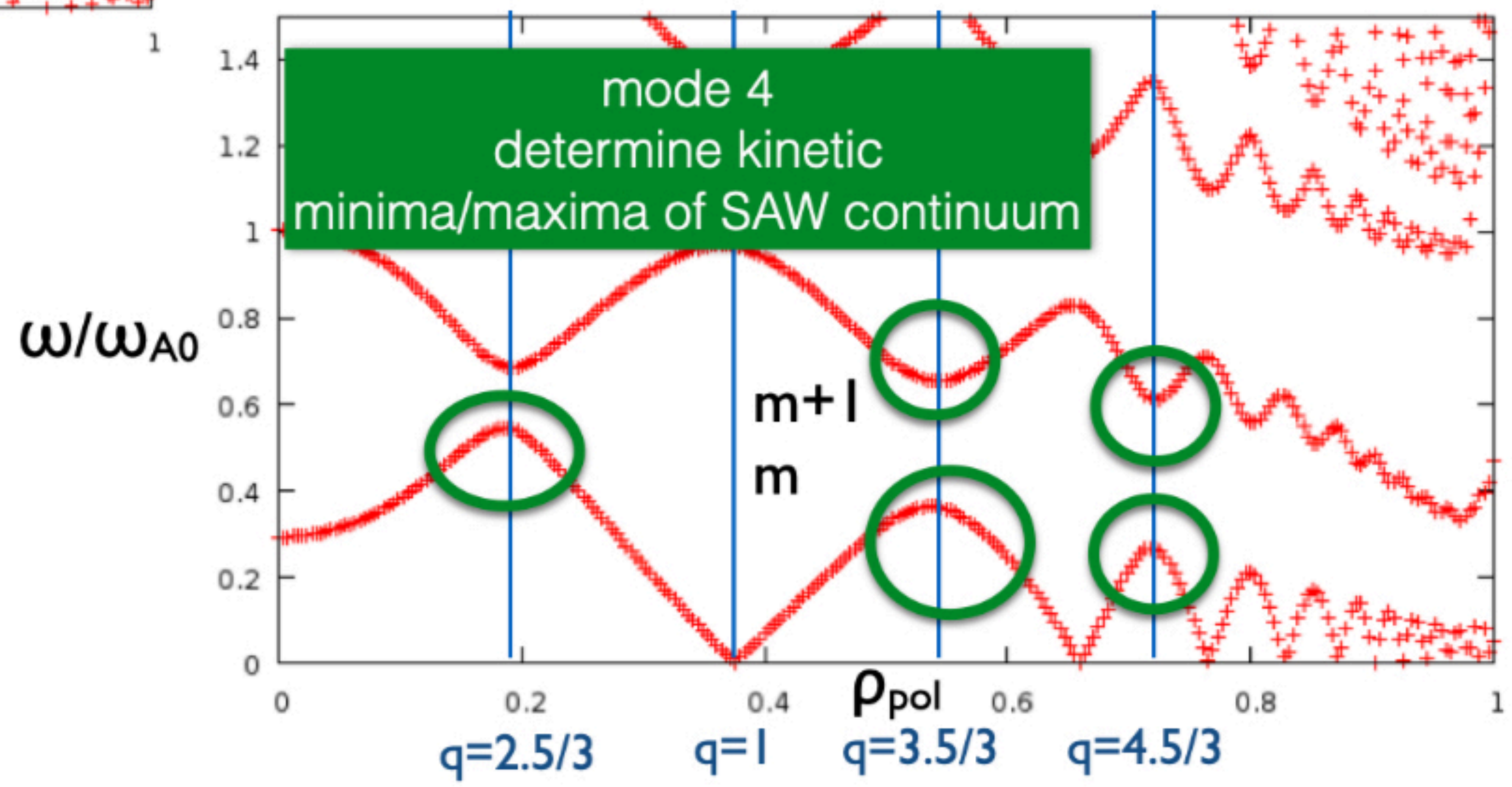
- Lauber PhD Thesis 2003: http://nbn-resolving.de/urn/resolver.pl?urn:nbn:de:bvb:91-diss2003111814131
- Lauber JCP 2007: 10.1016/j.jcp.2007.04.019
- Lauber PPCF 2009: http://stacks.iop.org/0741-3335/51/i=12/a=124009
- Lauber PREP 2013: https://doi.org/10.1016/j.physrep.2013.07.001
- Bierwage NF 2017: https://doi.org/10.1088/1741-4326/aa80fe
- Lauber JPC 2018 https://doi.org/10.1088/1742-6596/1125/1/012015
- ITPA EP: https://sharepoint.iter.org/departments/POP/ITPA/EP/Pages/default.aspx
- more information: http://www2.ipp.mpg.de/~pwl/

- and git ITER repository: git clone ssh://git@git.iter.org/stab/ligka.git ; git checkout develop

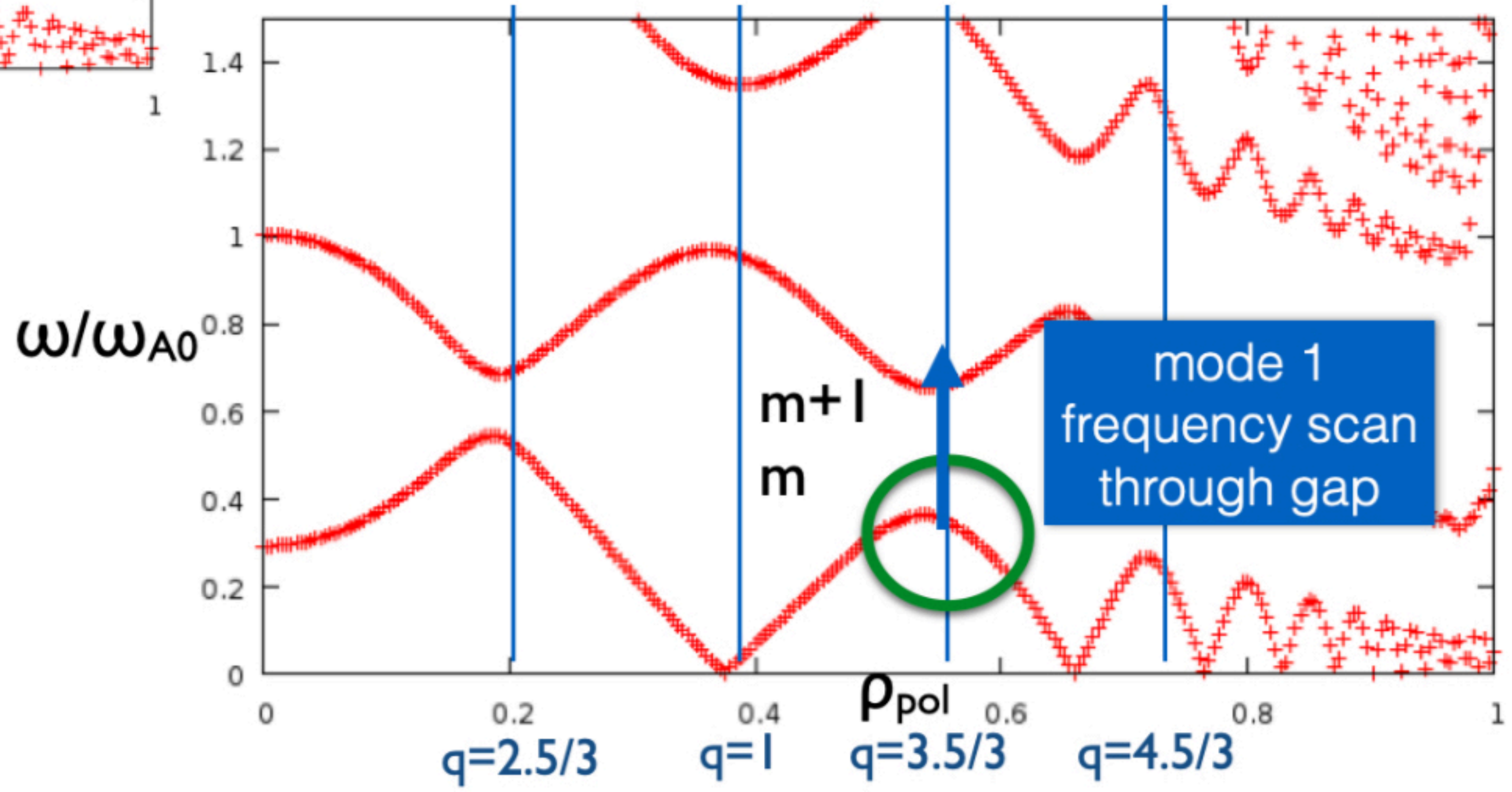
use local information for setting up global simulation



local

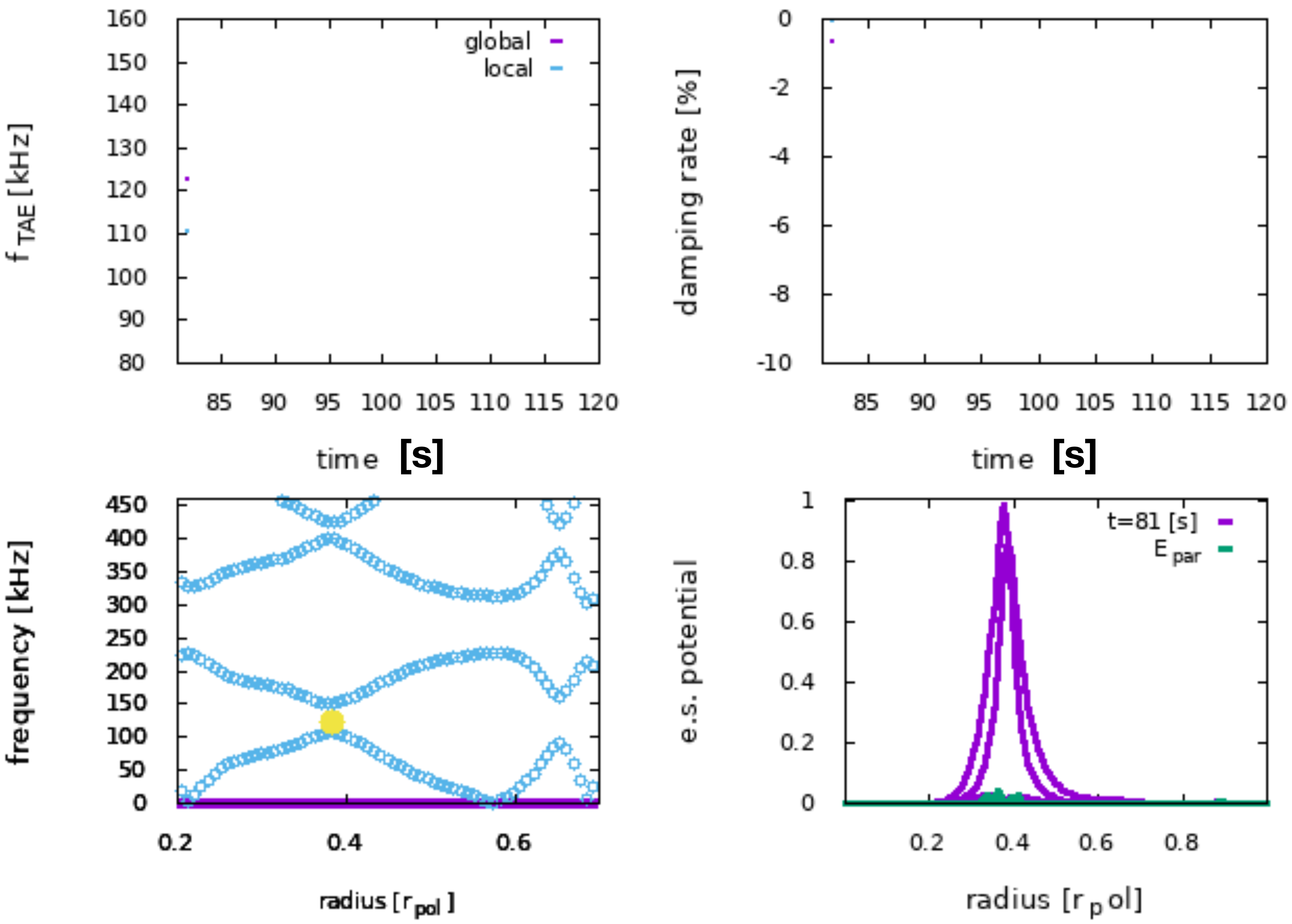


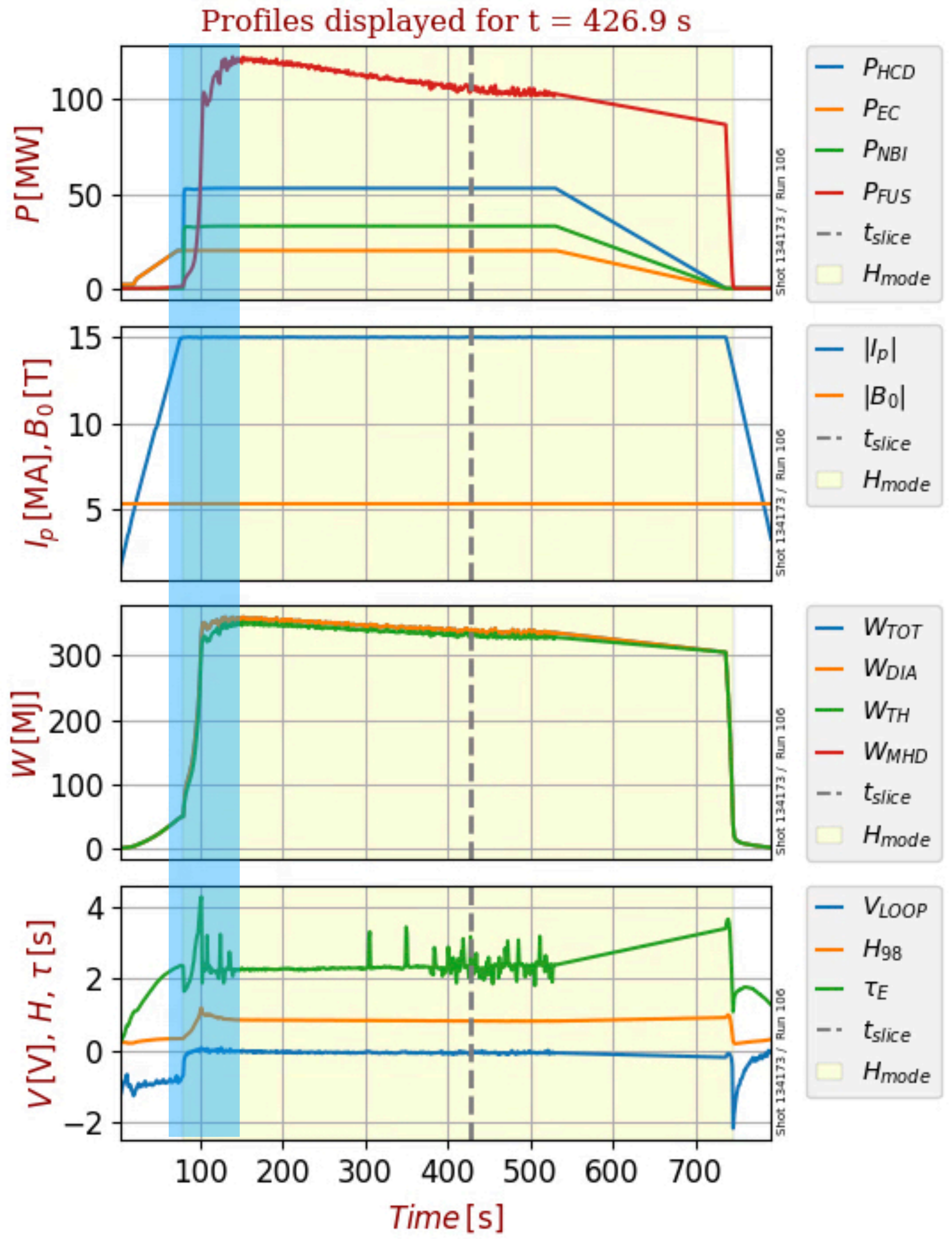
global



automated application of EP stability workflow projected ITER scenarios (HFPS): #134173, 106 [S.D. Pinches EPS 2022]

TAE n=12

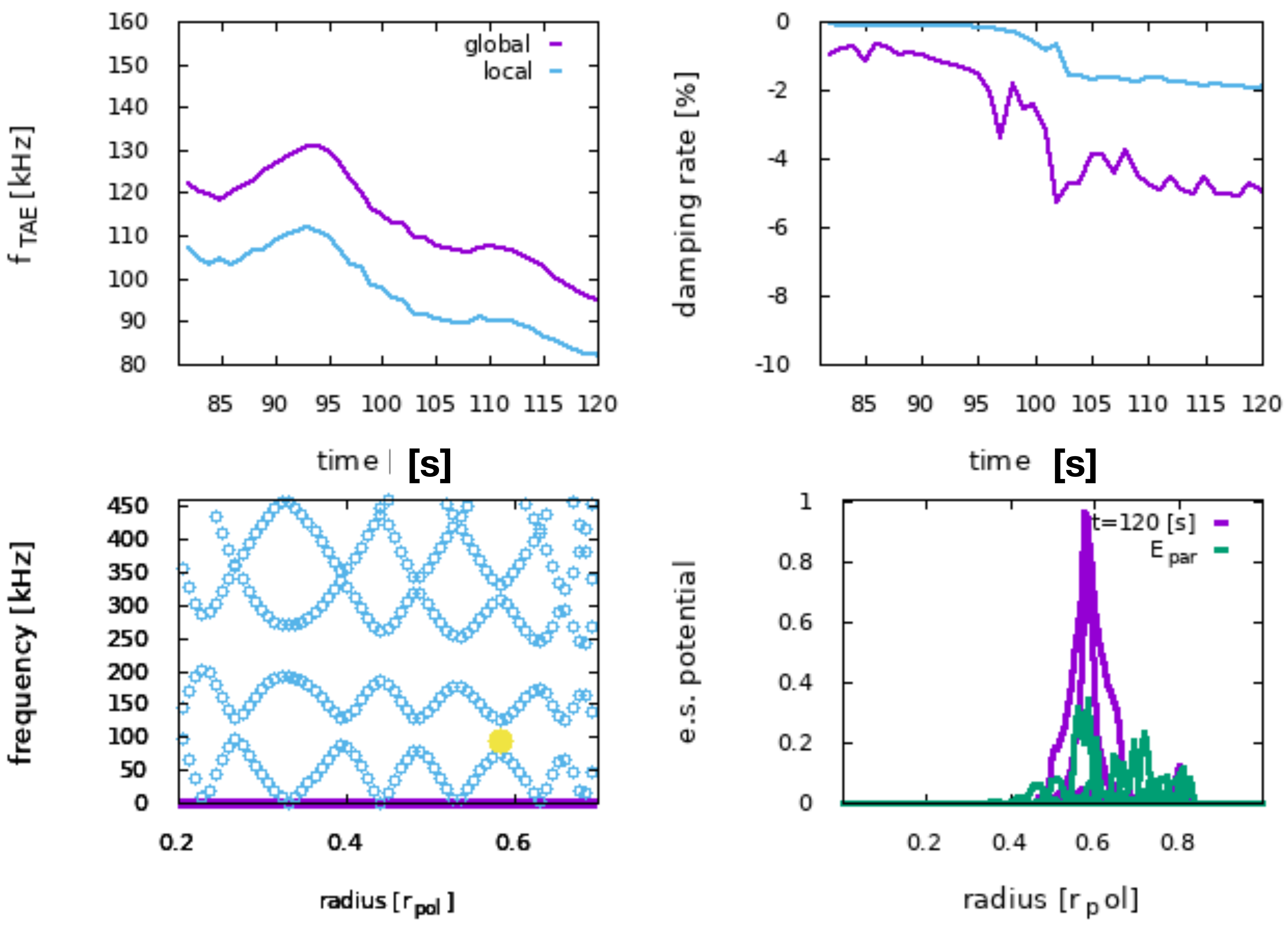


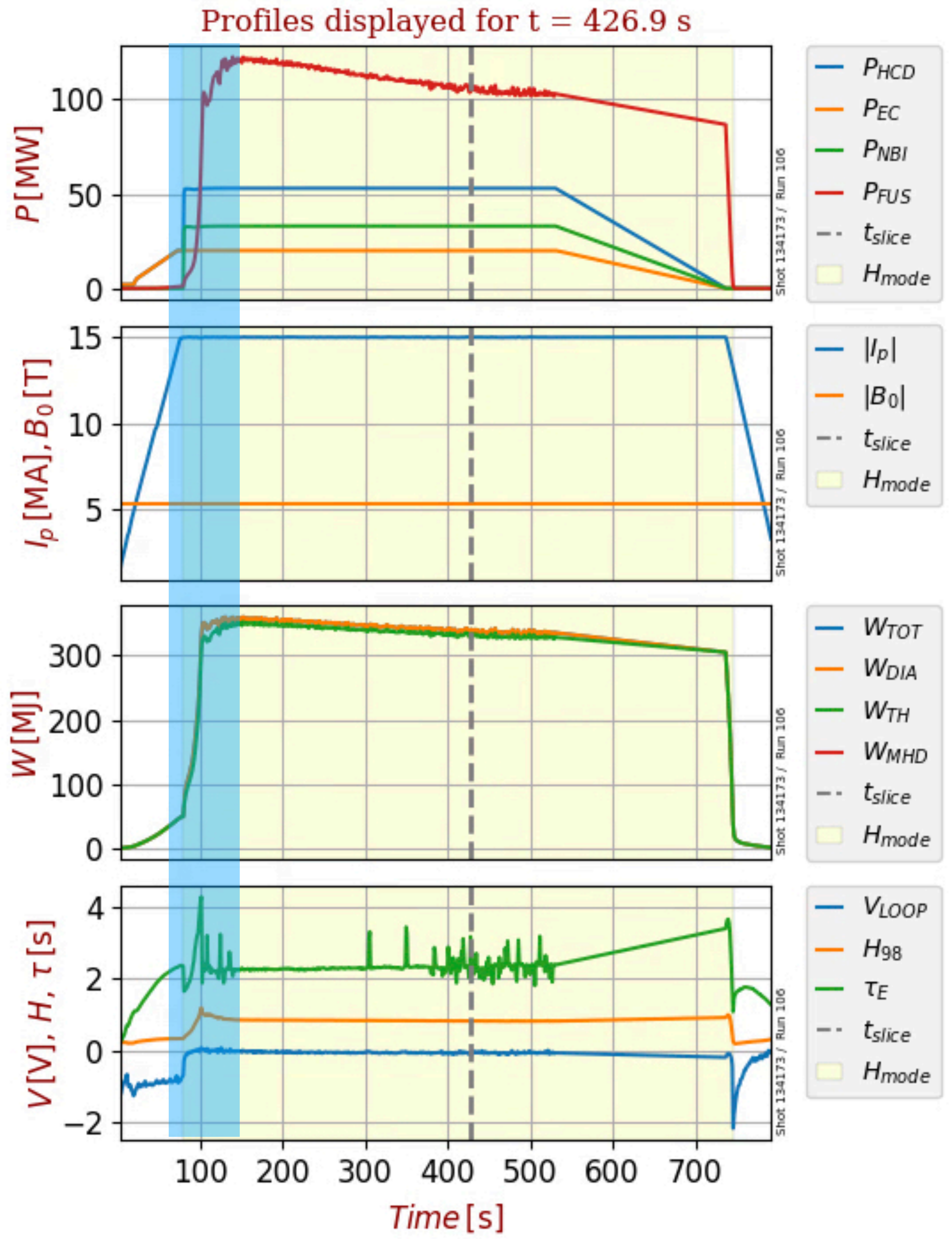


low damping rates during/at the end of the power ramp-up phase

automated application of EP stability workflow projected ITER scenarios (HFPS): #134173, 106 [S.D. Pinches EPS 2022]

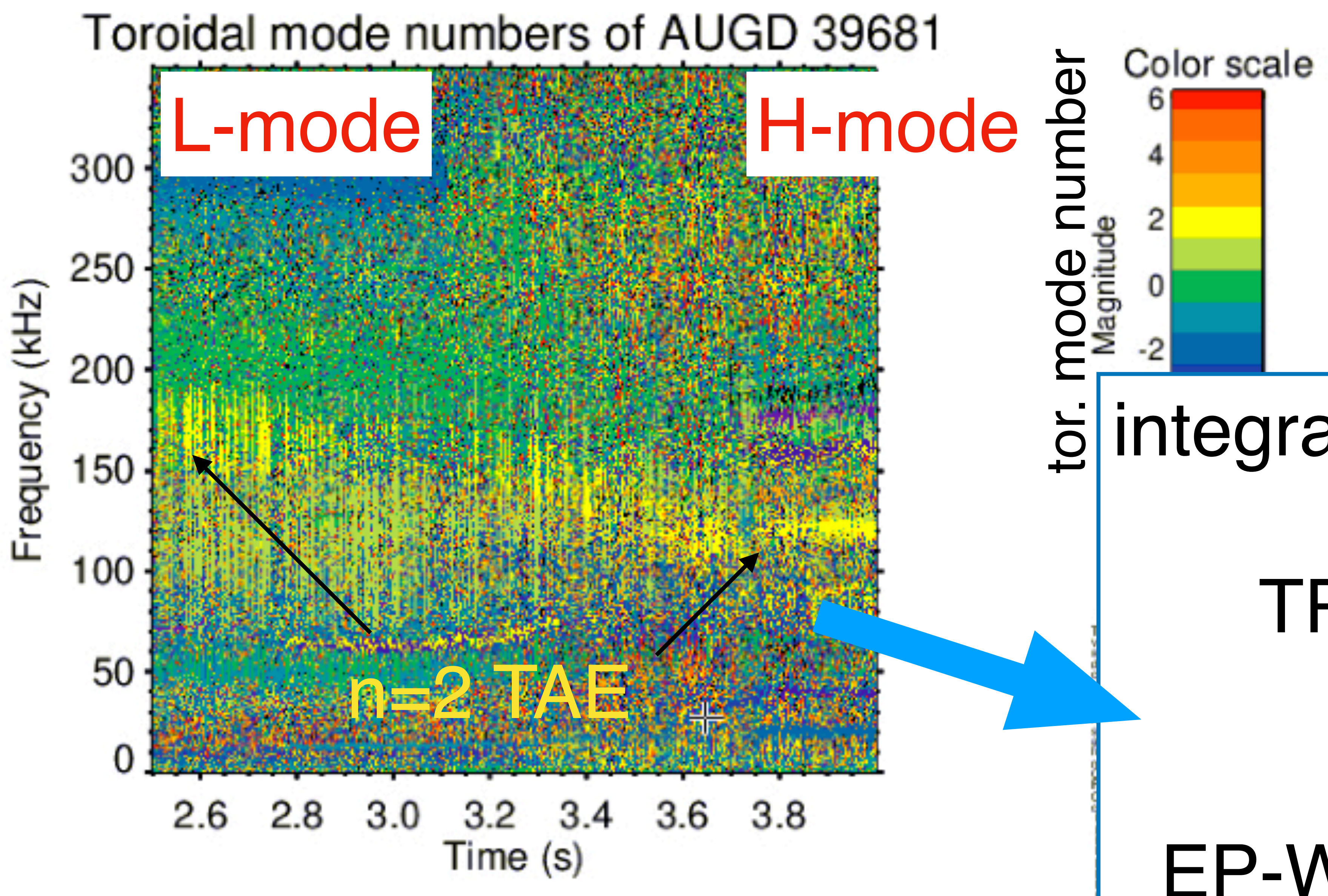
TAE n=18





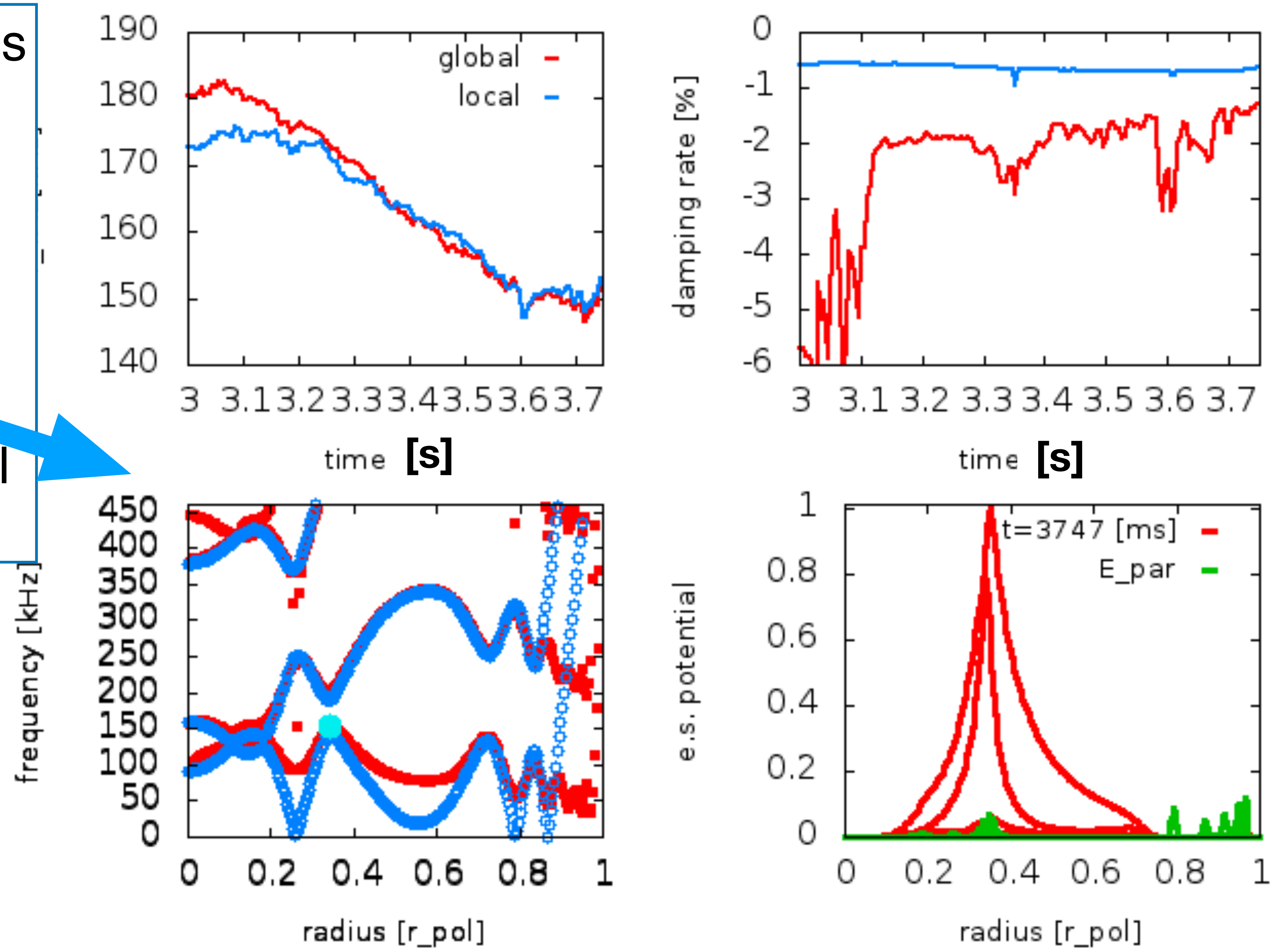
low damping rates during/at the end of the power ramp-up phase

exploit EP stability workflow: AUG data example: L-H transition in presence of TAEs



- automated processing of 160 time slices based on IDA equilibria and profiles
- fully implemented in IMAS, ensuring reproducibility

integrated data analysis
+
TRVIEW(IMAS interface)
+
EP-WF: LIGKA local
+
EP-WF: LIGKA global

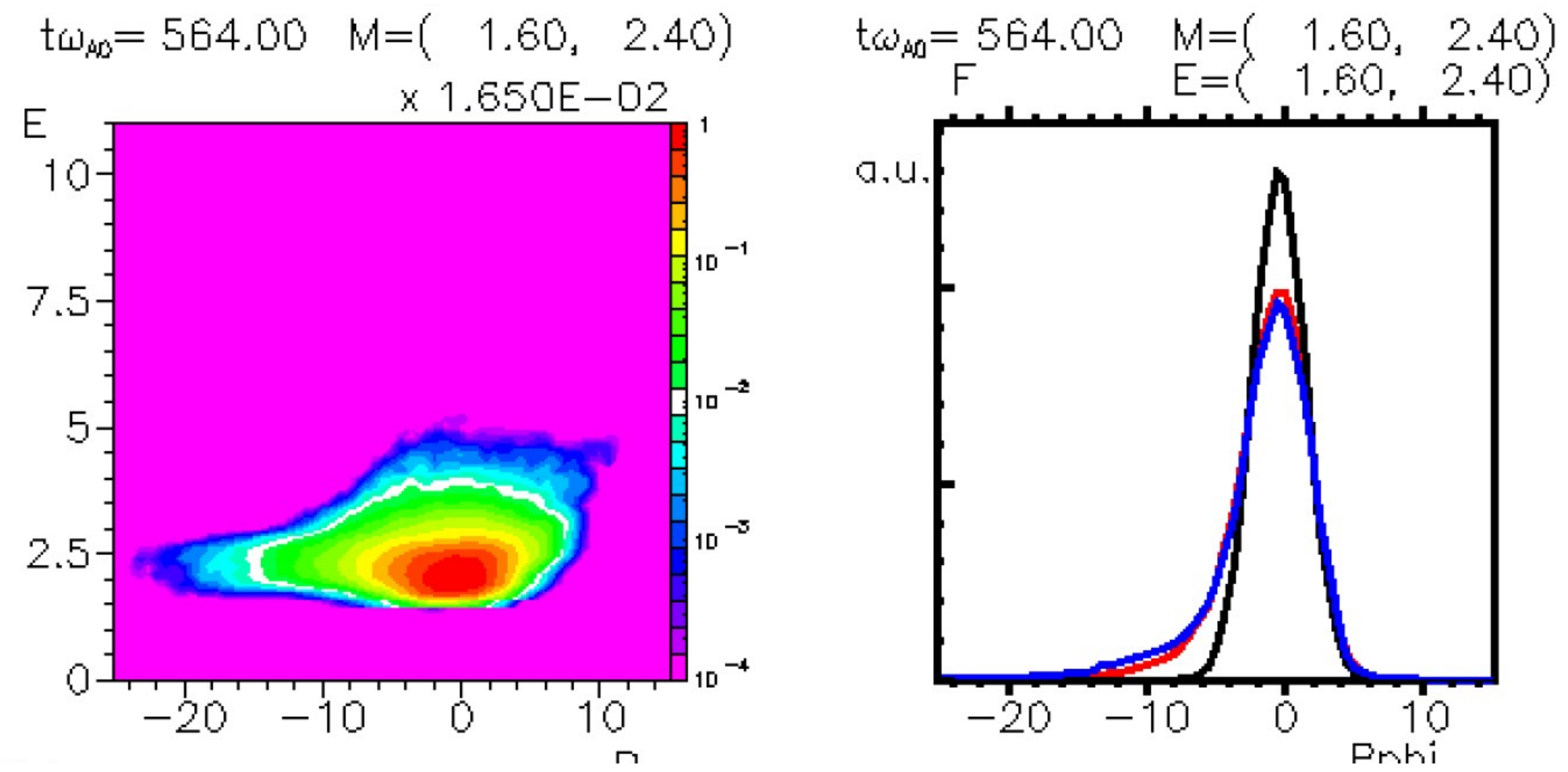


- analyse L-mode,H-mode and transition phase using
- also systematic uncertainty quantification feasible

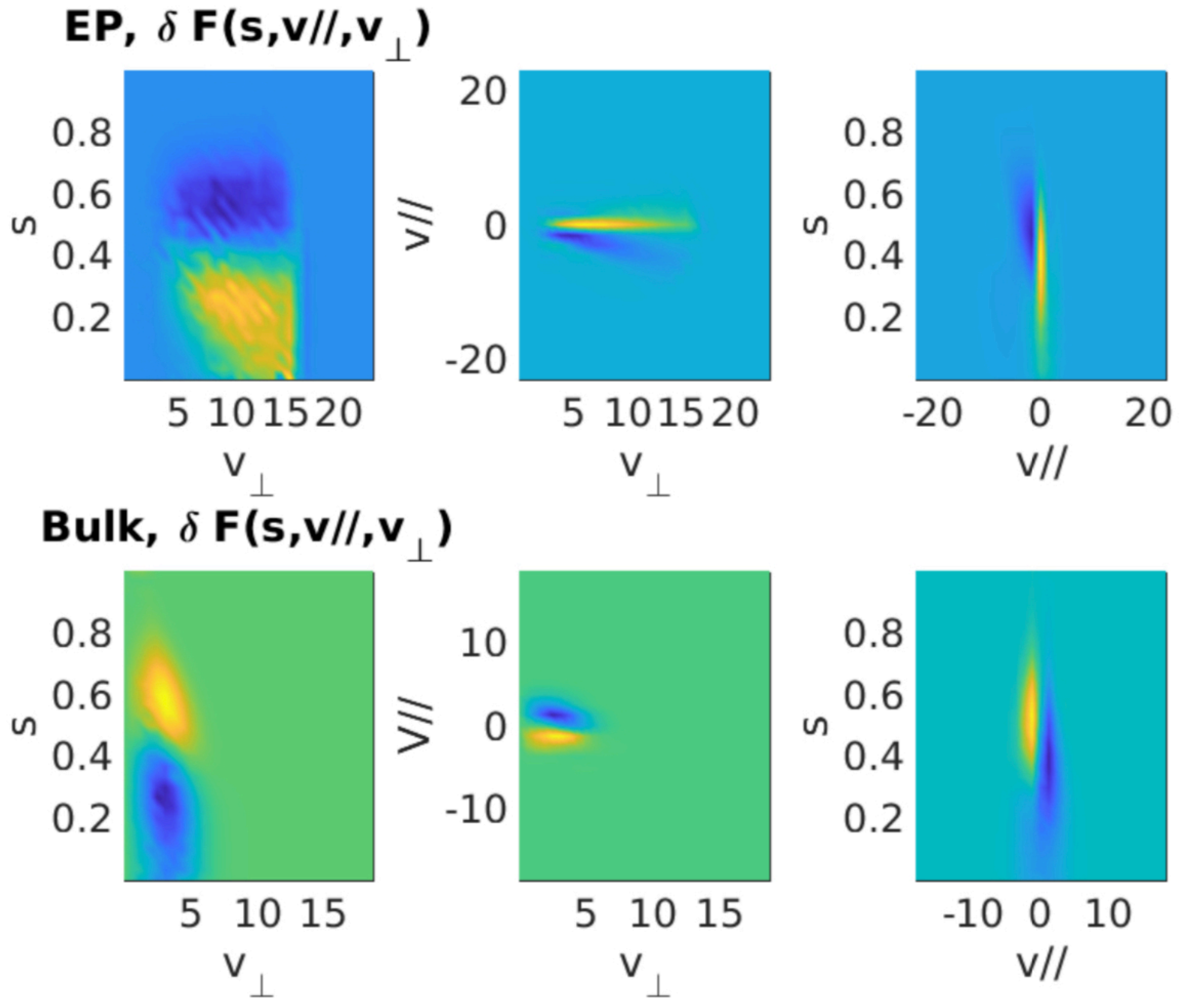
calculating PSZSs

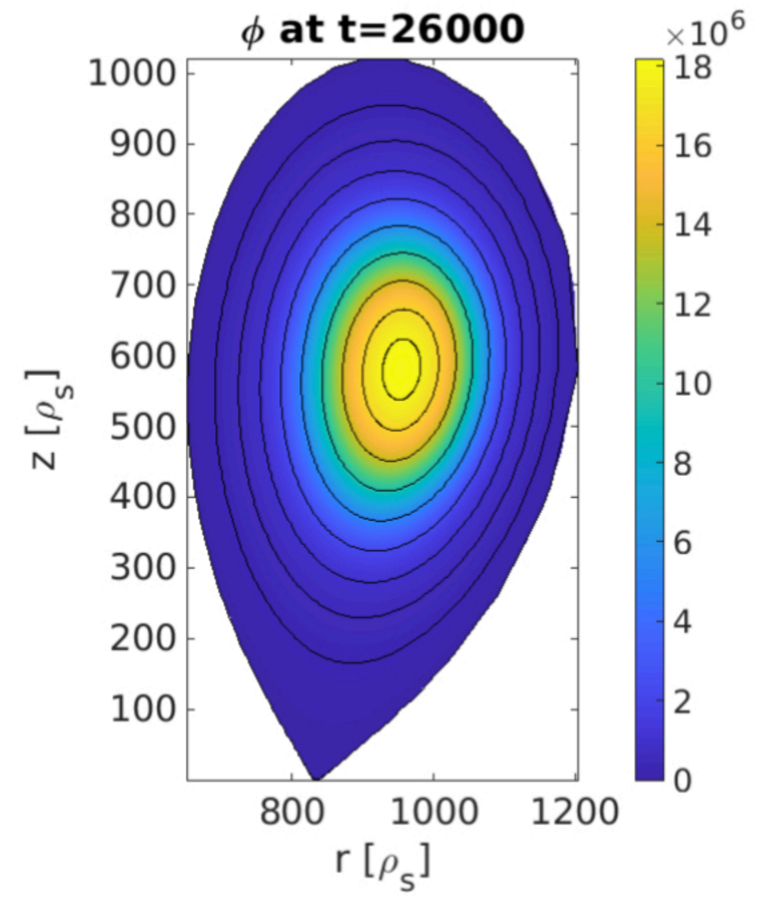
implementation of PSZS in NL MHD-hybrid and GK codes

PSZSs have been extracted from HMGC and HYMAGYC MHD-kinetic hybrid codes [S. Briguglio, G. Vlad et al 2019-2022]



recently also in non-linear GK code ORB5 NLED AUG EPM/TAE [A. Bottino, Varenna 2022]

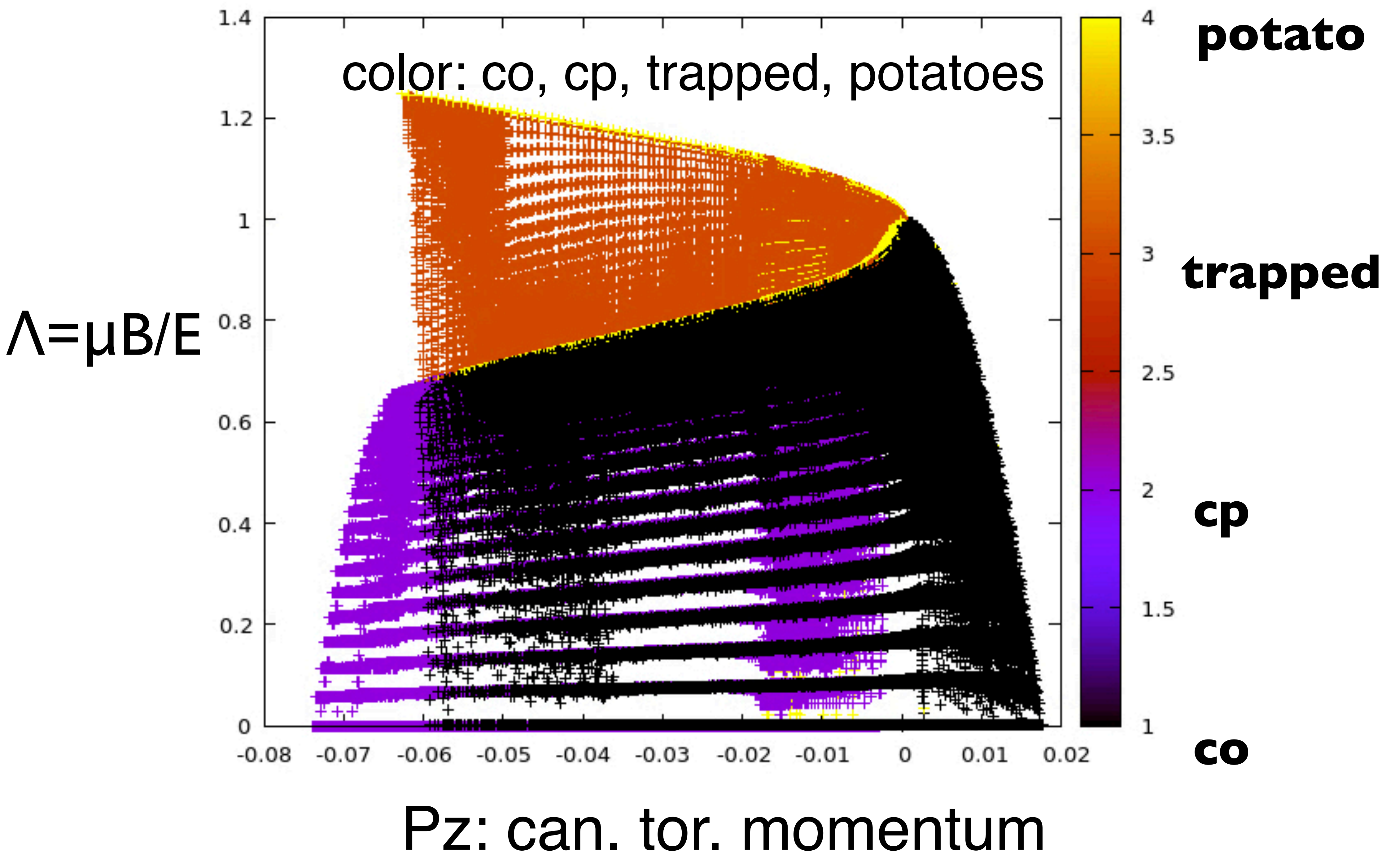


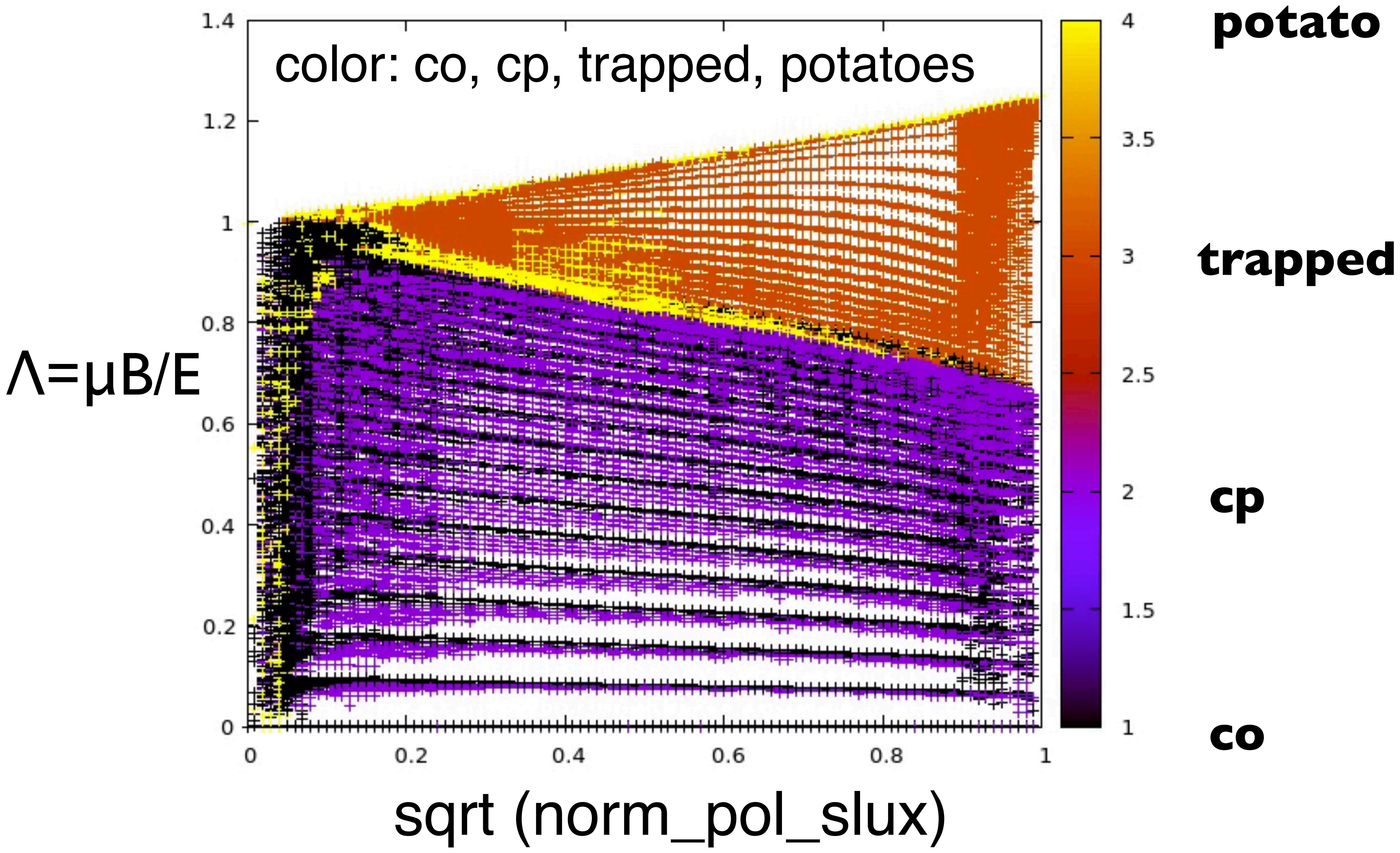


calculating PSZSs based on orbit/zonal averaging

- use IMAS-based wrapper program for HAGIS to set up marker space, determine trapped-passing boundary, sort, classify, orbit averages for unperturbed equilibria
- originally developed to calculate propagator integrals for LIGKA

[A. Bierwage, CPC 2022, LIGKA orbit integrals, CPC 2007]



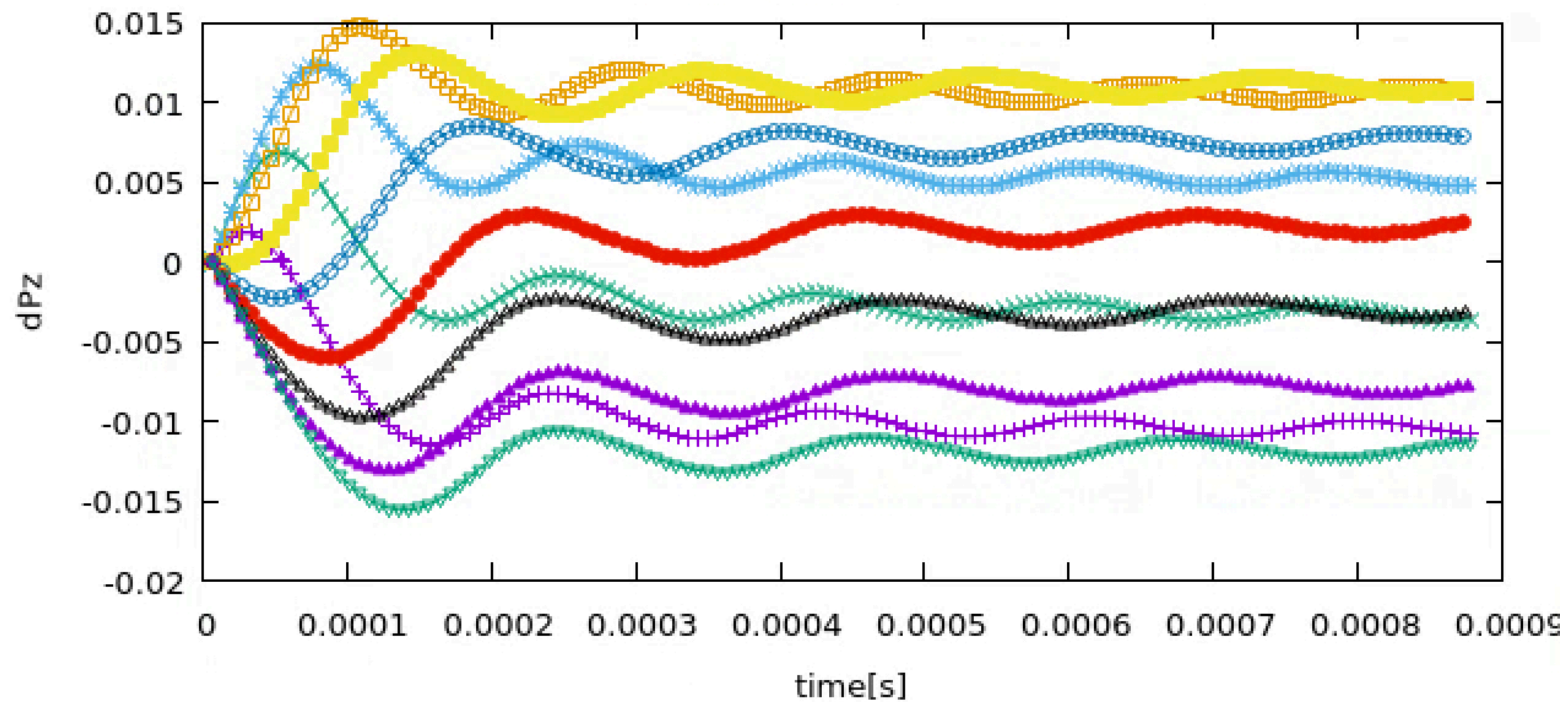


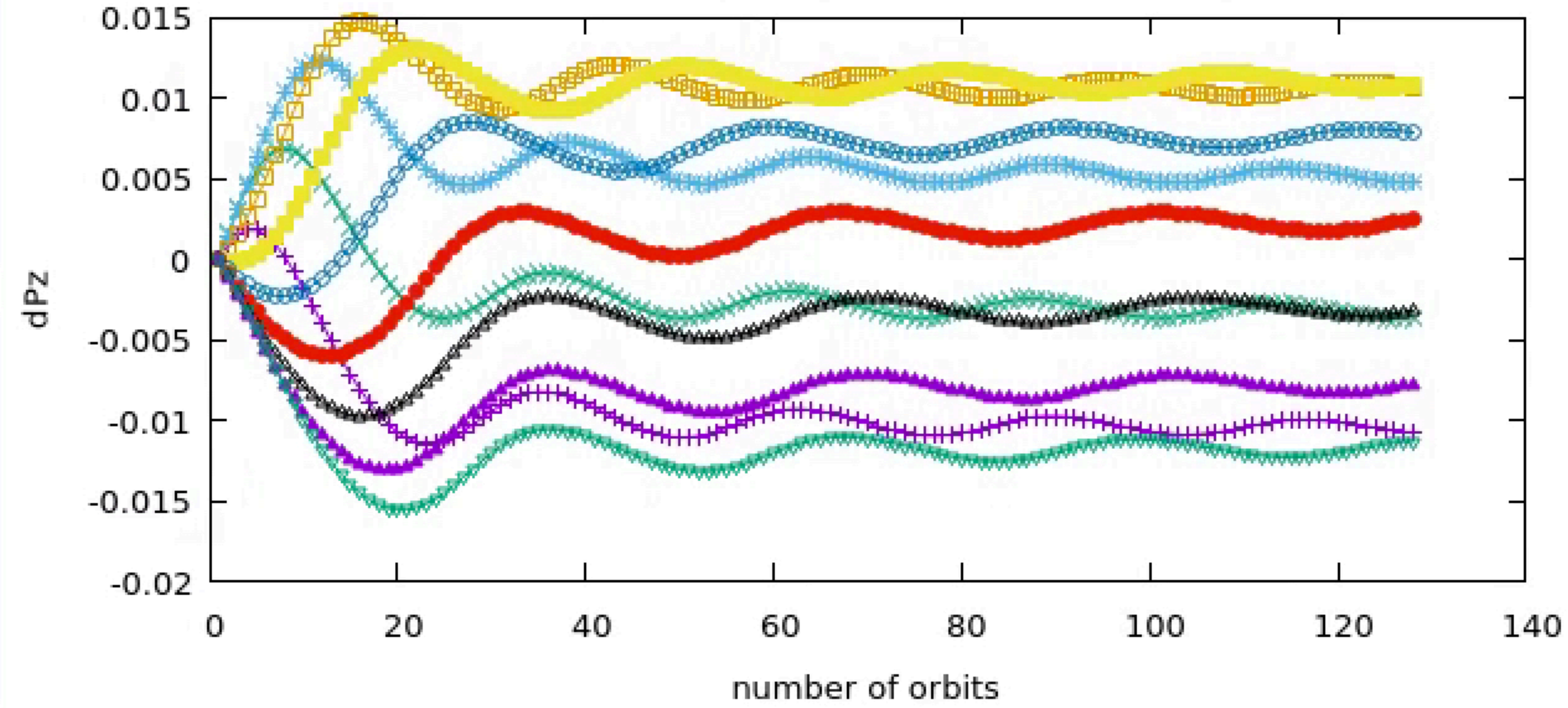
- distributions IDS holds all orbit-averaged information about marker space
- fast, repetitive calls of HAGIS library within IMAS are possible - **mapping between Pz and <radial position>**!

calculating PSZS using HAGIS

adding LIGKA calculated perturbation: follow set of market for wave-periods, time or number of orbits

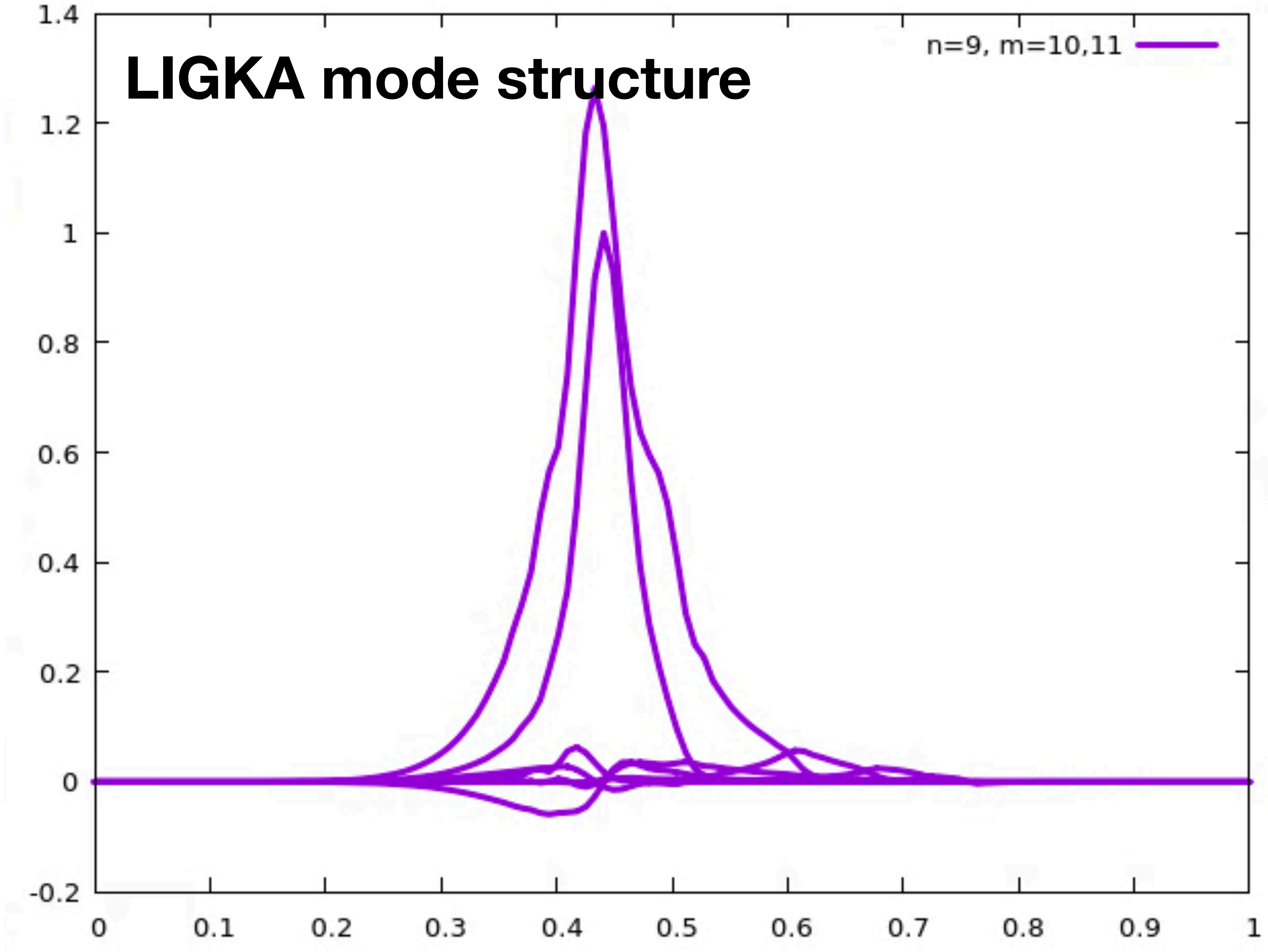
mid-radius, 1 MeV, He, co-passing, Λ=0, n=9 TAE with $dB/B=10^{-3}$





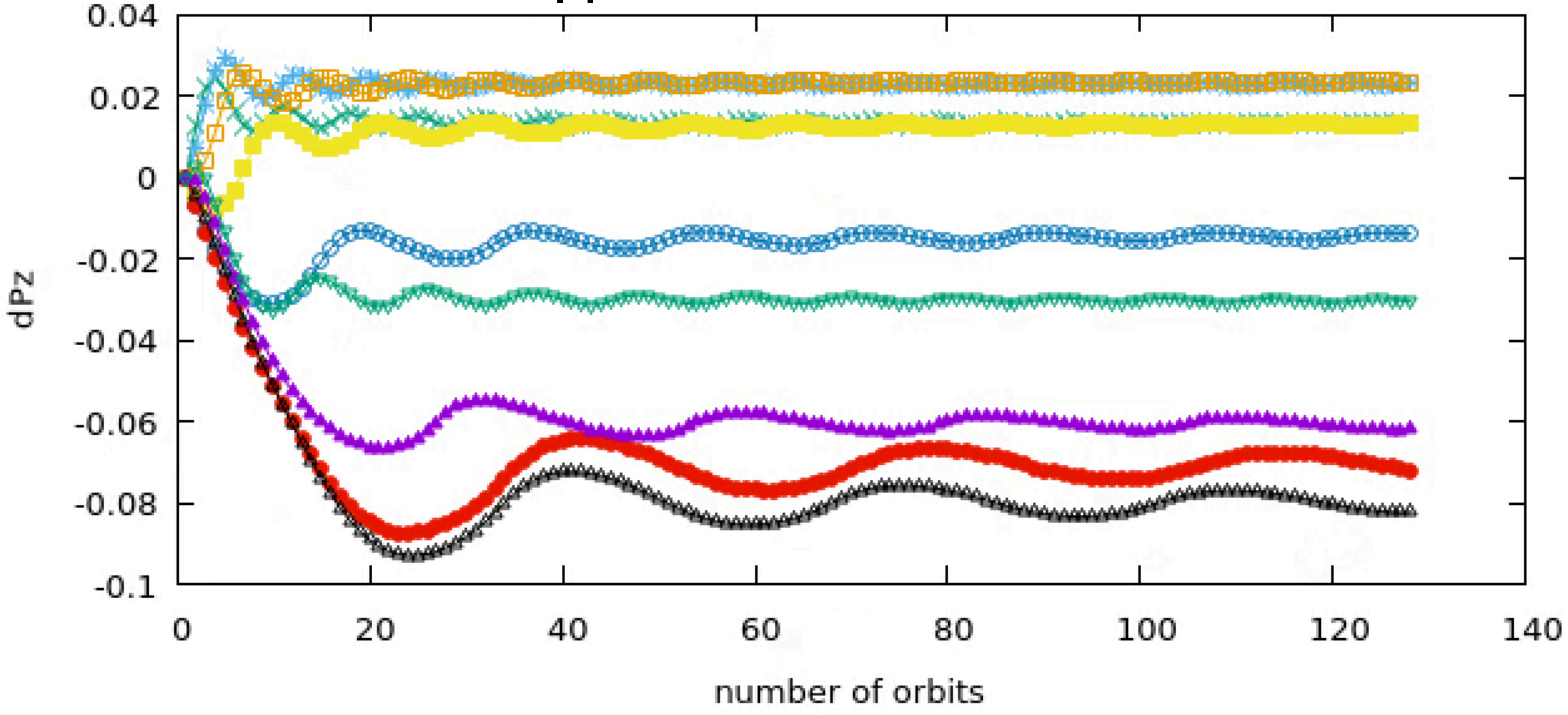
colours: different starting phase, 10 markers with starting tor. angle [0: 2π/n]

important: averaging over phase is crucial to obtain correct fluxes



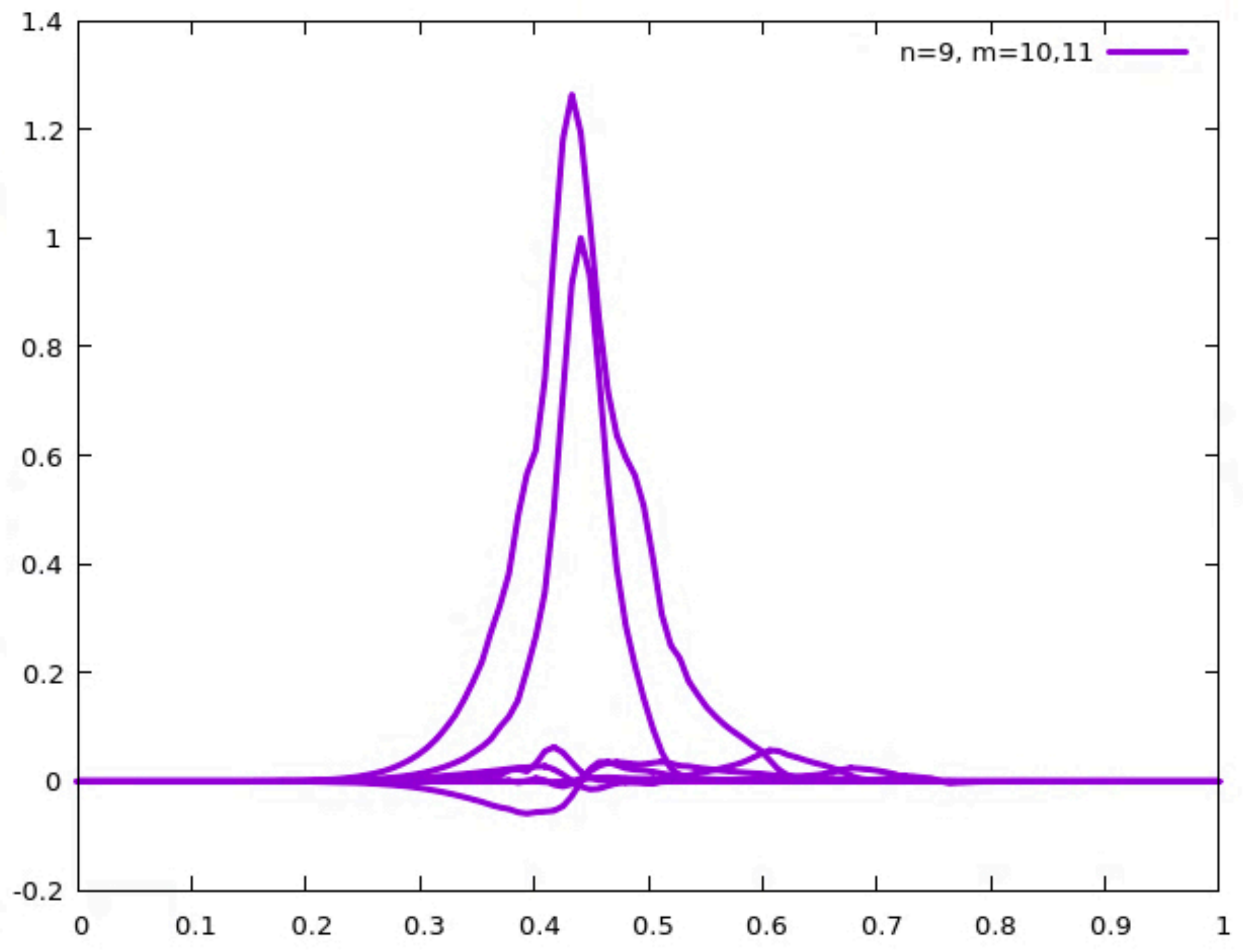
calculating PSZS using FINDER/HAGIS

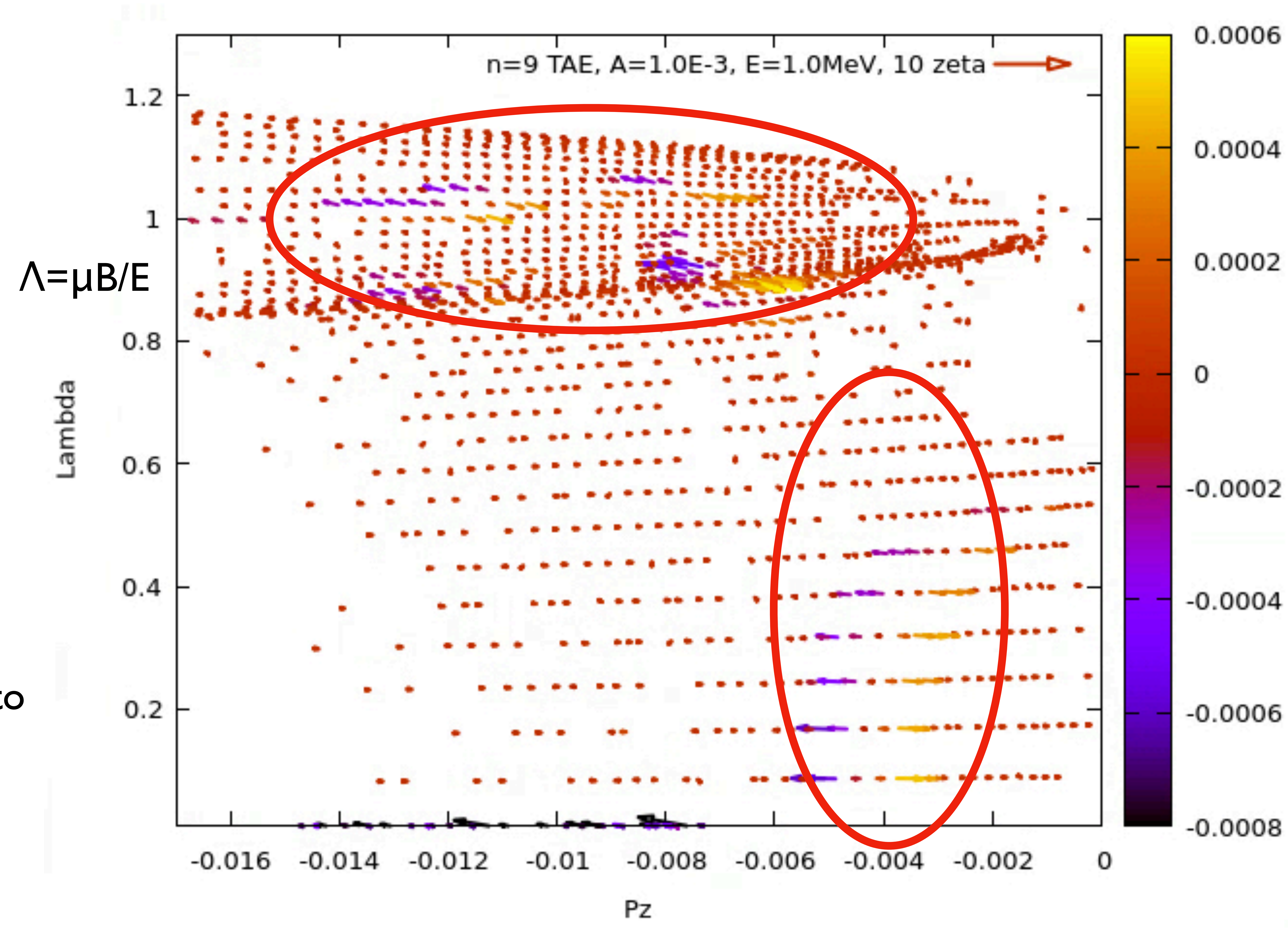
1 MeV, He, trapped, Λ=1.03, n=9 TAE with dB/B=10^{-3}



averaging over markers with different phase gives effective poloidally and toroidally averaged dPz

what is dPz, dE, dΛ for given perturbation after x completed orbits?



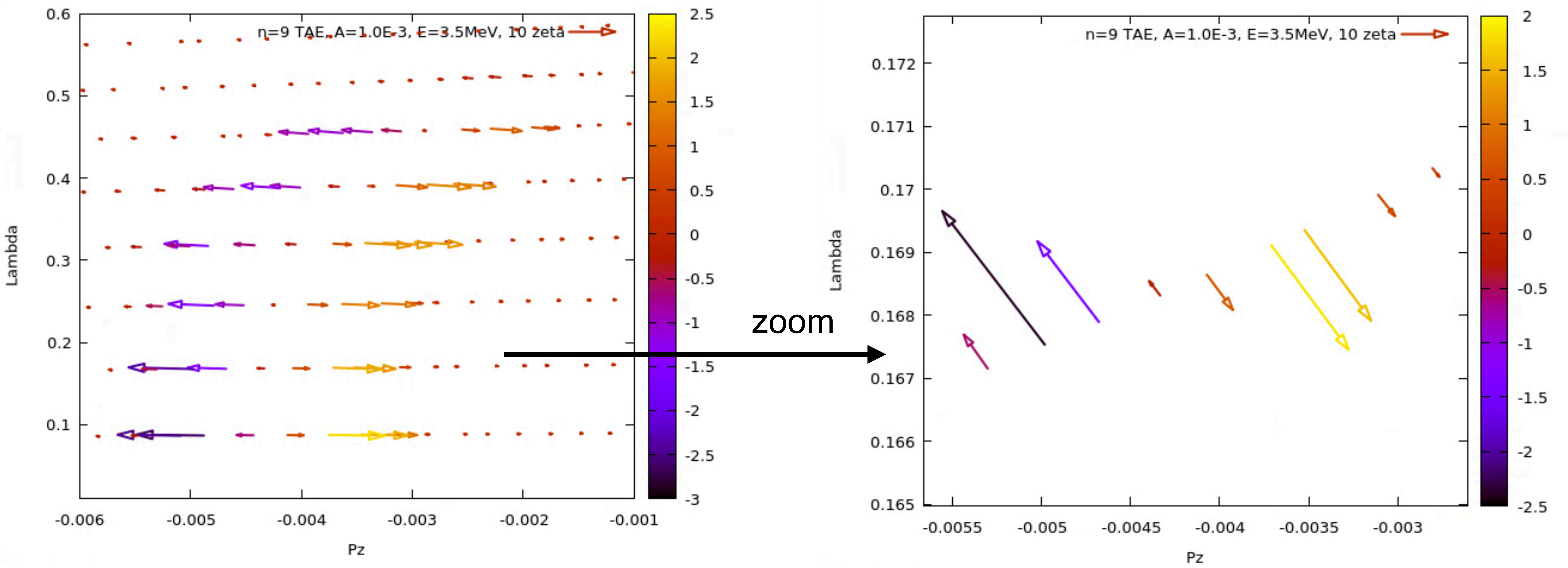


- arrows: initial (Pz,Λ) → (Pz+δPz,Λ+δΛ)
- color: δPz
- averages over 10 phases, 10 orbits
- 3-5 minutes to calculate
- modular structure of wrapper code allows to replace HAGIS with newer/faster code of same functionality

calculate fluxes: dPz/dt [(eV/s)/s]

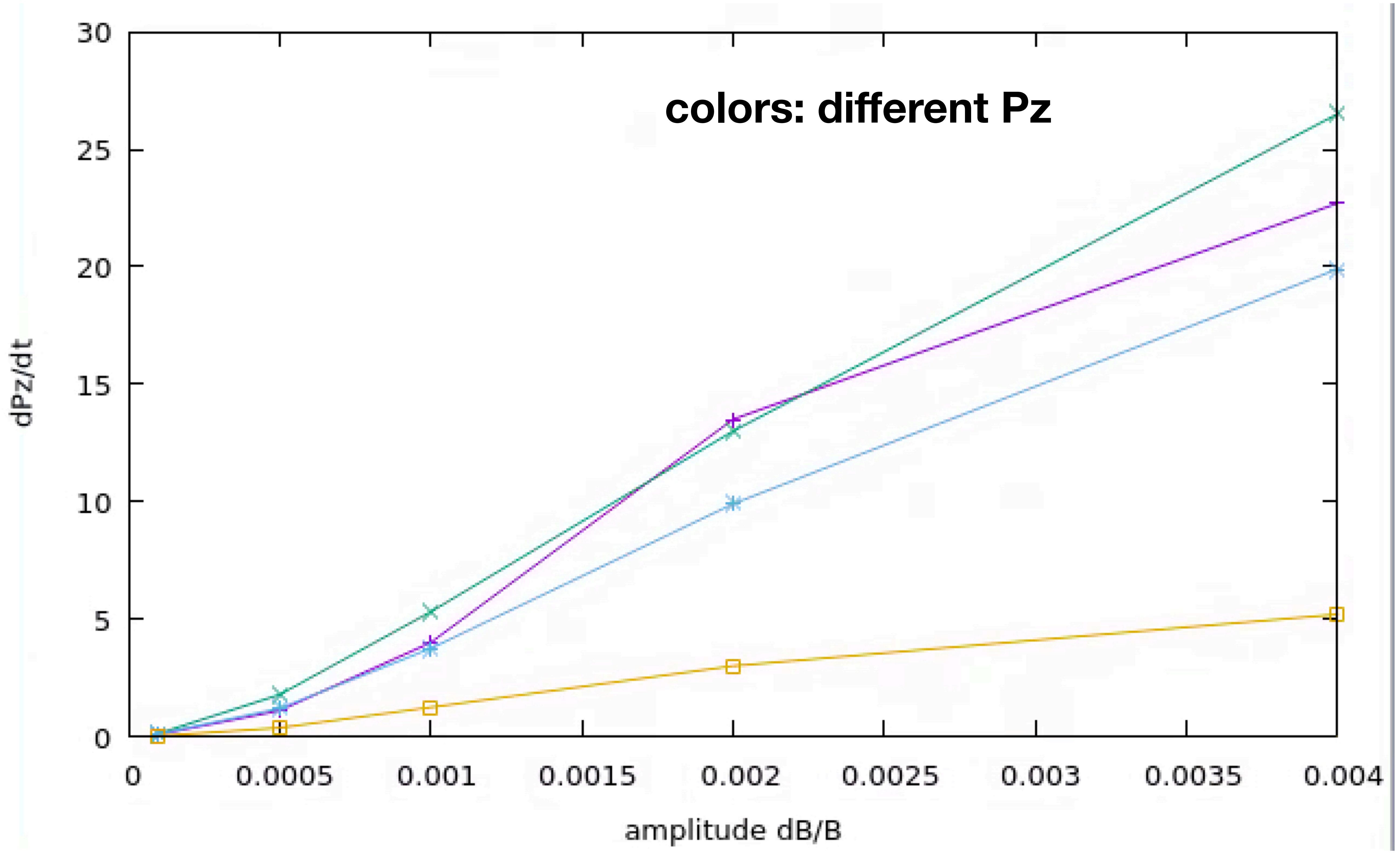
color: dPz/dt

color: dPz/dt



- divide δPz by orbit transit time and number of orbits (here 32)
- the same information is available for Λ and E
- transport coefficients $D_{Pz}=(dPz)^2/dt$ and $K_{Pz}=(dPz)/dt$ can be evaluated

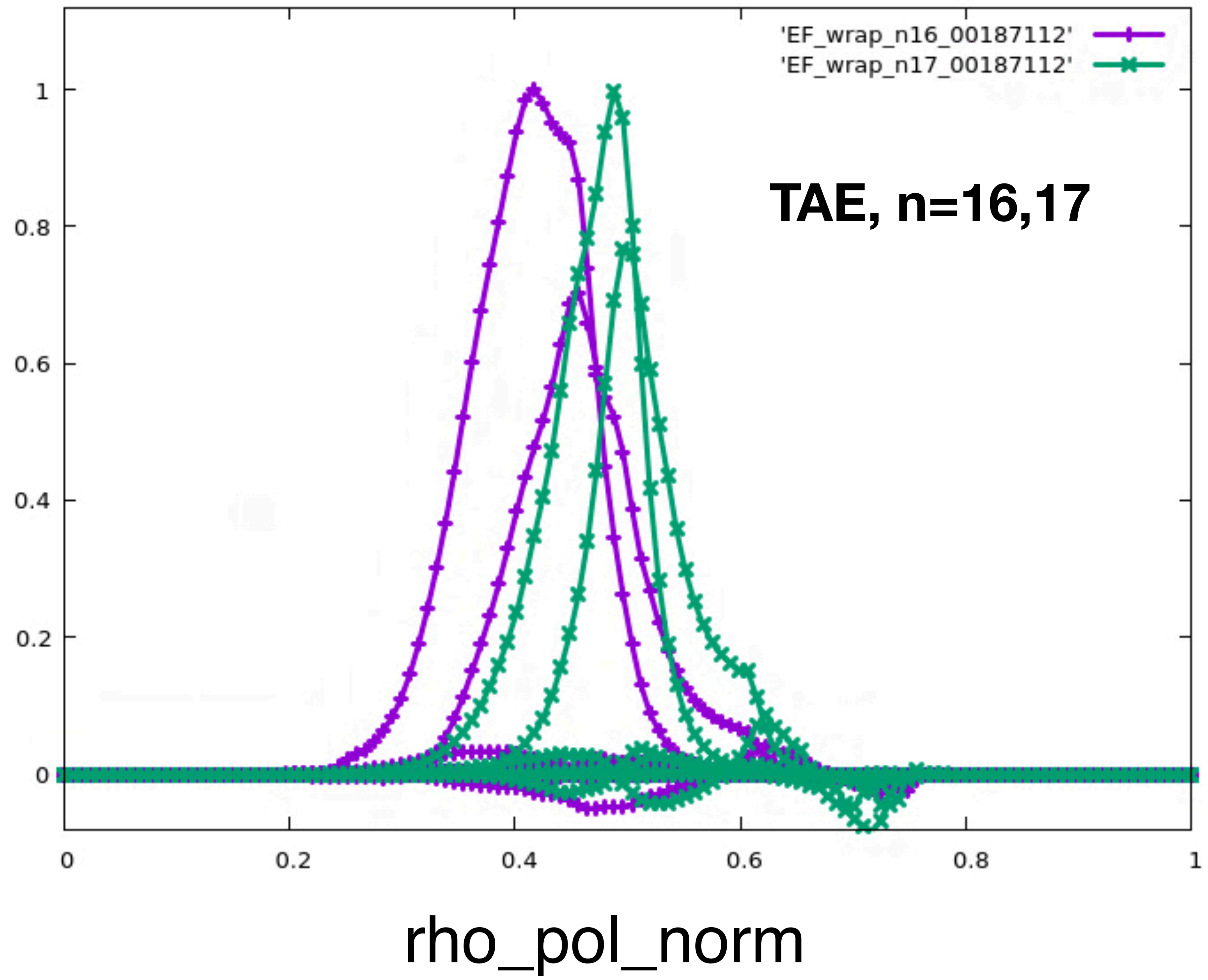
determine amplitude dependence: dB/B =[10^{-4} - $4 \cdot 10^{-3}$]

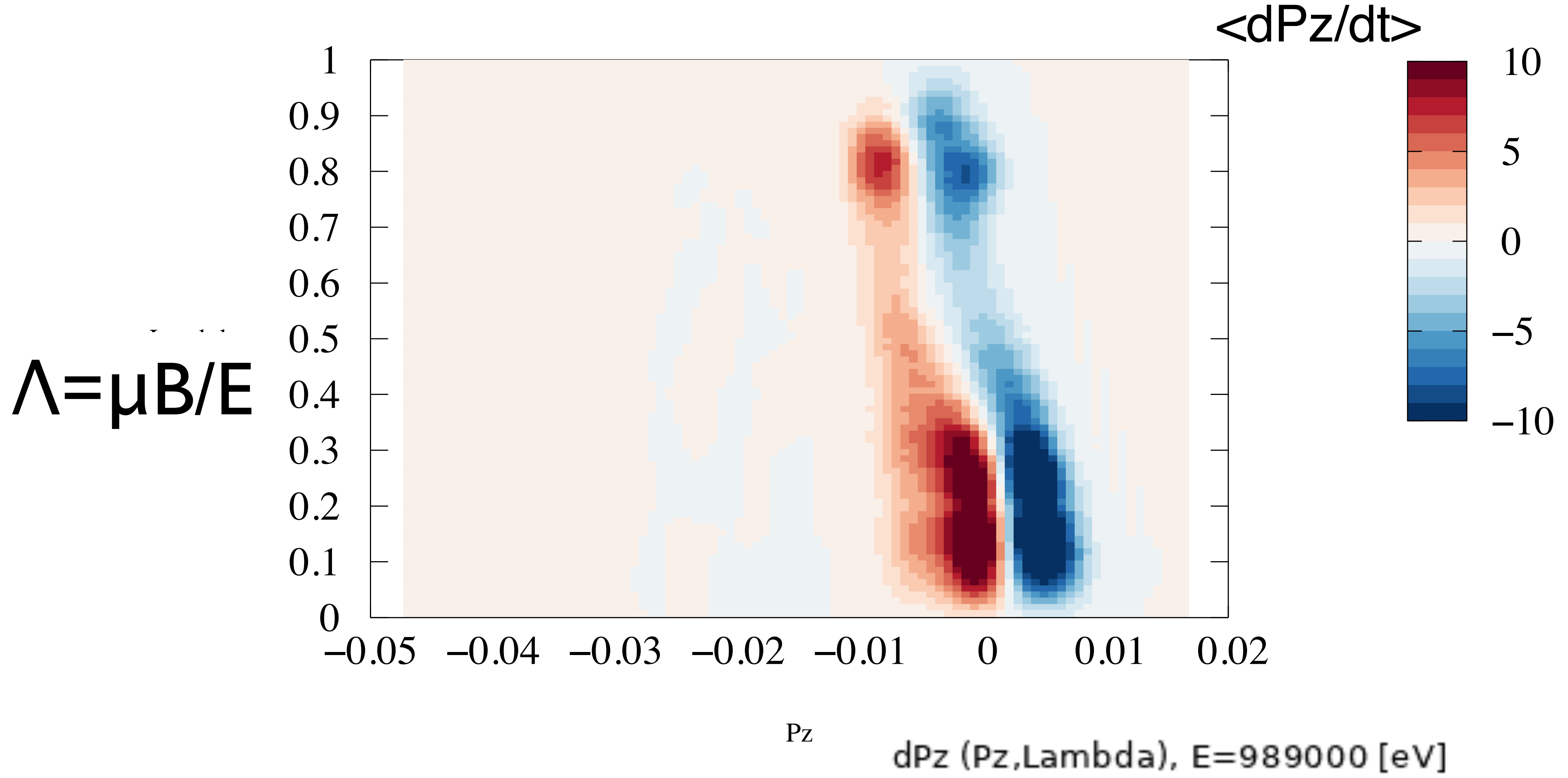


- dPz/dt as function of perturbation size: simple interpolation captures the amplitude scaling

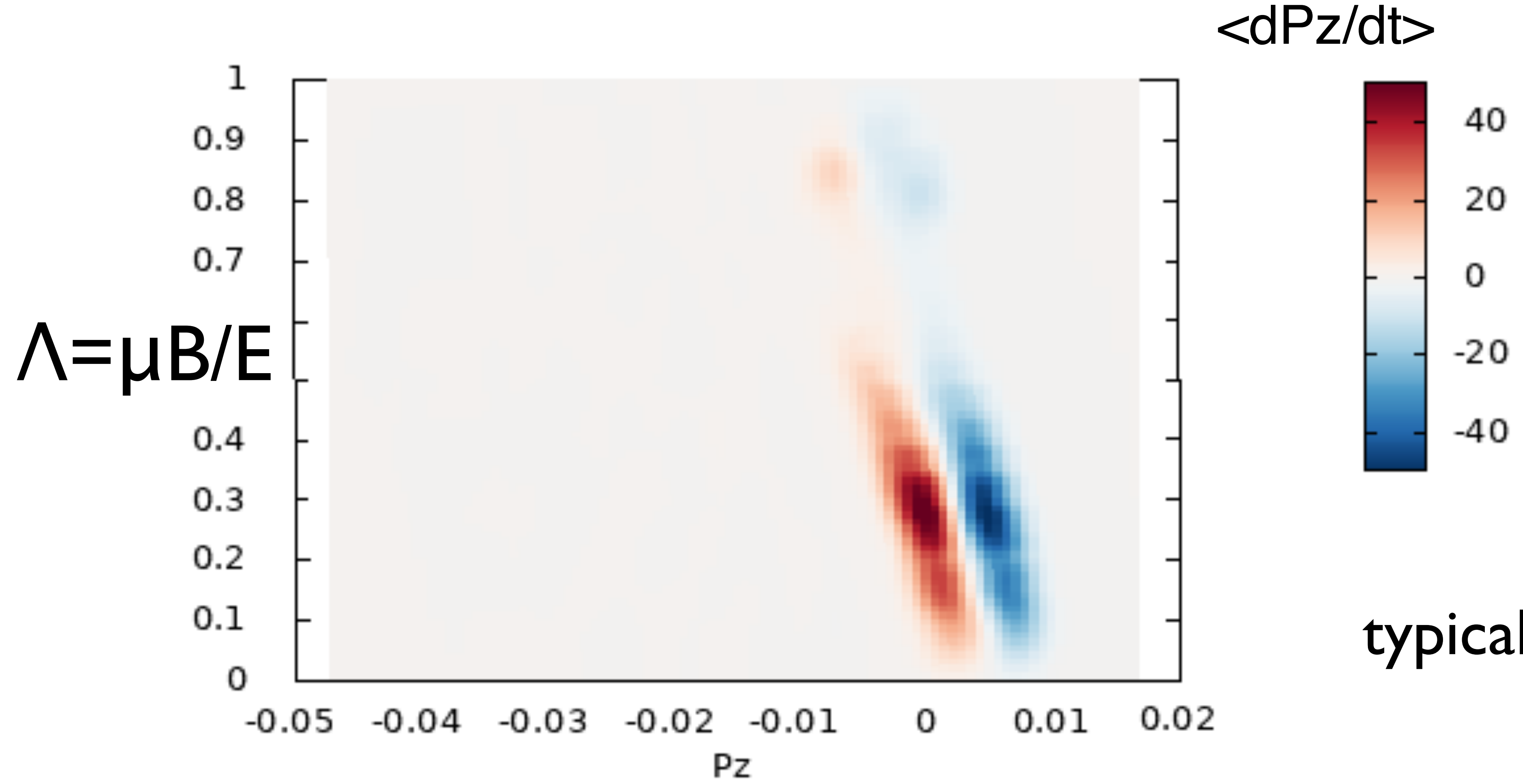
implementation details: construct 3d spline in COM space

- calculate <dPz/dt> , <dE/dt> for given fixed mode structures at fixed amplitude with FINDER/HAGIS, write into IDS ($dB/B=5*10^{-3}$)
- ATEP code: read PSZS data, use 3D bspline methods to create <dPz/dt> , <dE/dt> on 3D grid as F_{EP}
- use 3d scattered-data b-spline algorithm [Scattered Data Interpolation with Multilevel B-Splines, Lee 1997] - post-smoothing





co-passing particles, energy averaged



typical grid: (Pz,E,Λ) (128x40x40)

implementation details: example ITER 100015,1

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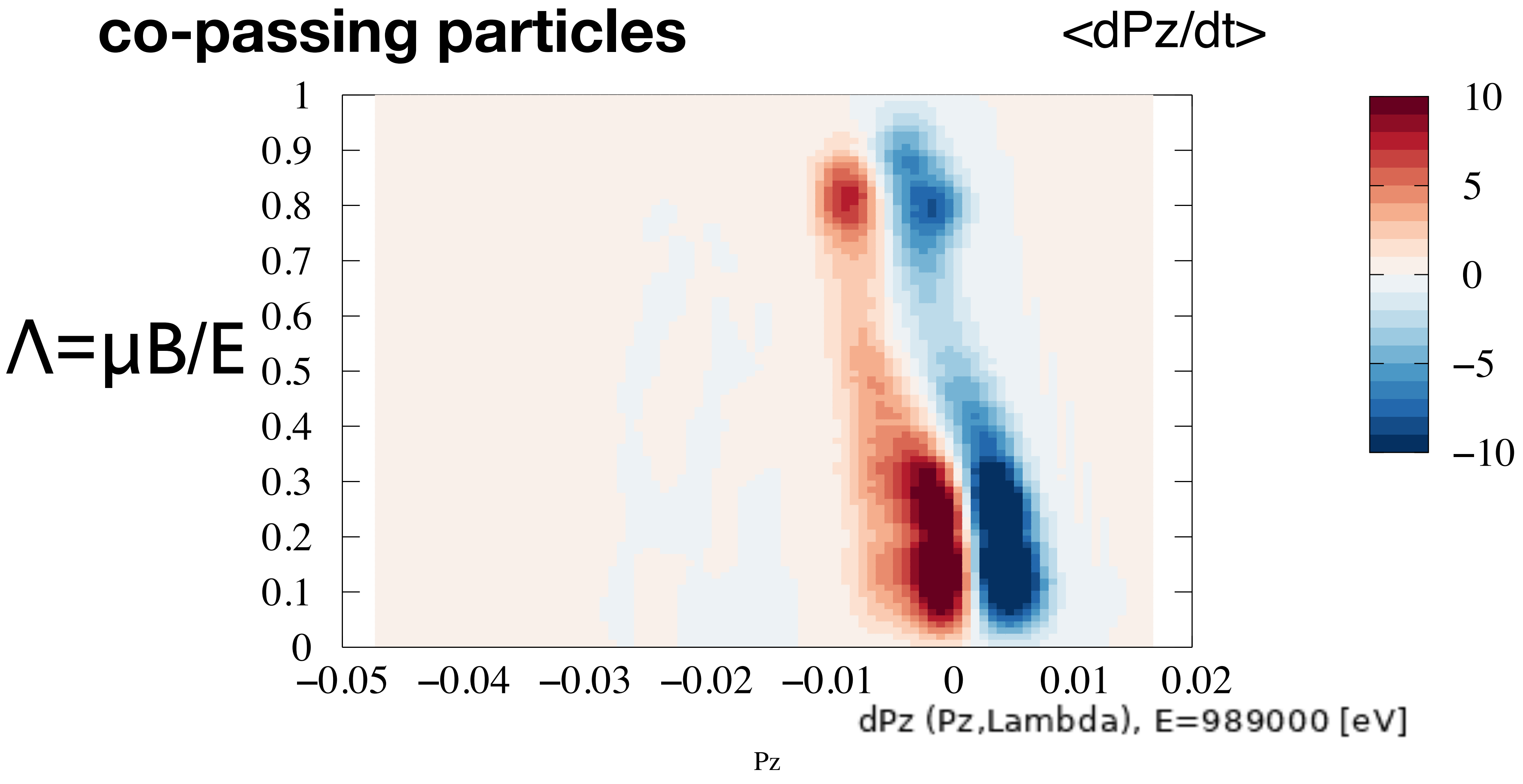
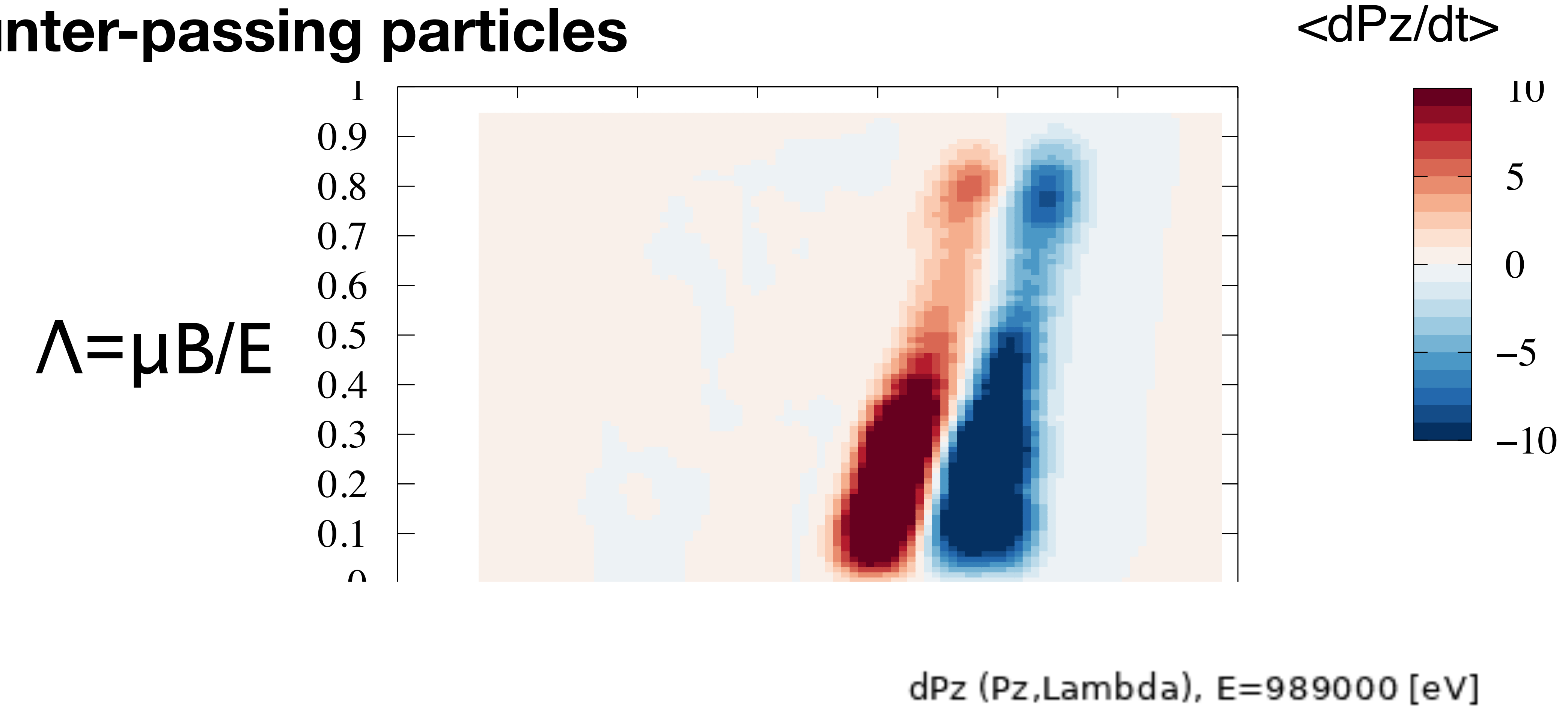
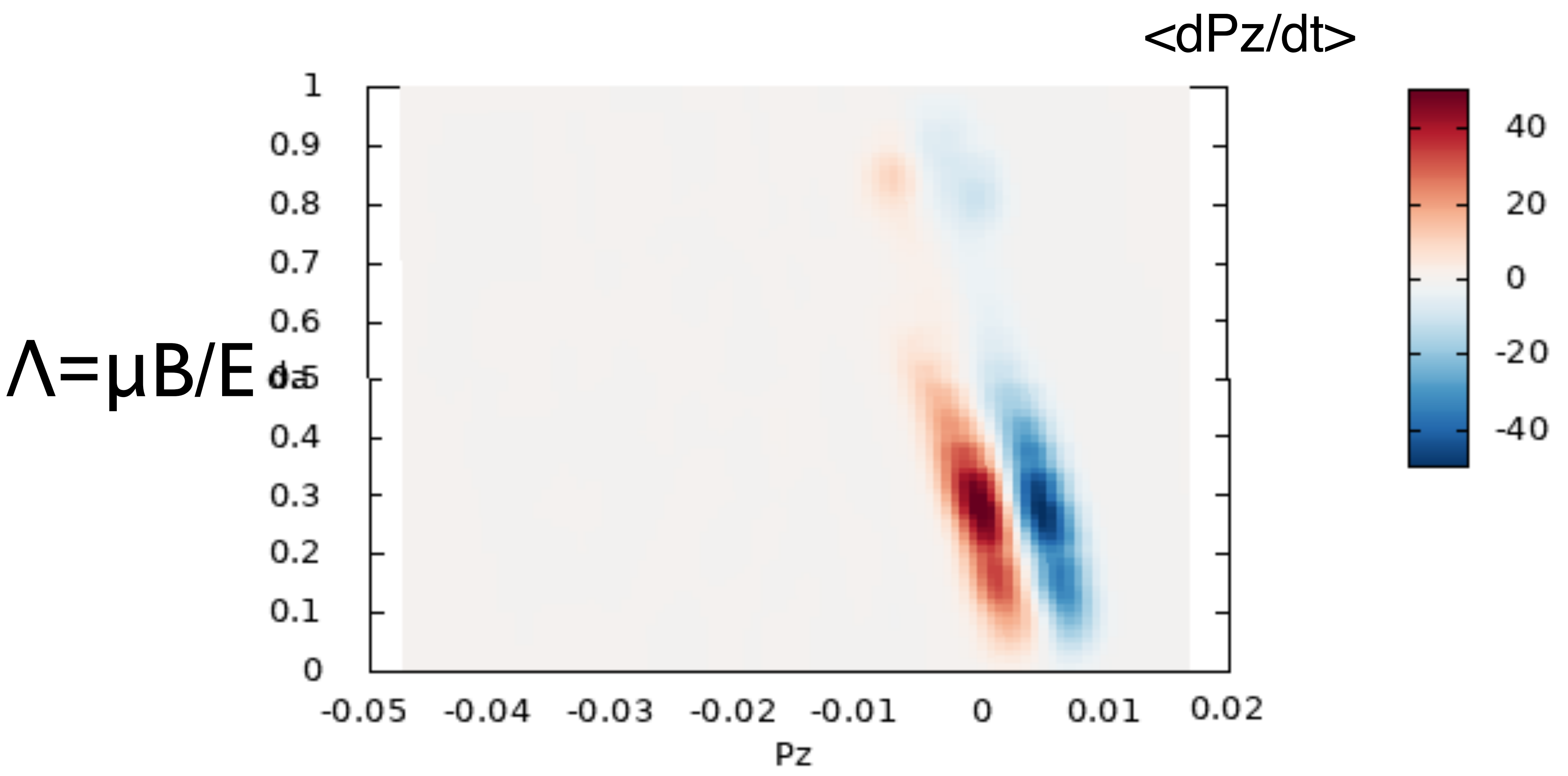
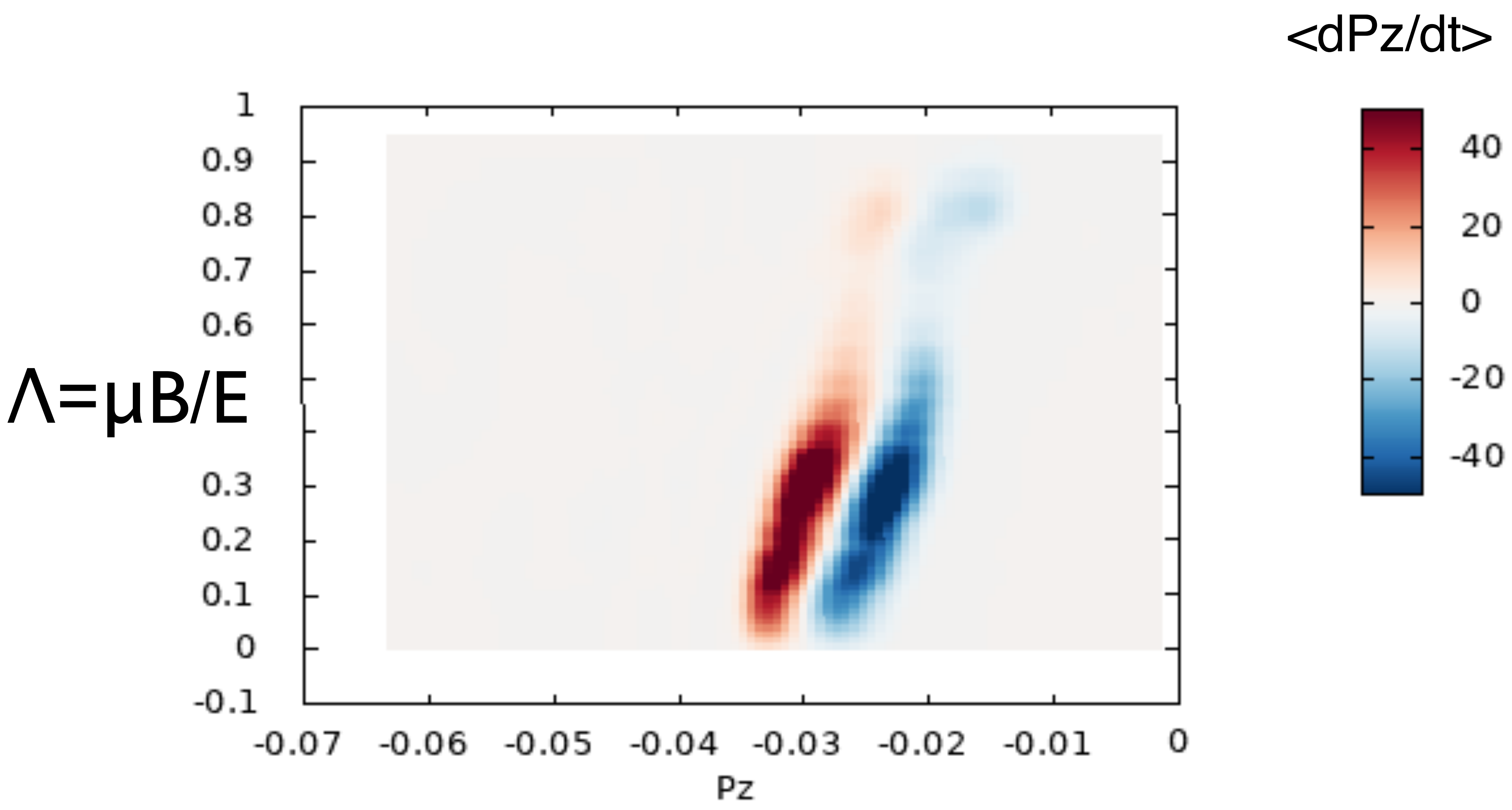
co-passing particles



counter-passing particles





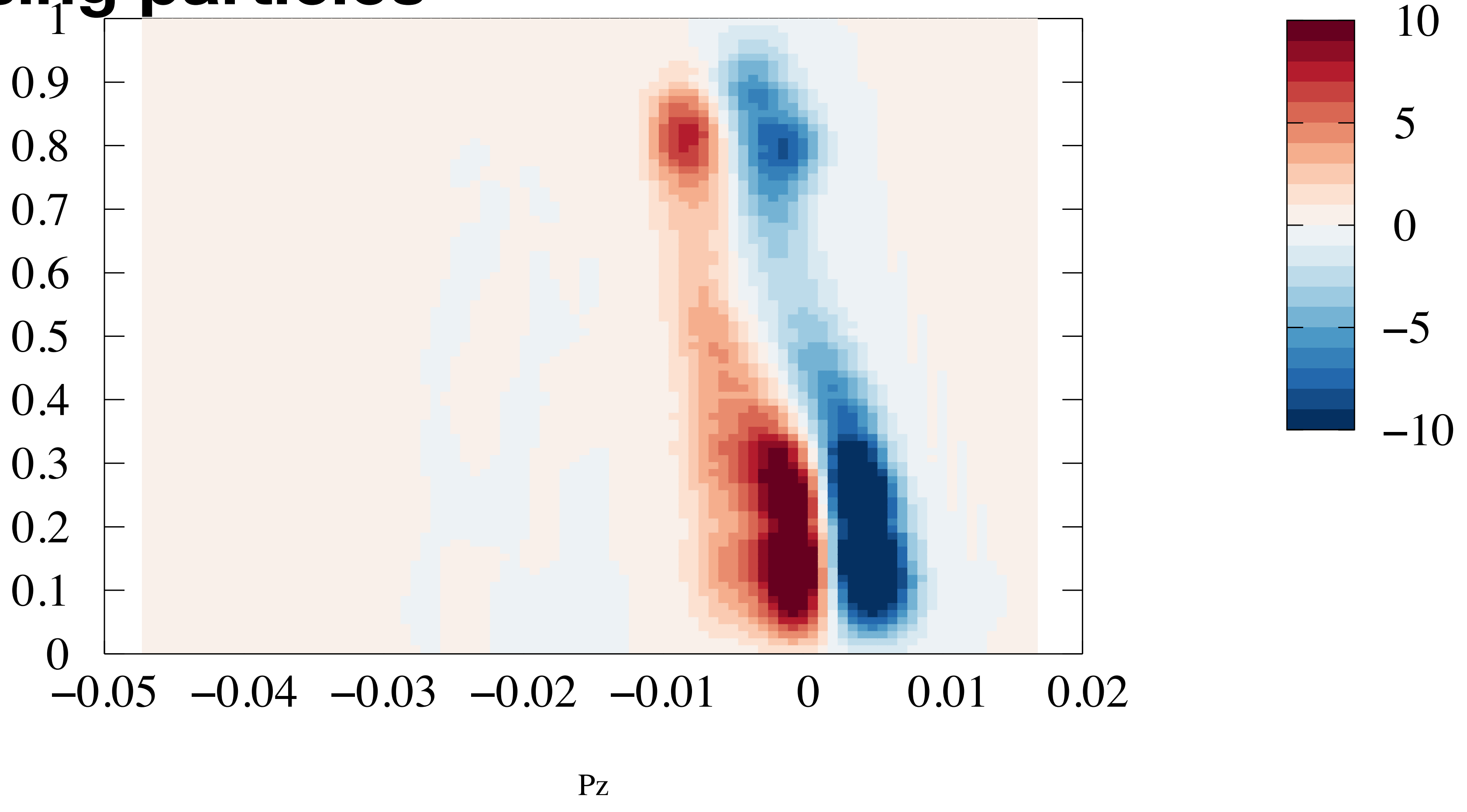


teral International

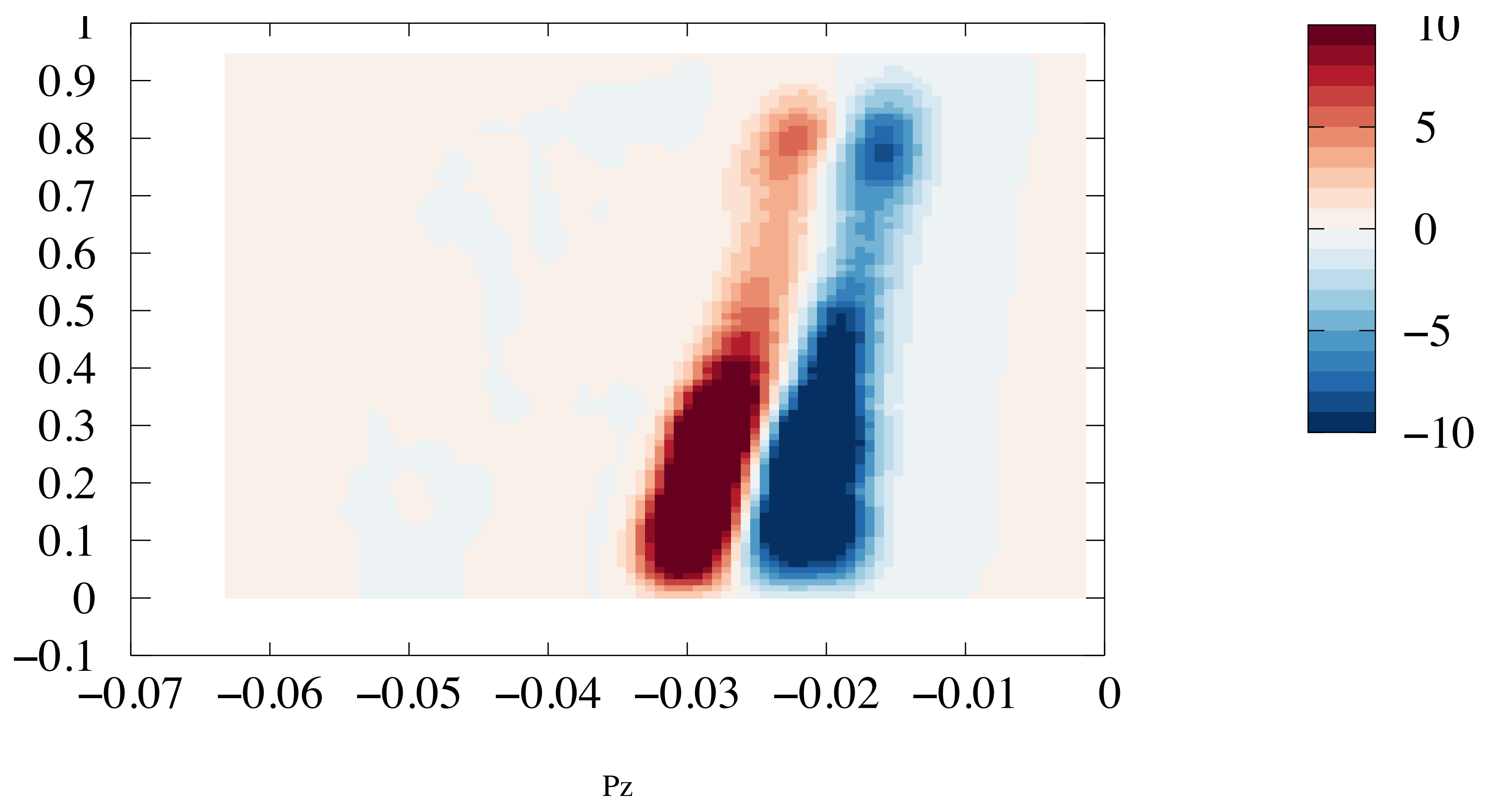
implementation details: example ITER 100015,1

- calculate <dPz/dt> , <dE/dt> for given fixed mode structures at fixed amplitude with FINDER/HAGIS, write into IDS
- ATEP code: read PSZS data, use 3D bspline methods to create <dPz/dt> , <dE/dt> on 3D grid as F_{EP}
- use 3d scattered-data b-spline algorithm [Scattered Data Interpolation with Multilevel B-Splines, Lee 1997] - post-smoothing

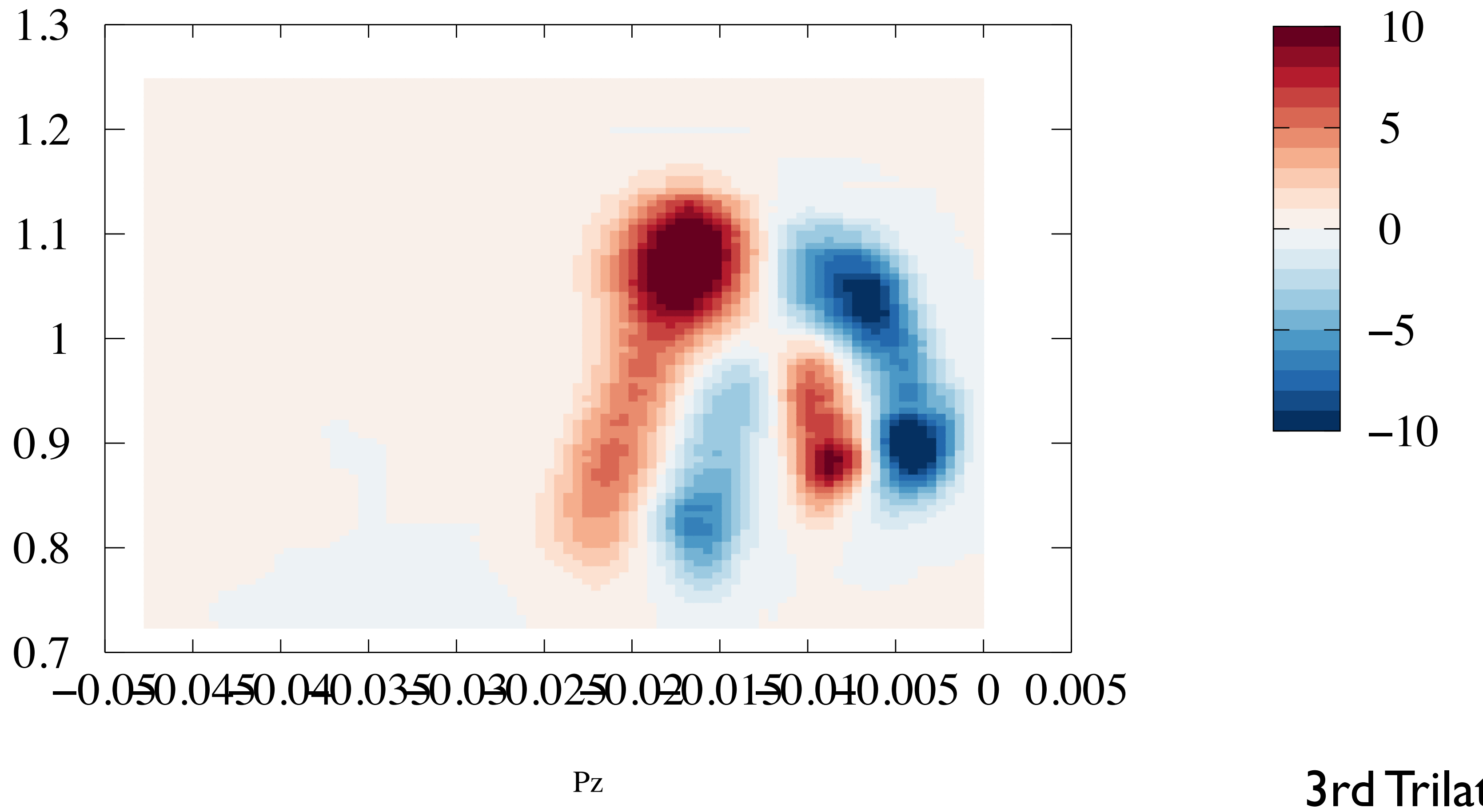
co-passing particles



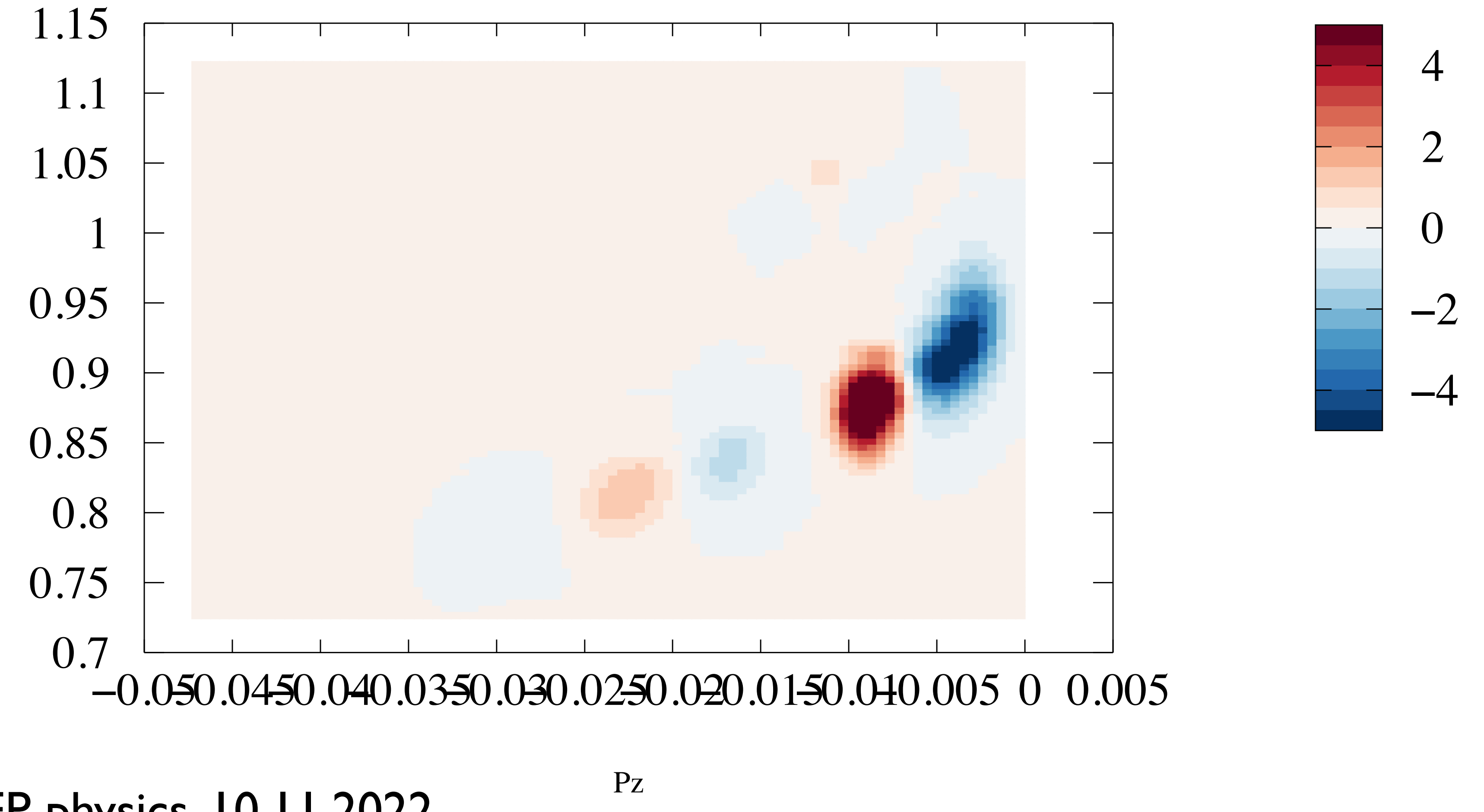
counter-passing particles



trapped particles



potato particles



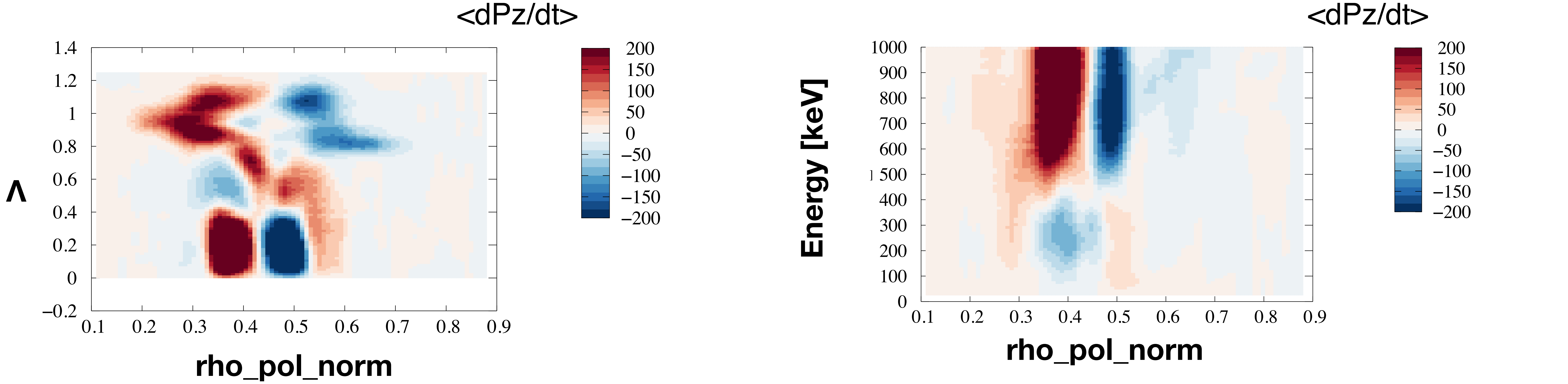
implementation details: example ITER 100015,1

MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

- calculate <dPz/dt> , <dE/dt> for given fixed mode structures at fixed amplitude with FINDER/HAGIS, write into IDS
- ATEP code: read PSZS data, use 3D bspline methods to create <dPz/dt> , <dE/dt> on 3D grid as F_{EP}
- use 3d scattered-data b-spline algorithm [Scattered Data Interpolation with Multilevel B-Splines, Lee 1997] - post-smoothing

all particles:

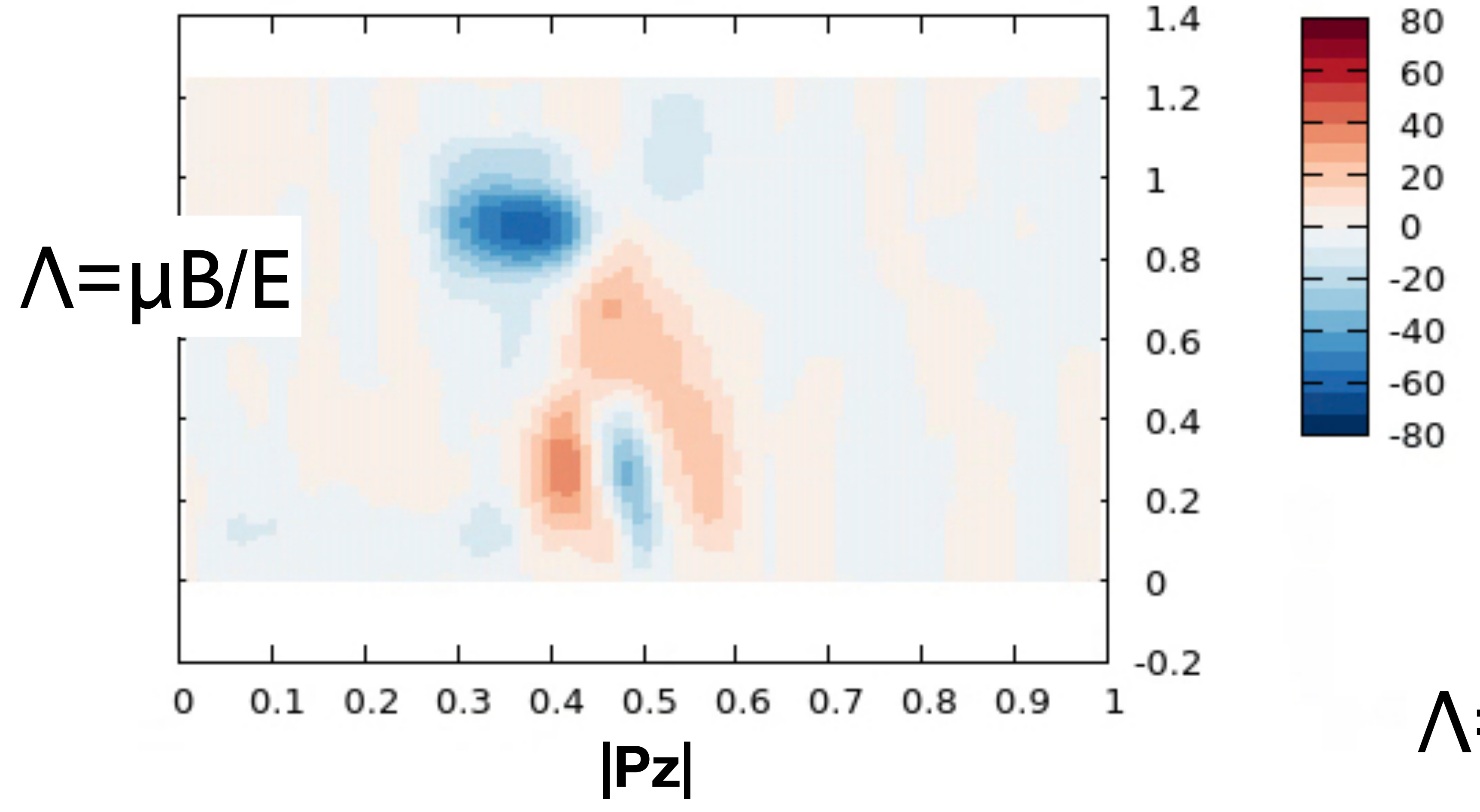
can be easily mapped to <s>:



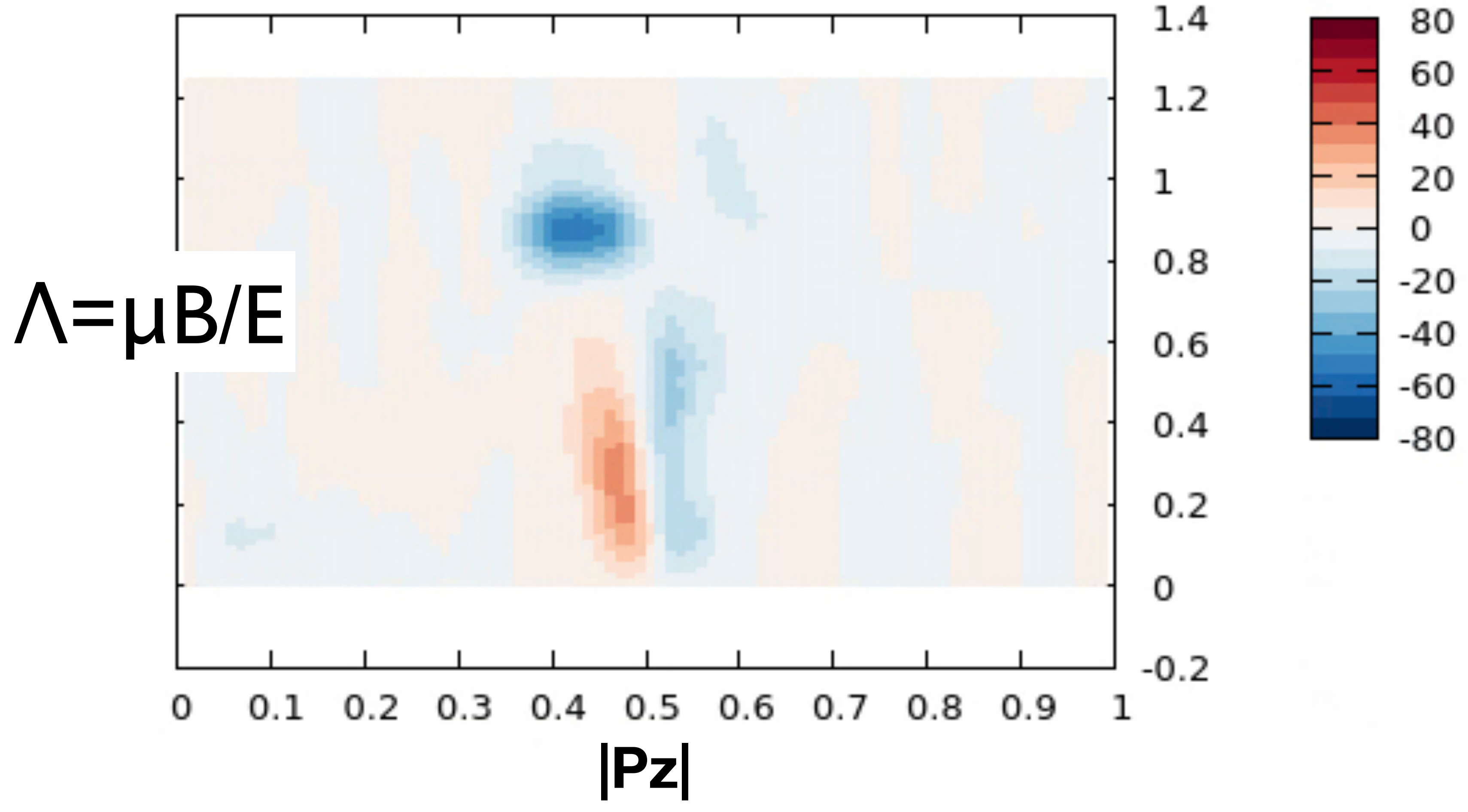
similar for <dE/dt>

detailed insight into multi-mode cases: amplitude scan: **dB/B=0.5 *10⁻³**

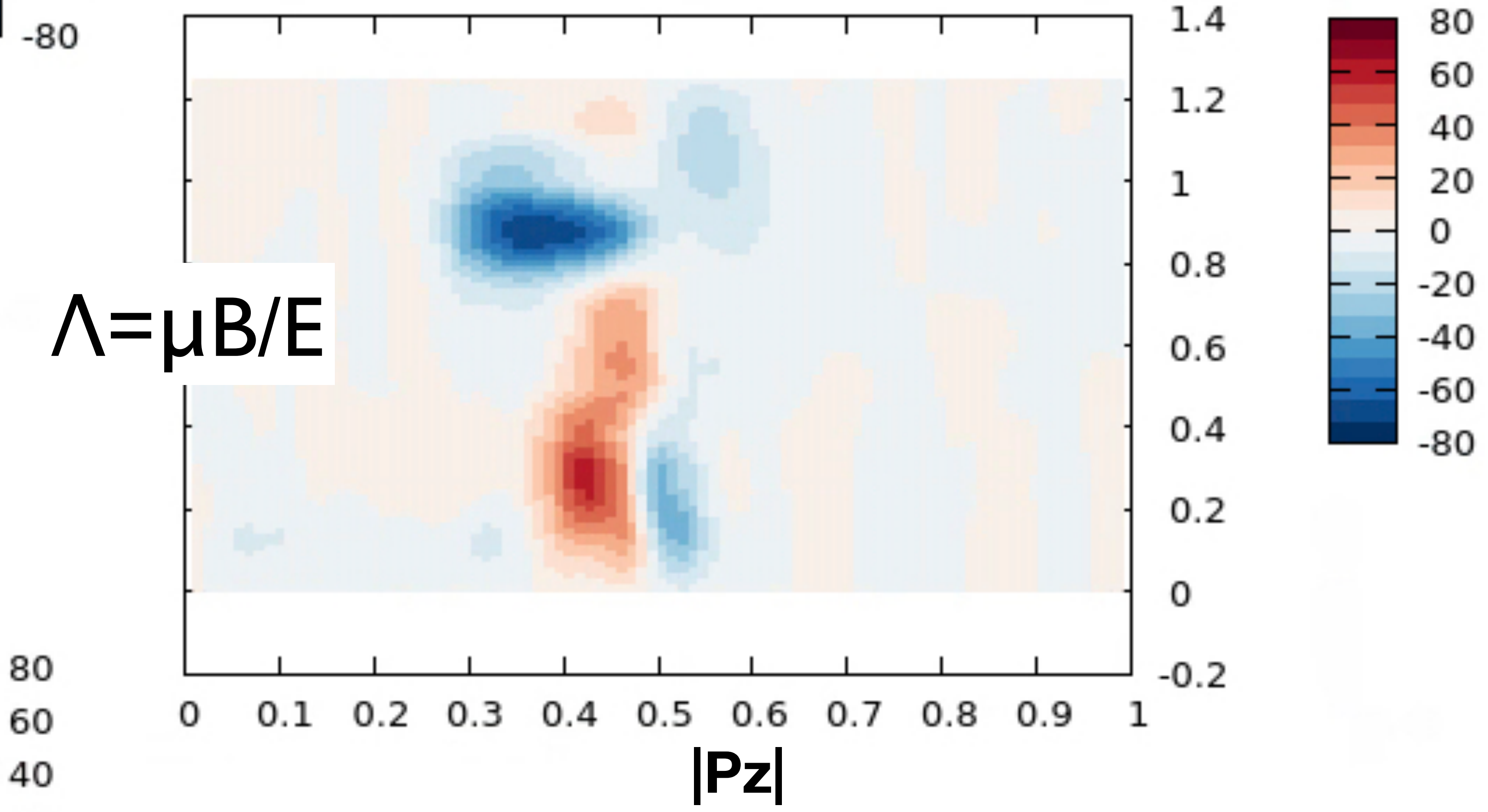
n=16 single



n=17 single

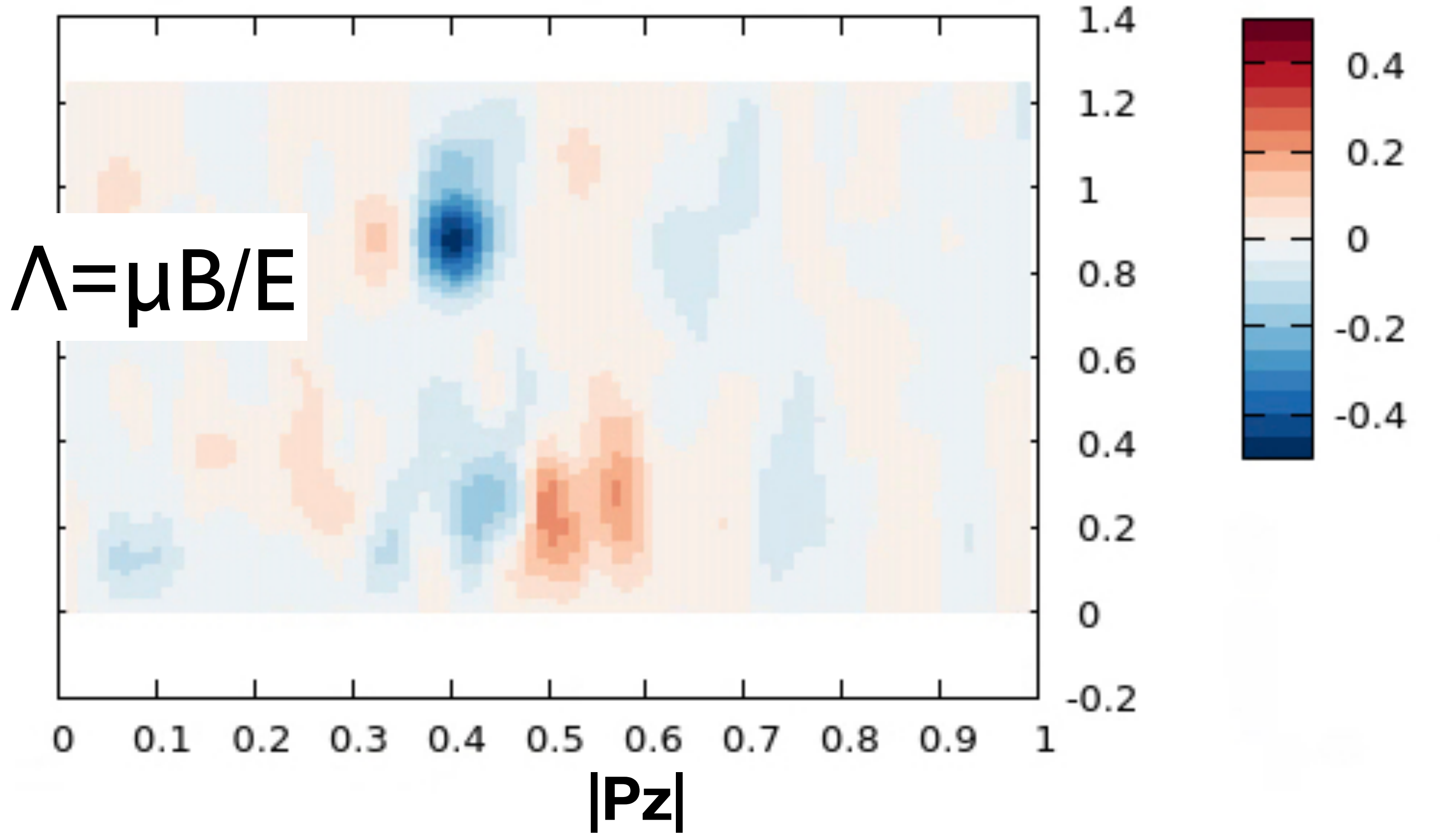


n=16+17 both



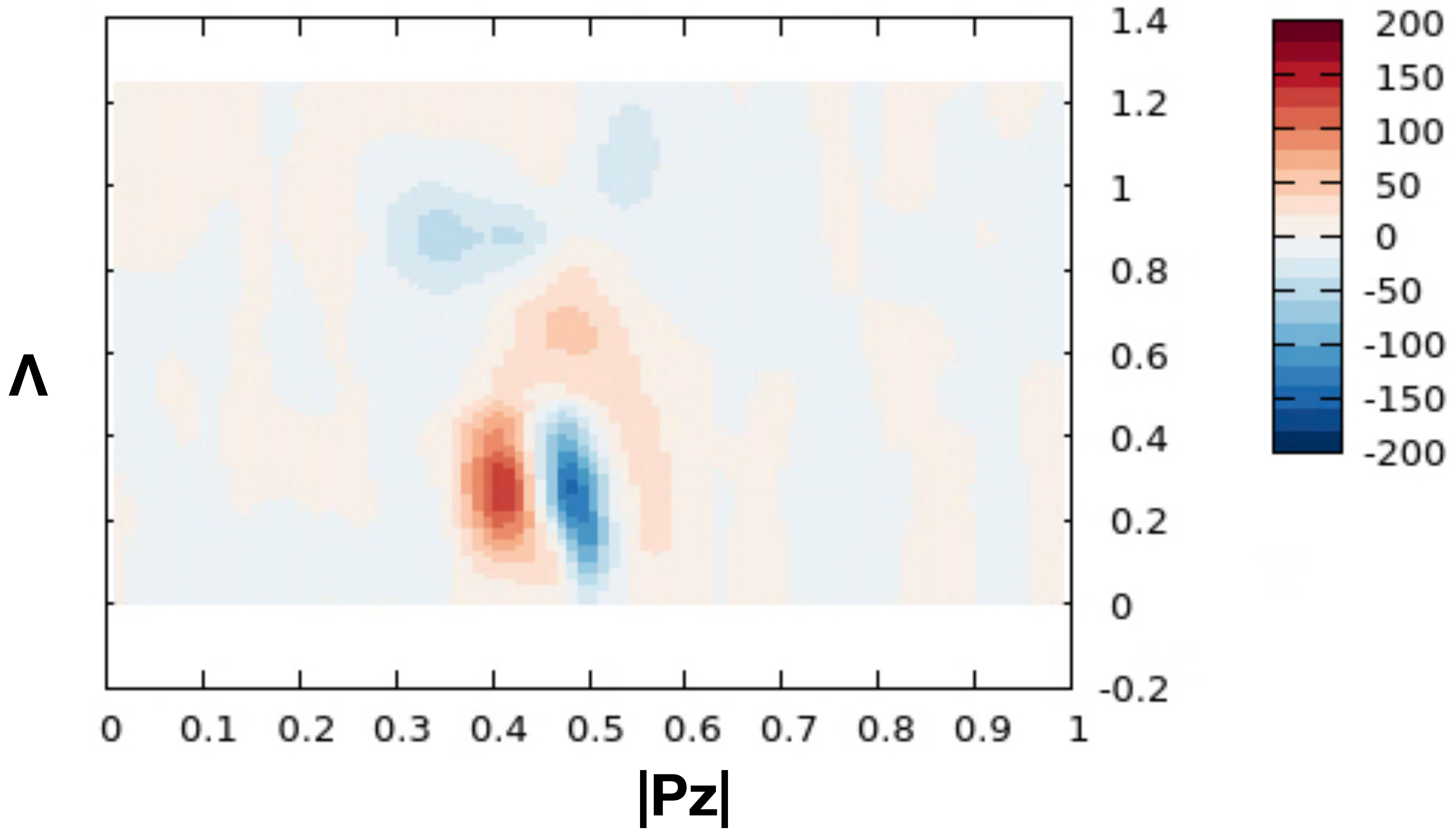
relative difference

$$\frac{(P16+P17)-P(16+17)}{P(16+17)max}$$

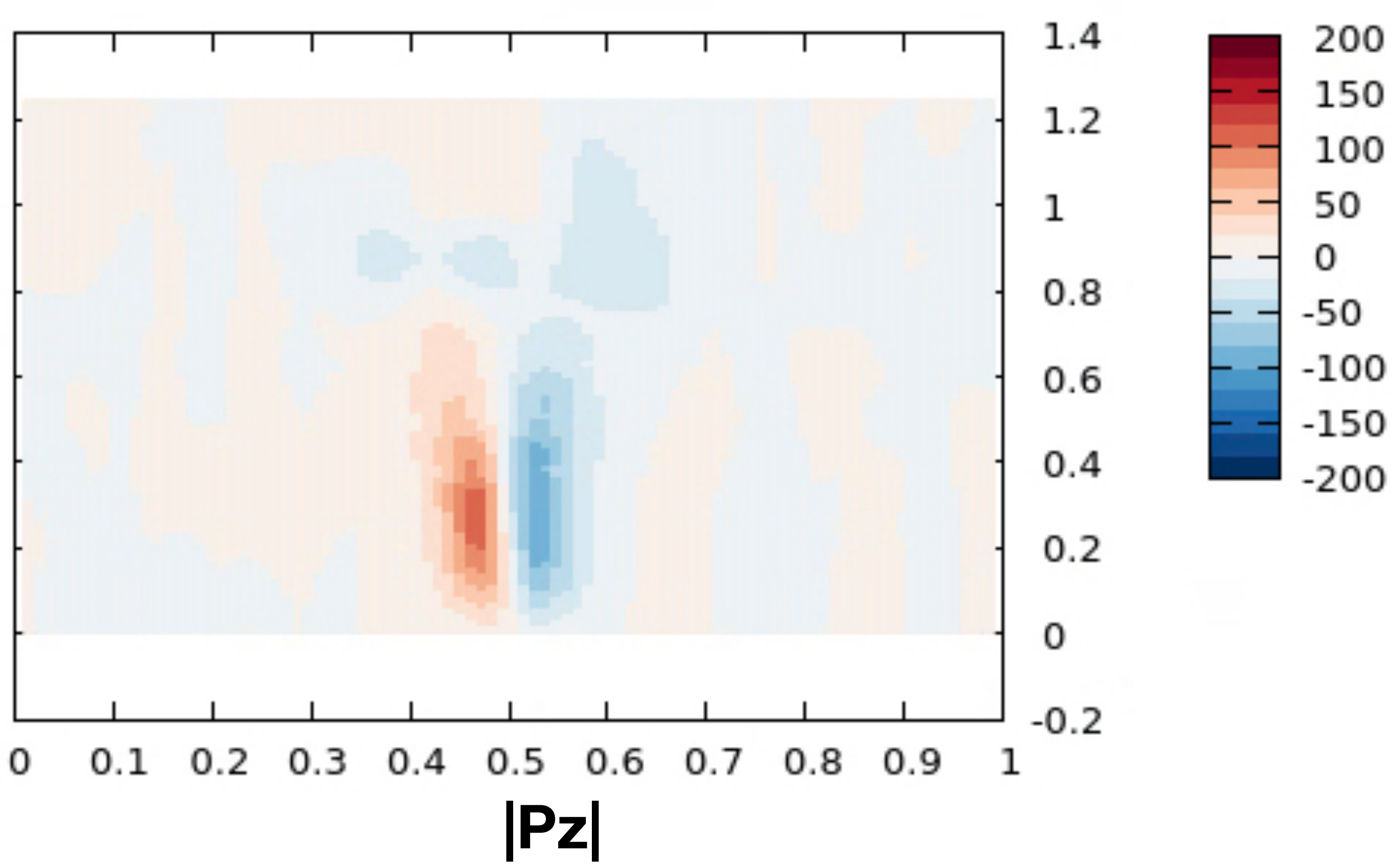


detailed insight into multi-mode cases: amplitude scan: **dB/B=1 *10^{-3}**

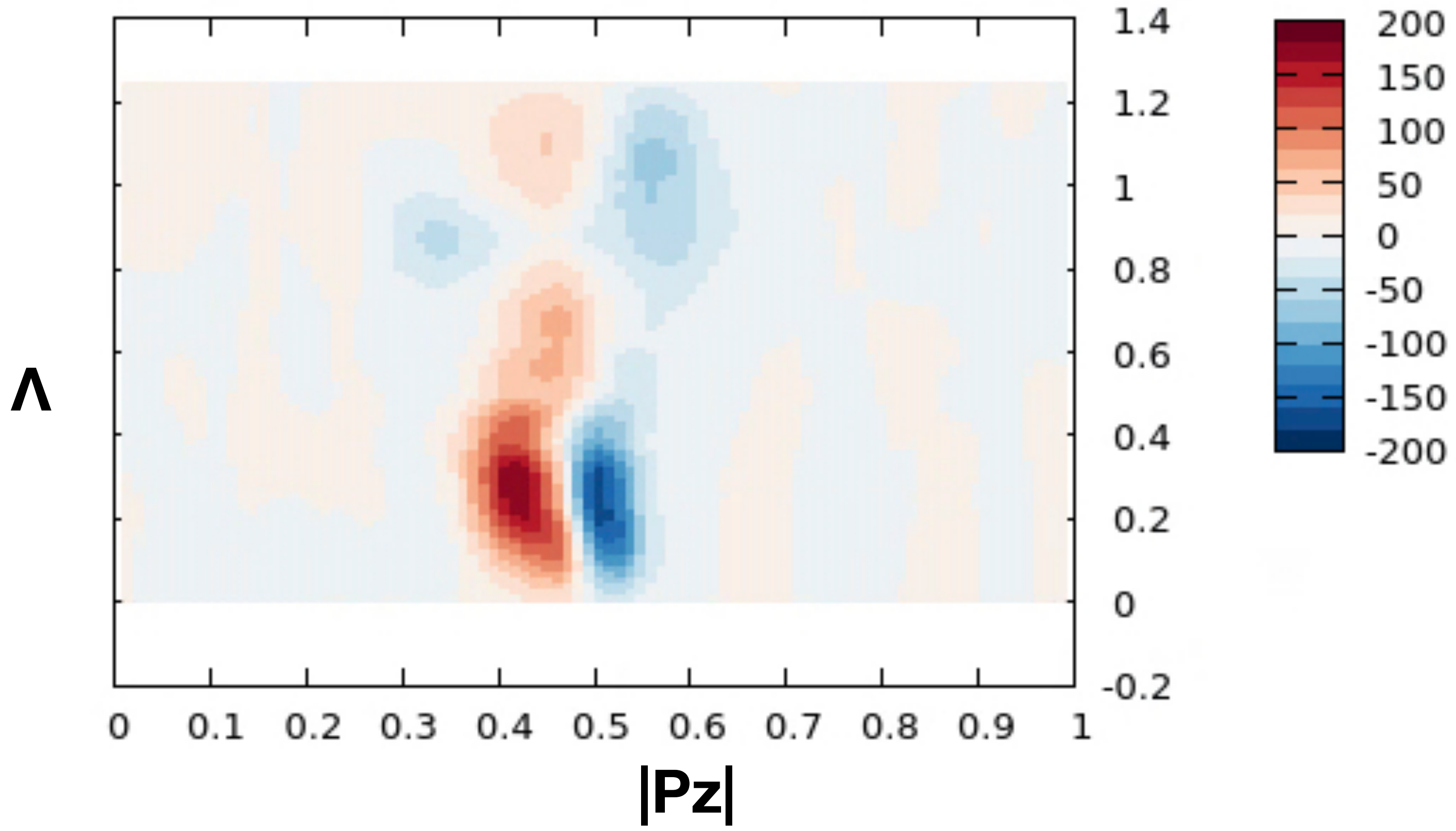
n=16 single



n=17 single

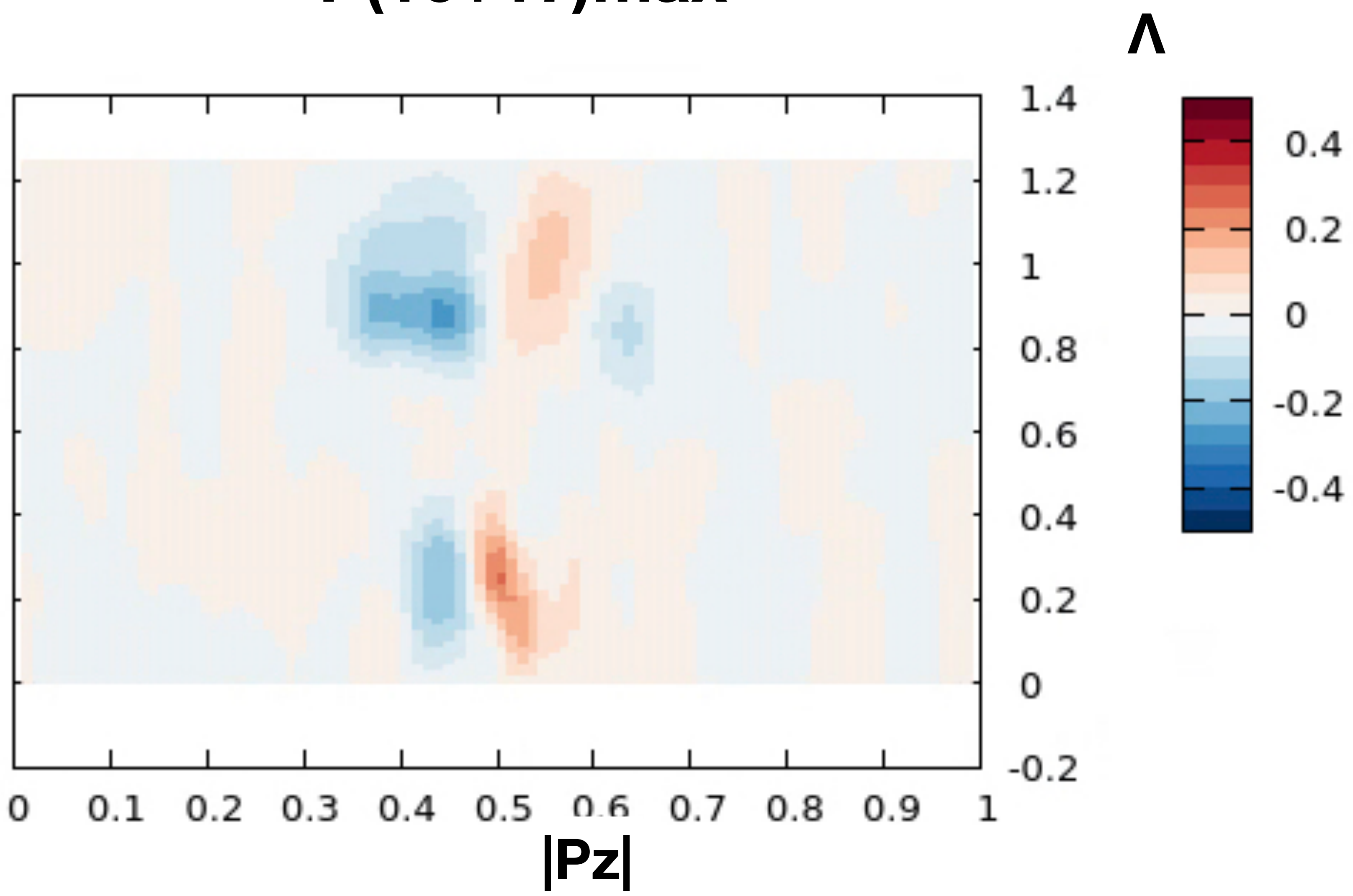


n=16+17 both



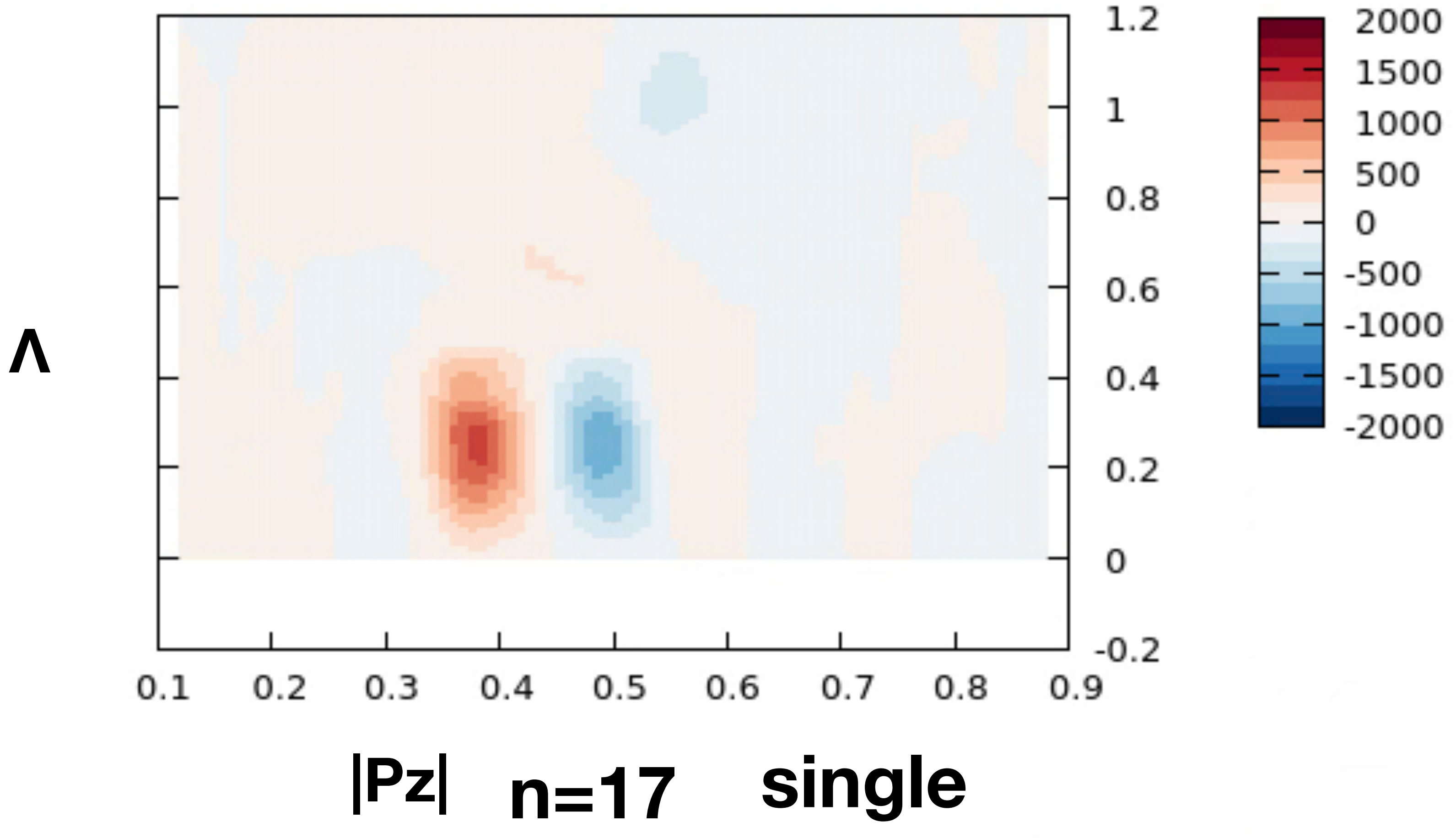
relative difference

$$\frac{P16+P17-P(16+17)}{P(16+17)max}$$

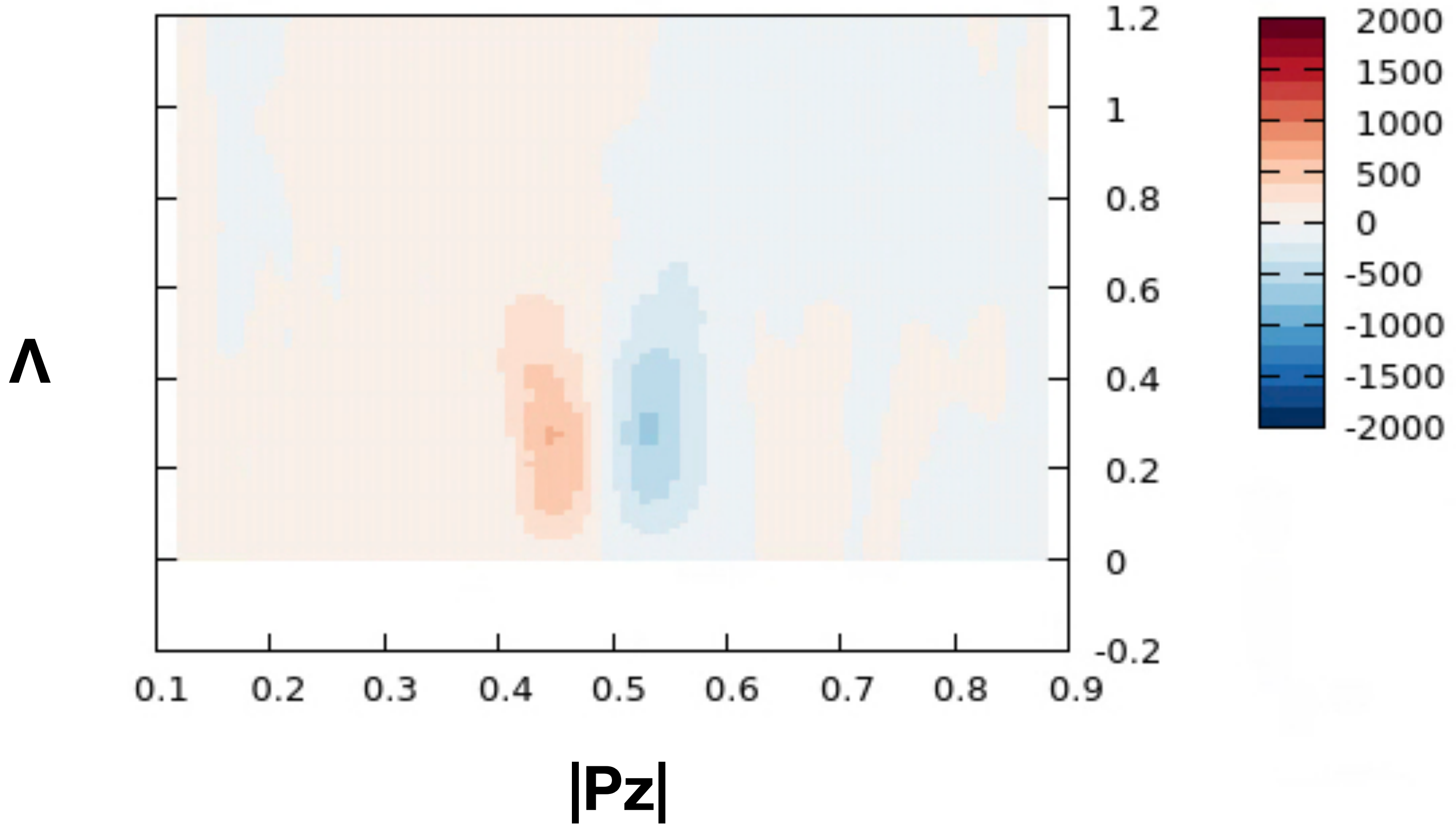


detailed insight into multi-mode cases: amplitude scan: **dB/B=5 *10^{-3}**

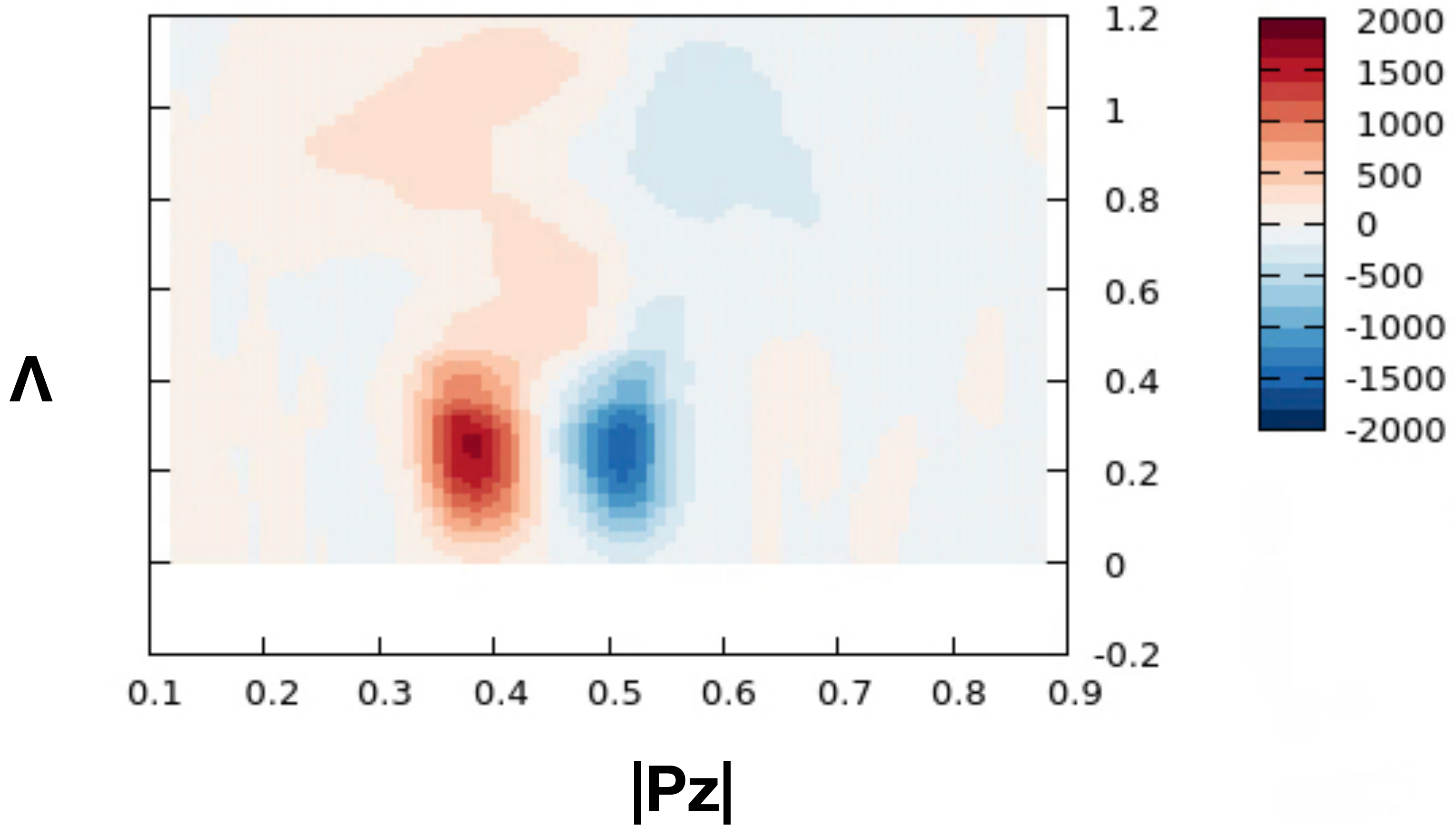
n=16 single



n=17 single

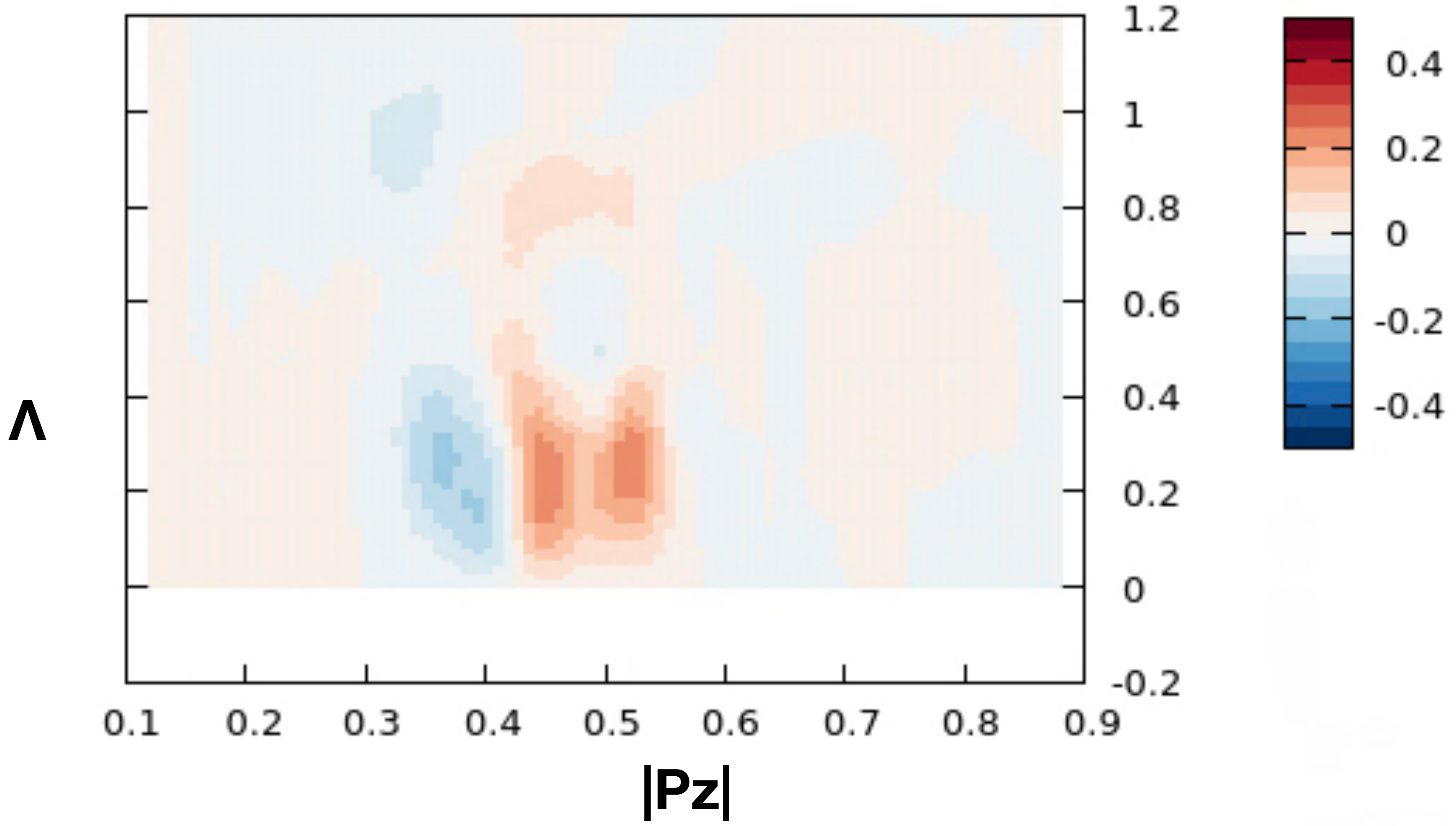


n=16+17 both



relative difference

$$\frac{P16+P17-P(16+17)}{P(16+17)max}$$



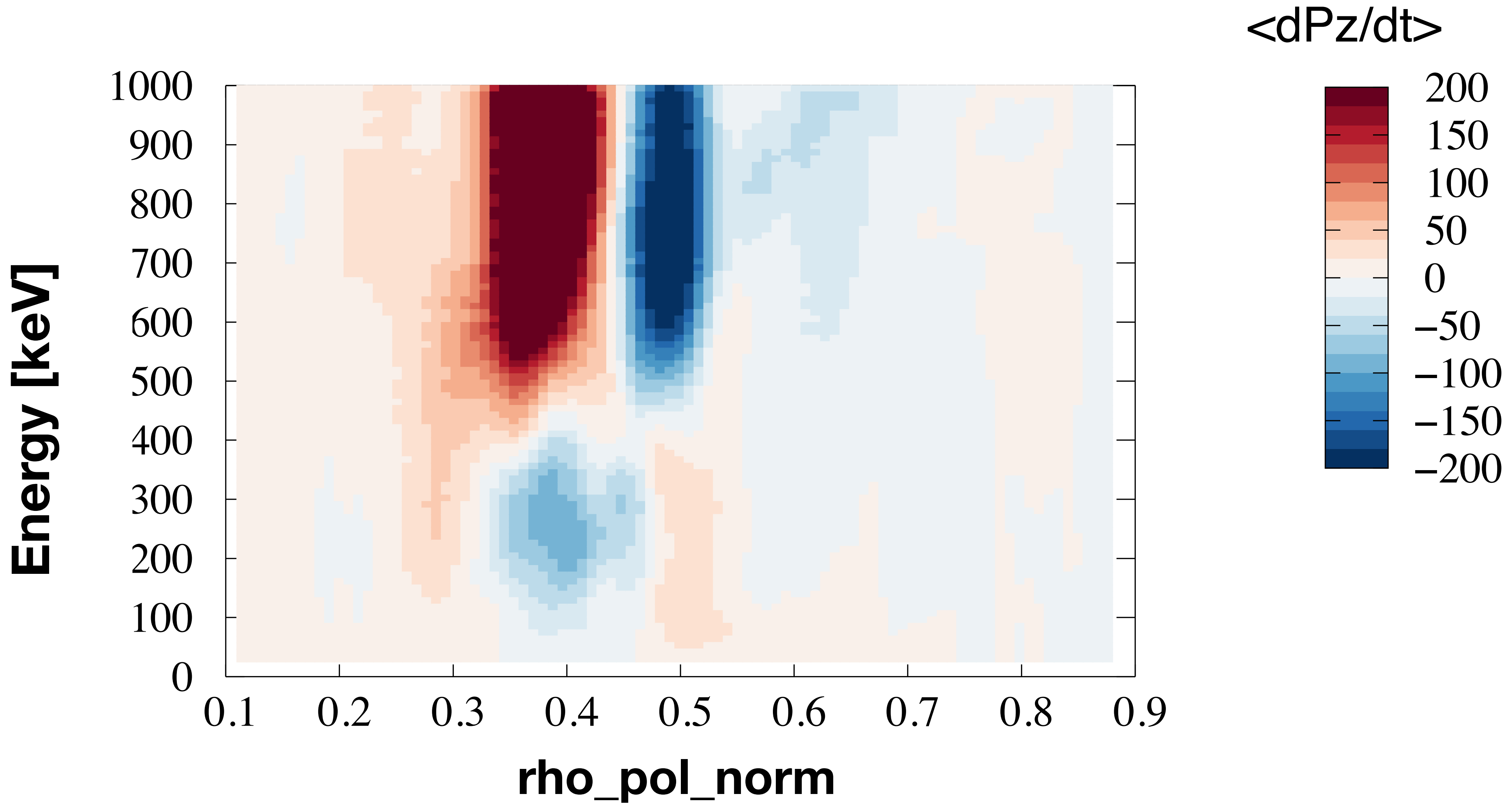
start to investigate multi-mode cases: amplitude scan

relative difference $\dfrac{(P16+P17)-P(16+17)}{P(16+17)max}$

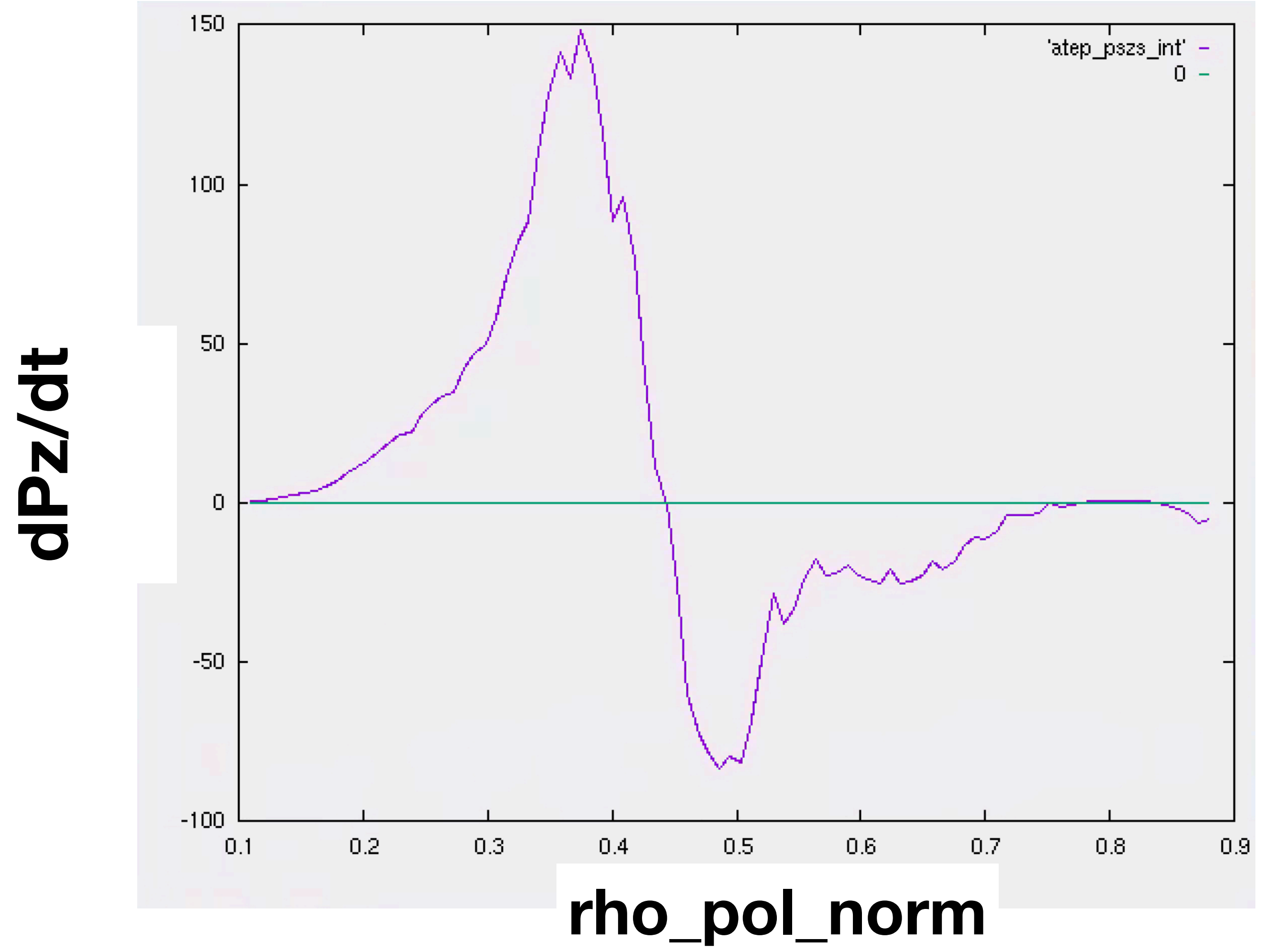
dB/B=0.5 $*10^{-3}$ dB/B=1 $*10^{-3}$ dB/B=5 $*10^{-3}$

- multi-mode systems need careful treatment when going from isolated mode case to resonance-overlap (diffusive) regime:
- depending on amplitude, trapped and passing particles show different relative importance for causing resonance overlap (FOW vs resonance width)
- example shows capability of model to check assumptions, understand underlying physics and to trigger next level of model hierarchy, if necessary

diffusions coefficients: D(s,E) and D(s)



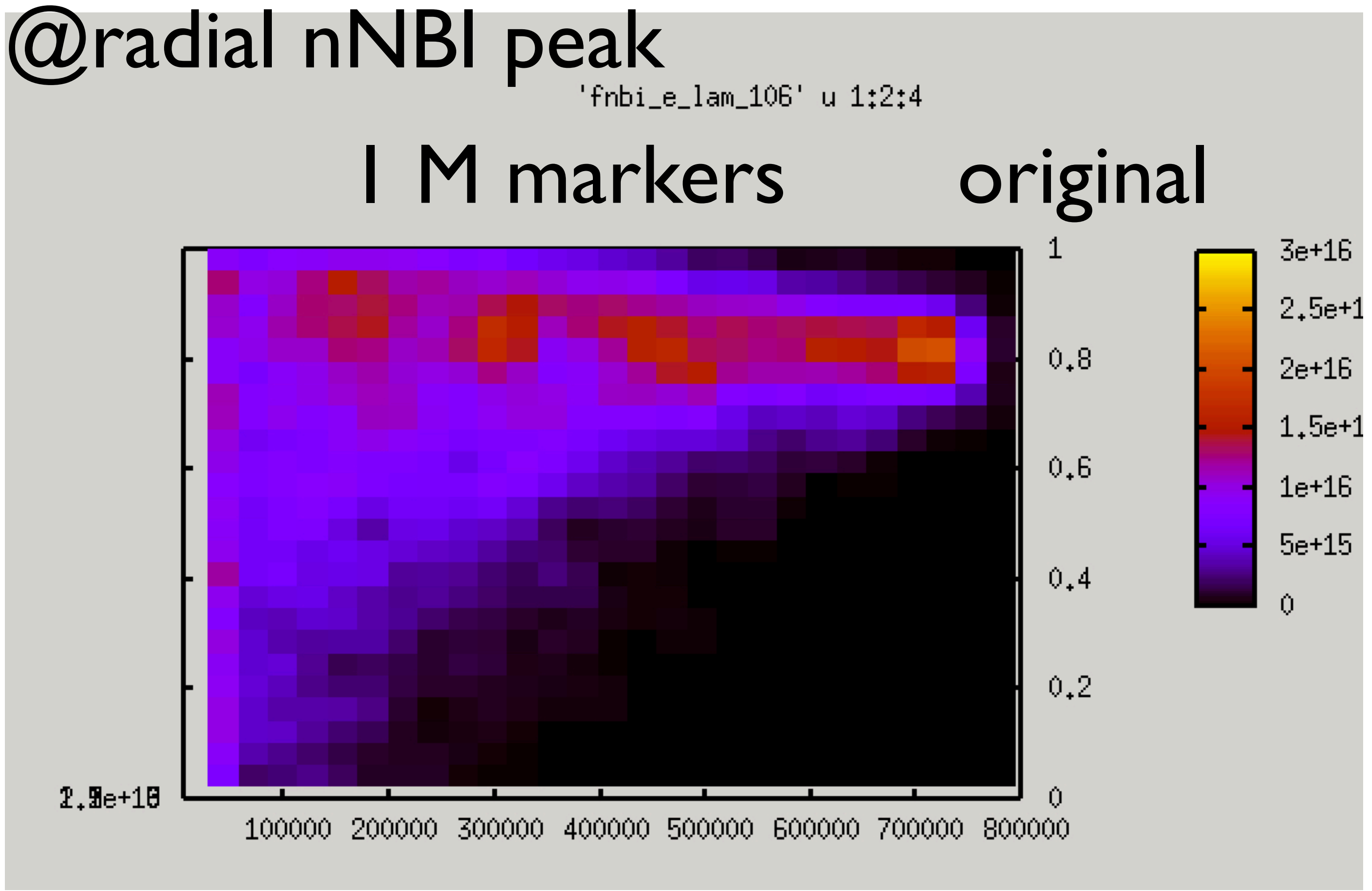
E integration

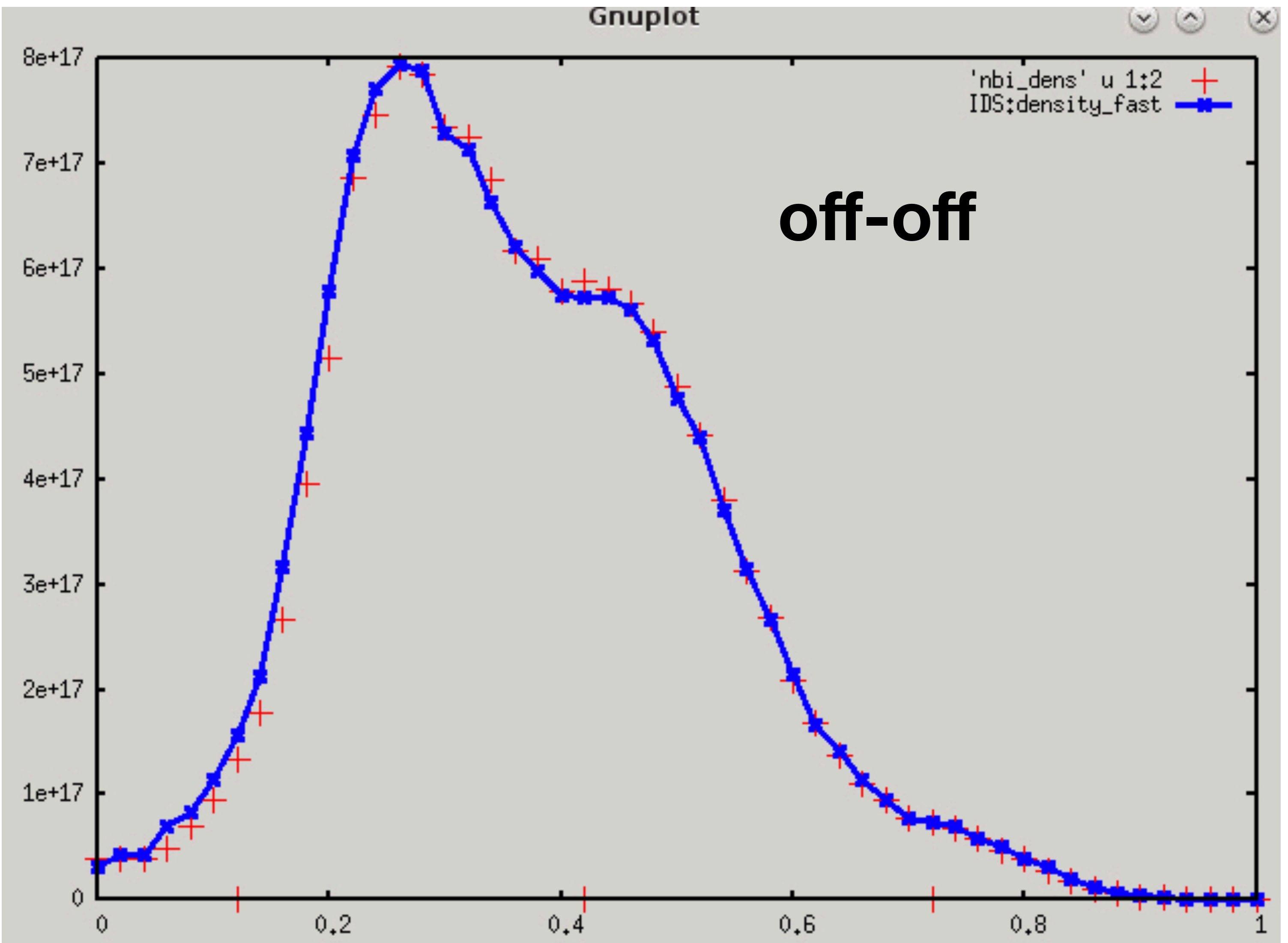


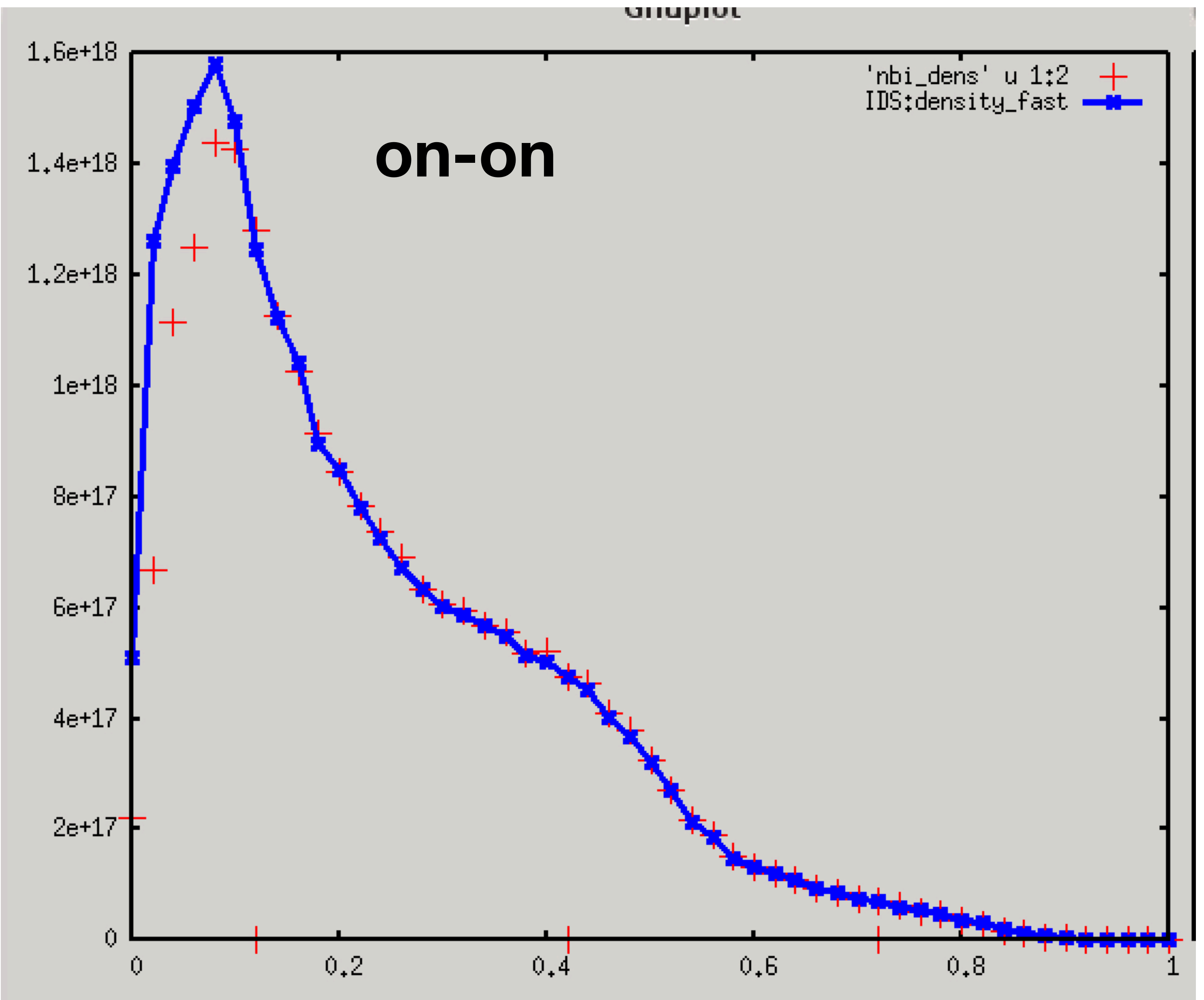
to be done: transform into $D(s,E)=\langle s\rangle^2/\langle t\rangle$
and feed back to transport code

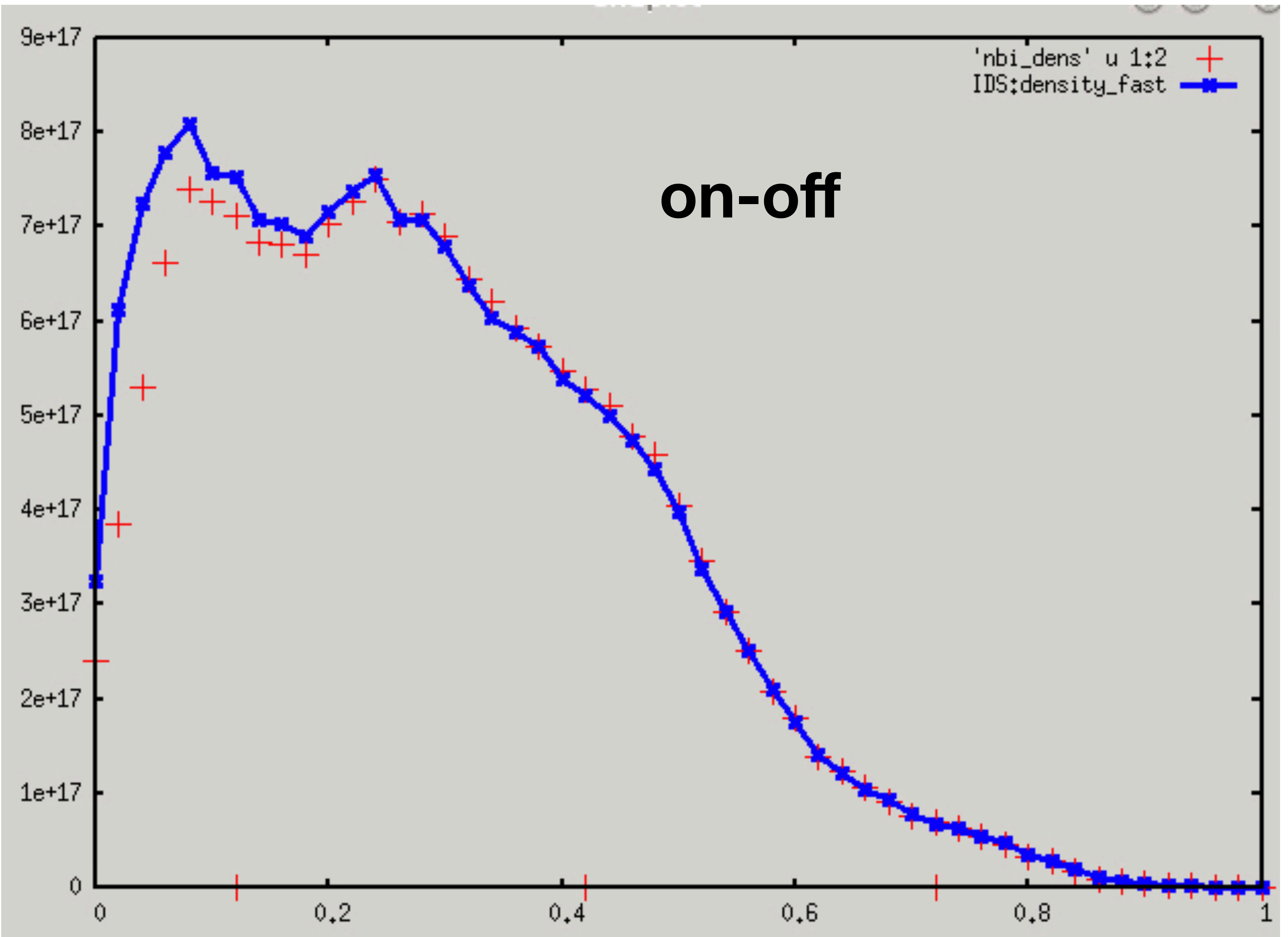
progress on implementation of transport model: ATEP code

ITER: 100015: F_{EP} is available from H&CD WF [thx. M. Schneider]



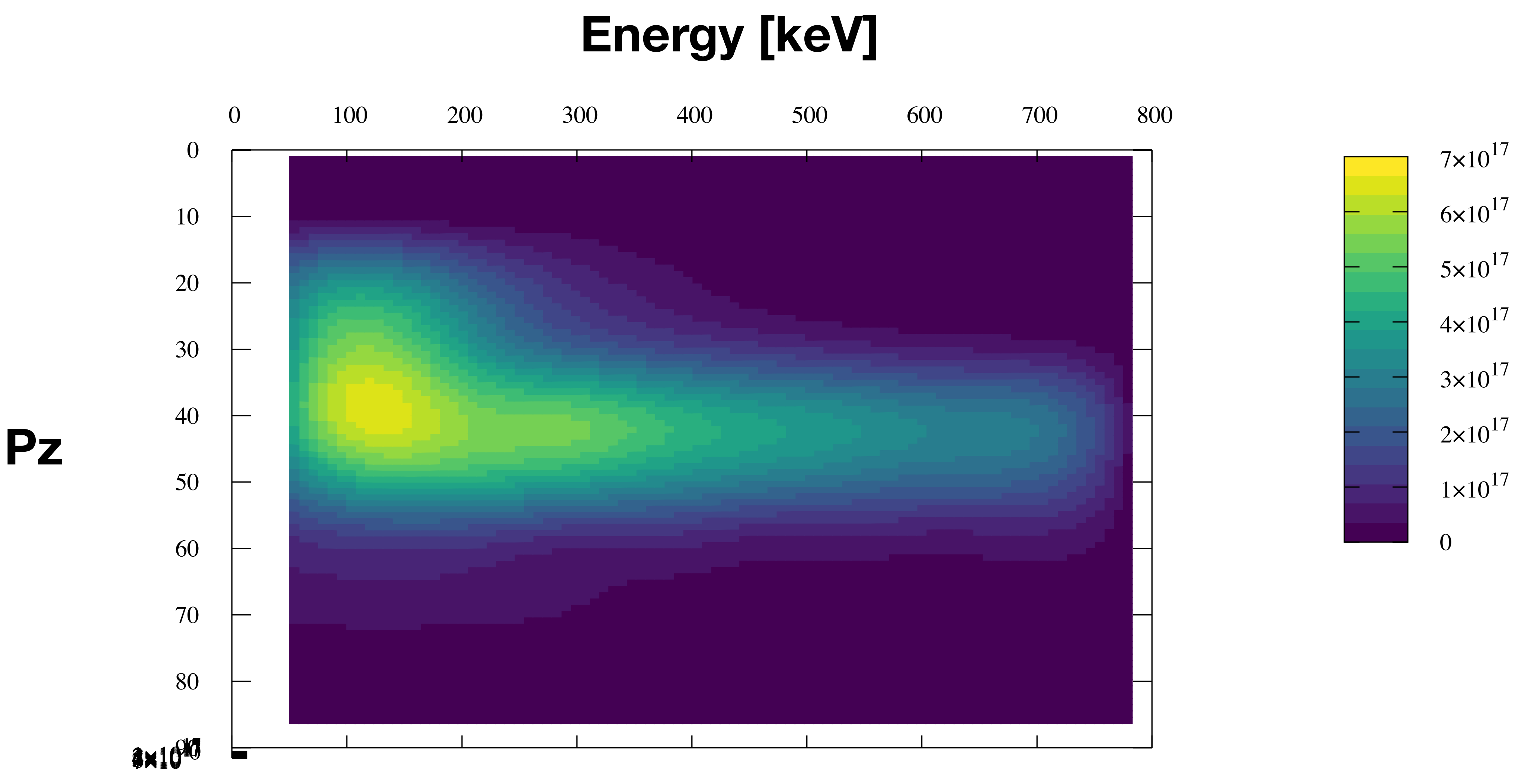


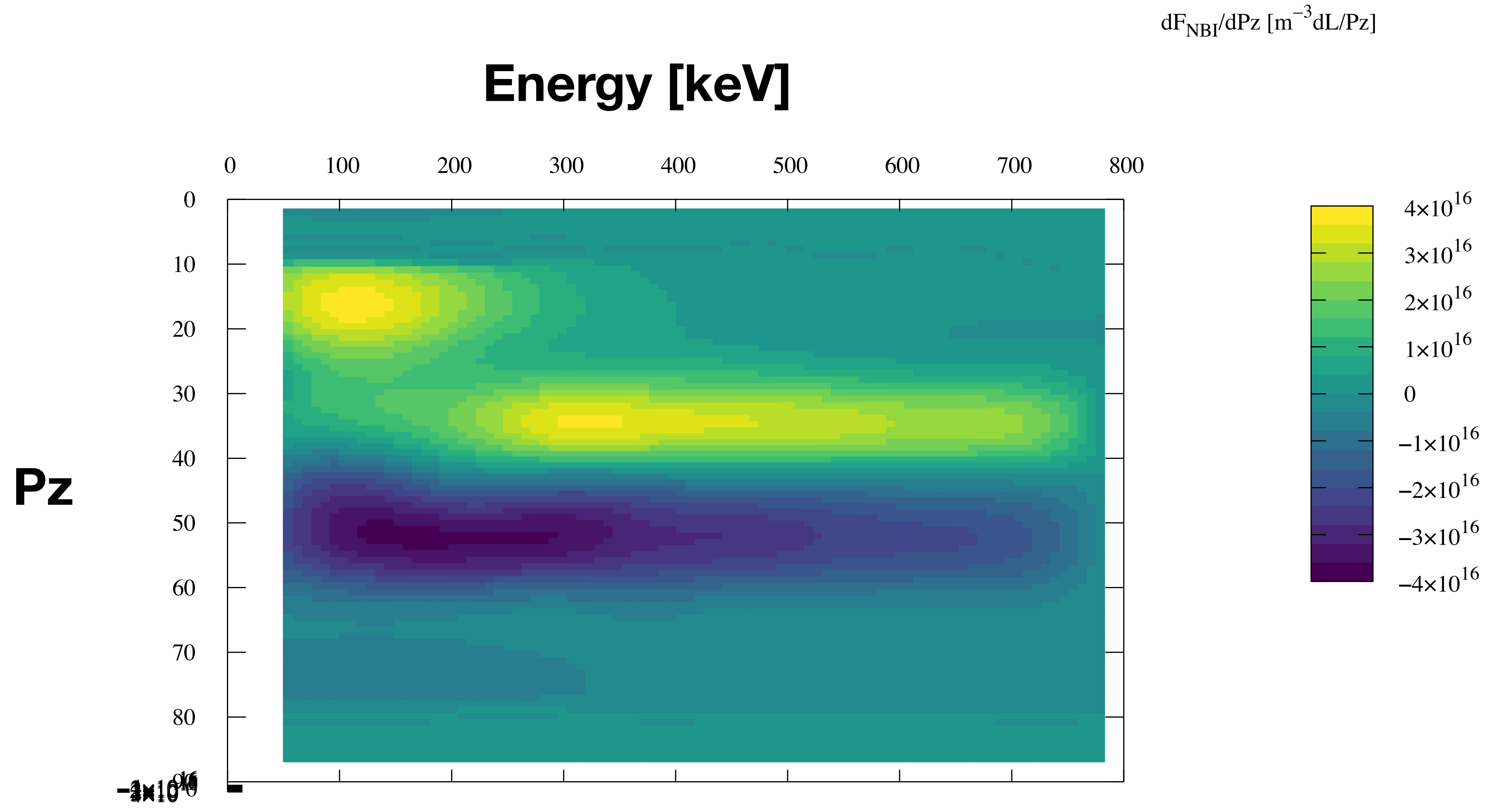


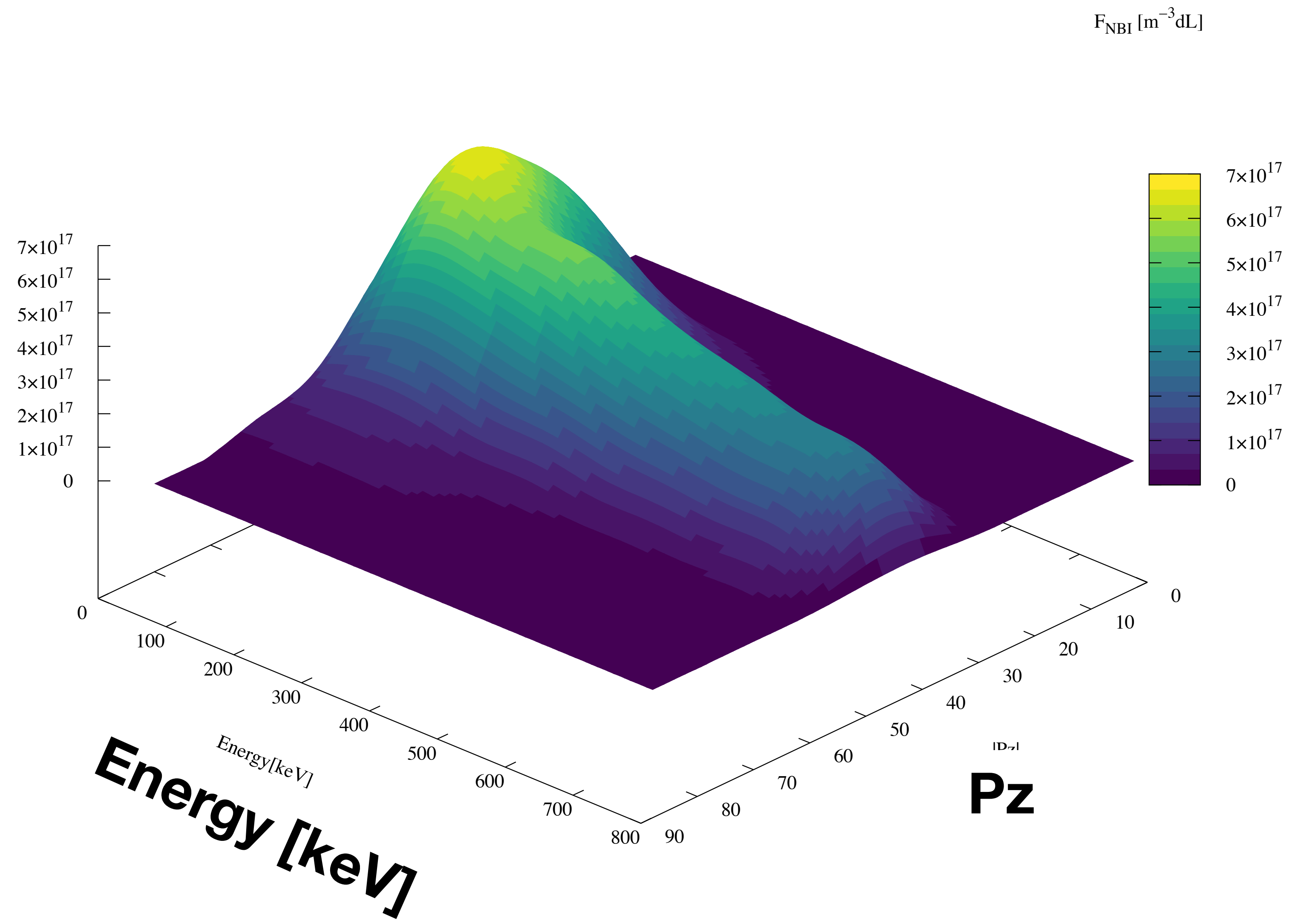


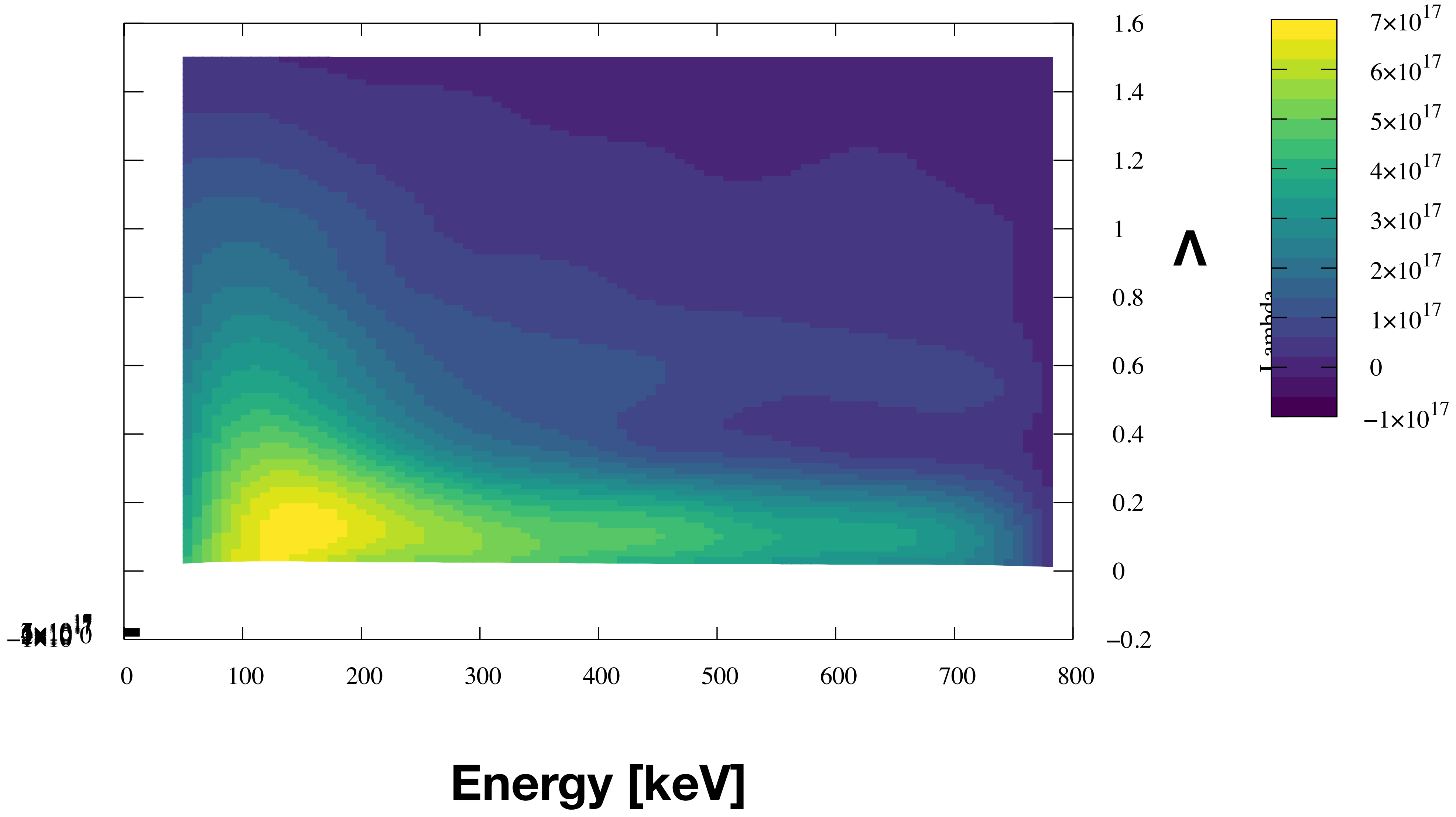
bin/smooth/map to same COM grid as PSZS

binning 1 M markers from H&CD, use 2d bsplines with smoothing in (Pz,E), (Pz,Λ) and (E,Λ), construct 3d spline









ATEP code: advance transport equation

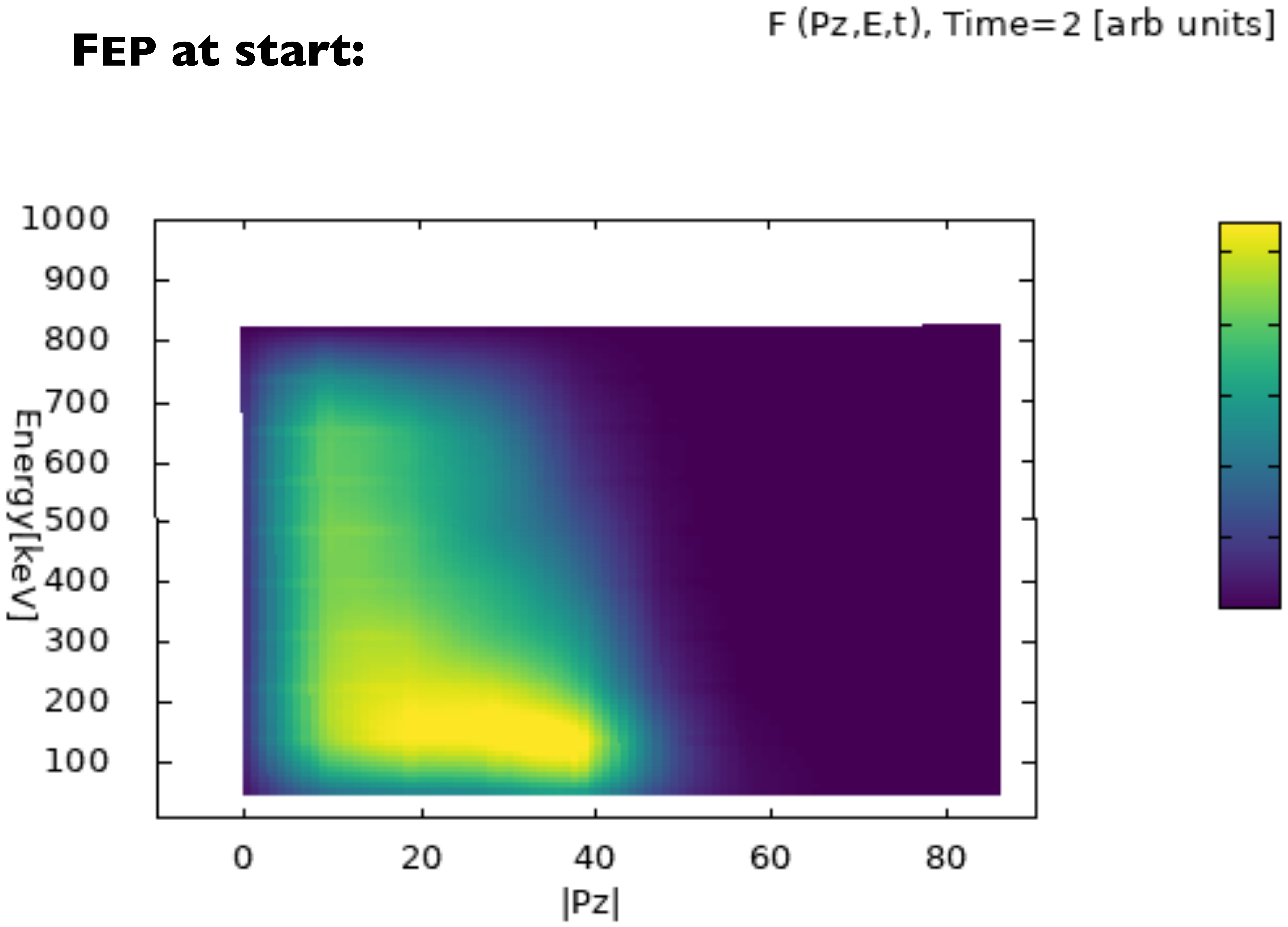
simple finite difference scheme to start with (final scheme to be decided when sources/collisions are implemented):

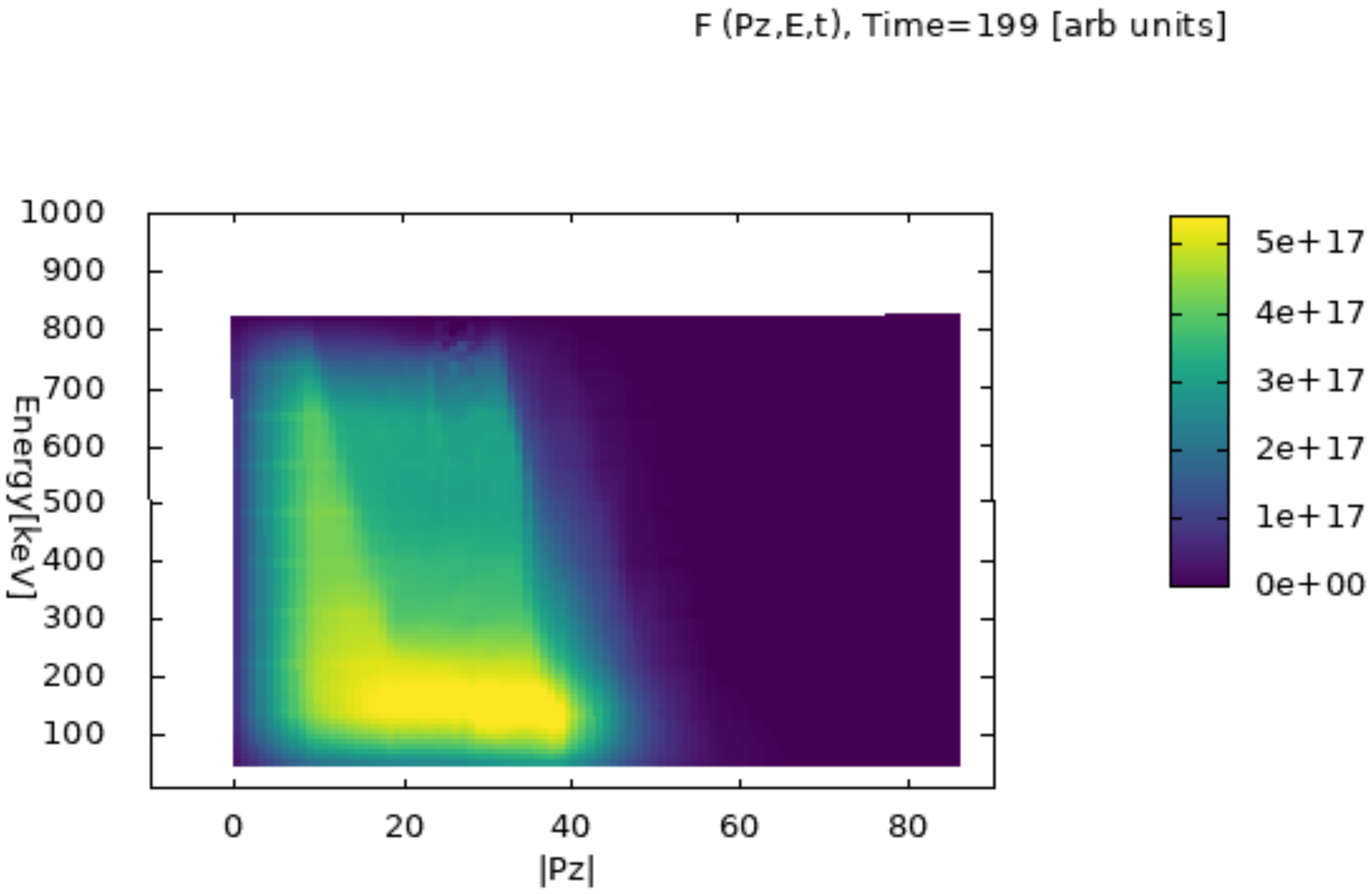
$$\frac{\partial F_{EP}}{\partial t} = \frac{\partial Pz}{\partial t}\frac{\partial F_{EP}}{\partial P_z} + \frac{\partial E}{\partial t}\frac{\partial F_{EP}}{\partial E}$$

note: $\frac{\partial^2 Pz}{\partial t \partial P_z} F_{EP}$ **term excluded so far: dPz/dt assumed constant -> kick model limit**

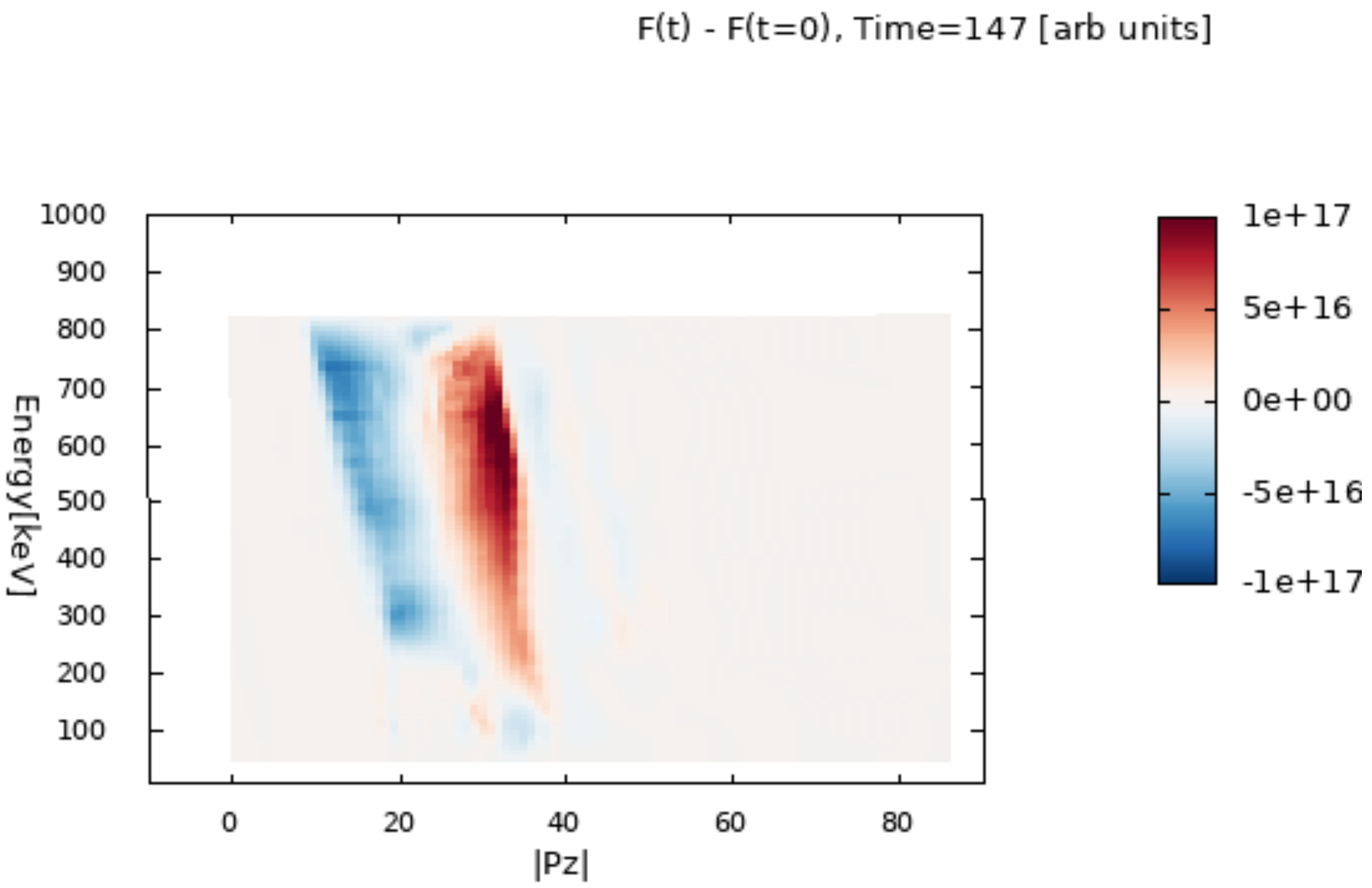
runtime: several seconds

FEP at start:

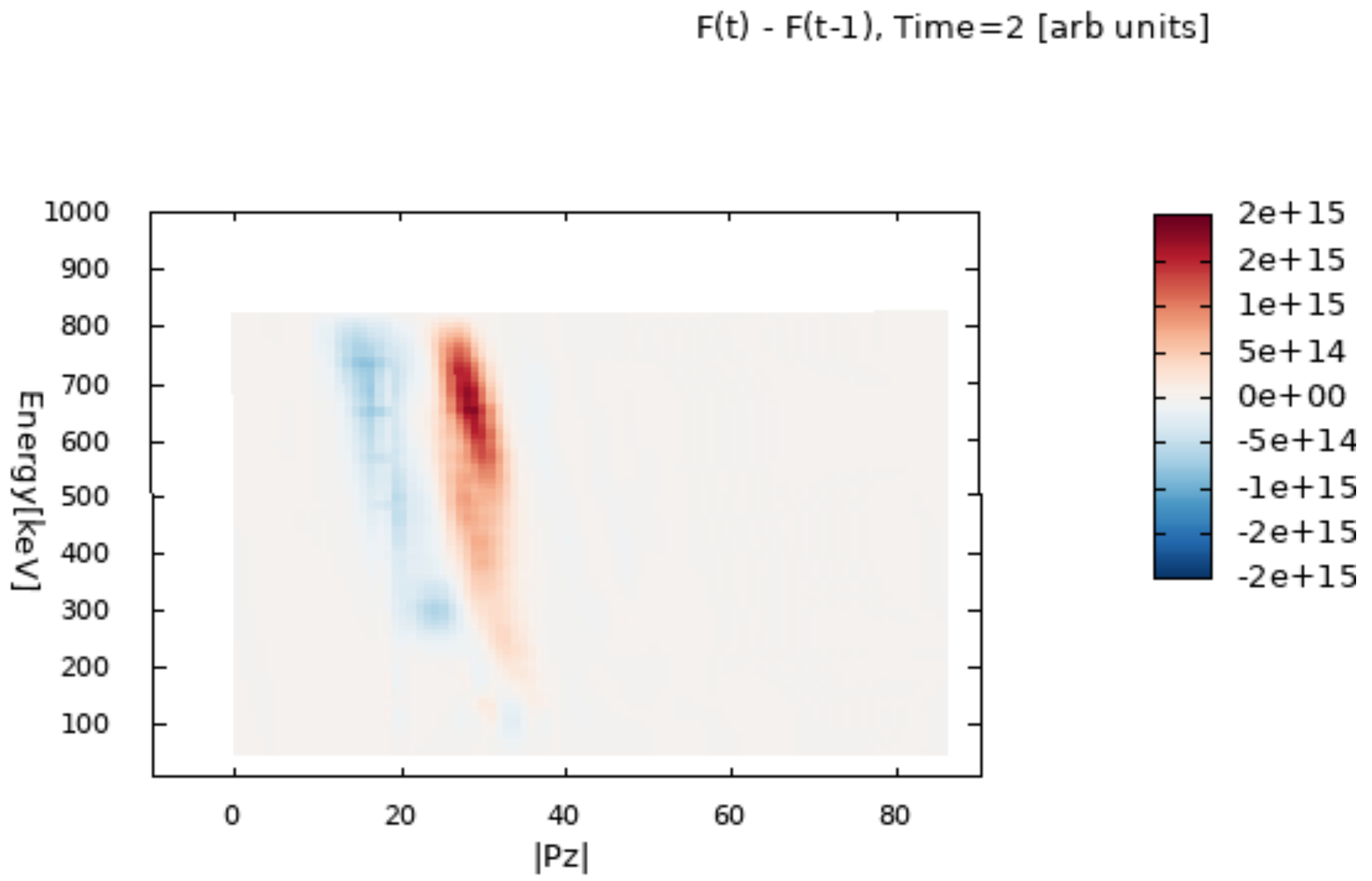




ATEP code: advance transport equation: δF

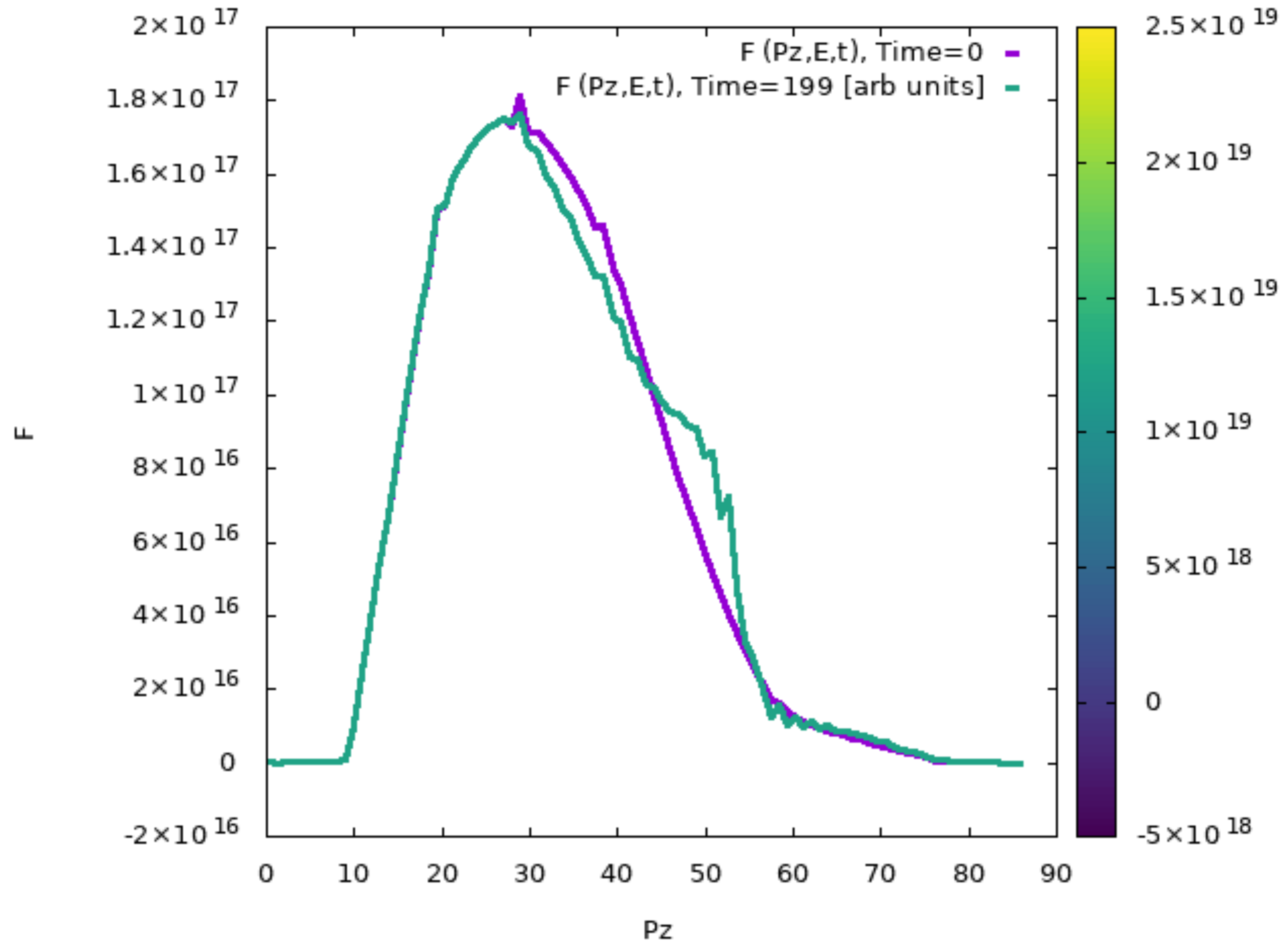


ATEP code: advance transport equation : differential δF



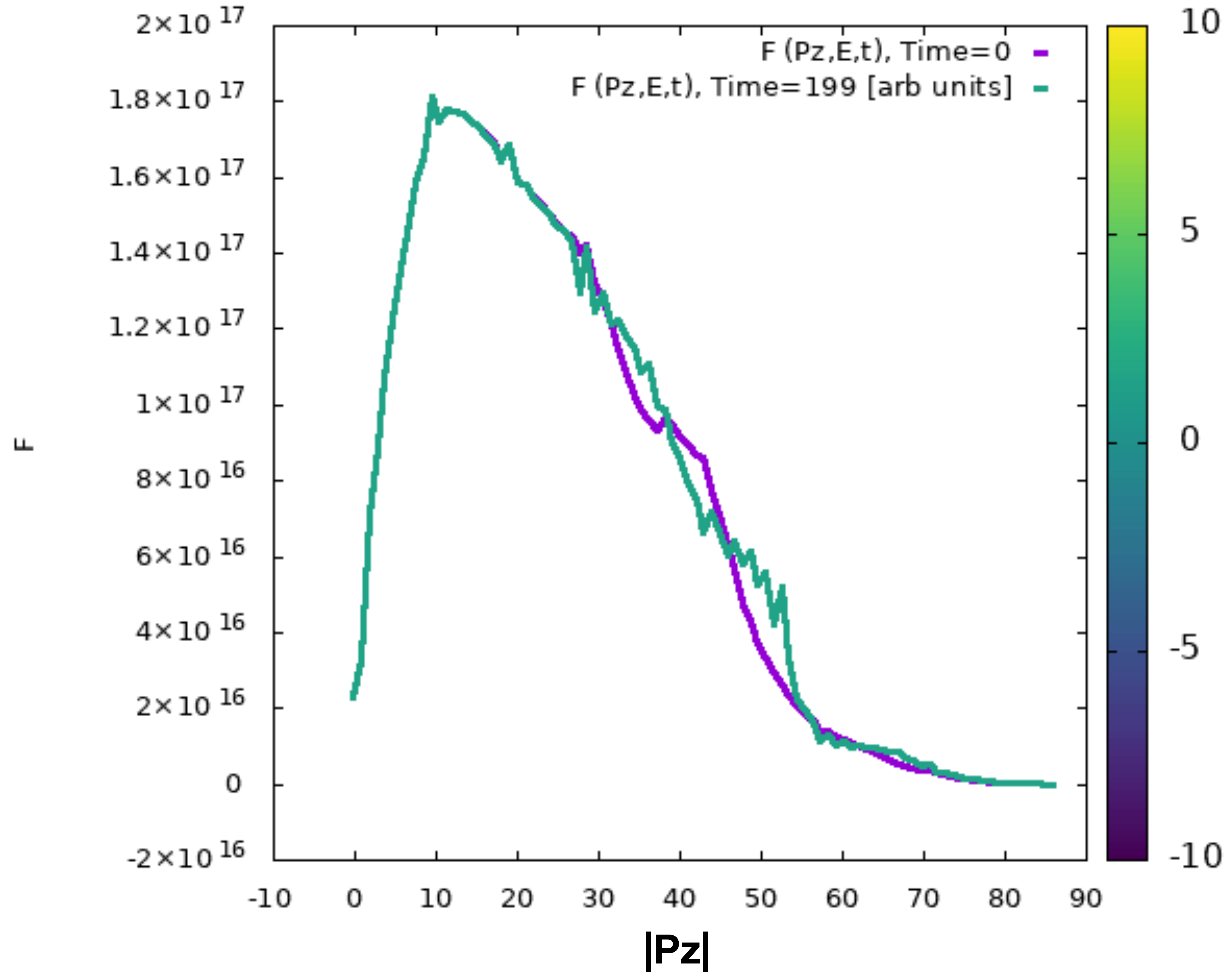
- secondary fine-structures start to evolve, as expected: in kick-model limit, amplitude is not changed - in real system amplitude would decay when gradients are exhausted
- source (RABBIT) and collisions models are currently implemented in ATEP code (G. Meng) - will smooth emerging steep gradients

ATEP code: advance transport equation: 1d projection

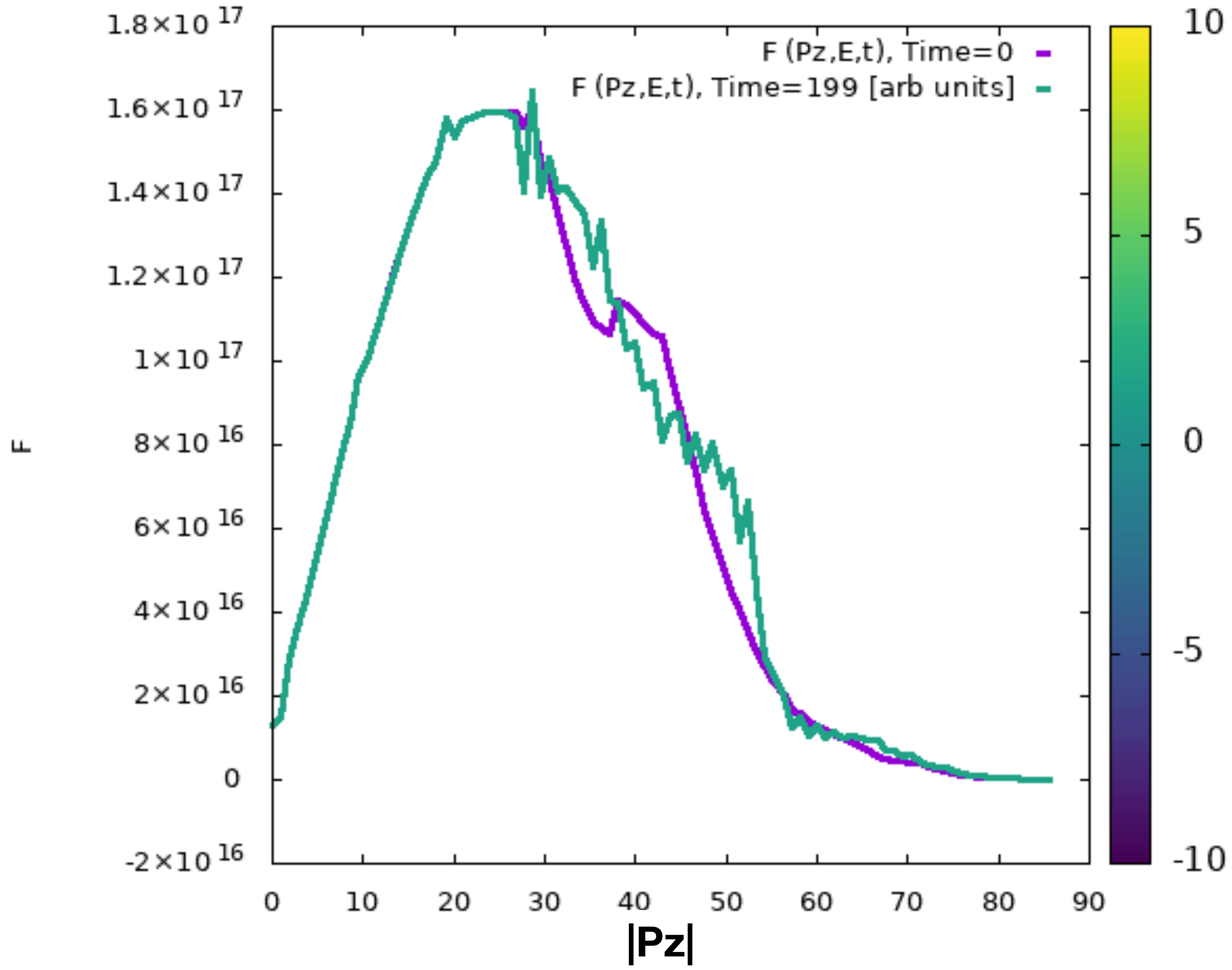


using ITER NBI off-off configuration **|Pz|**

ATEP code: advance transport equation: 1d projection

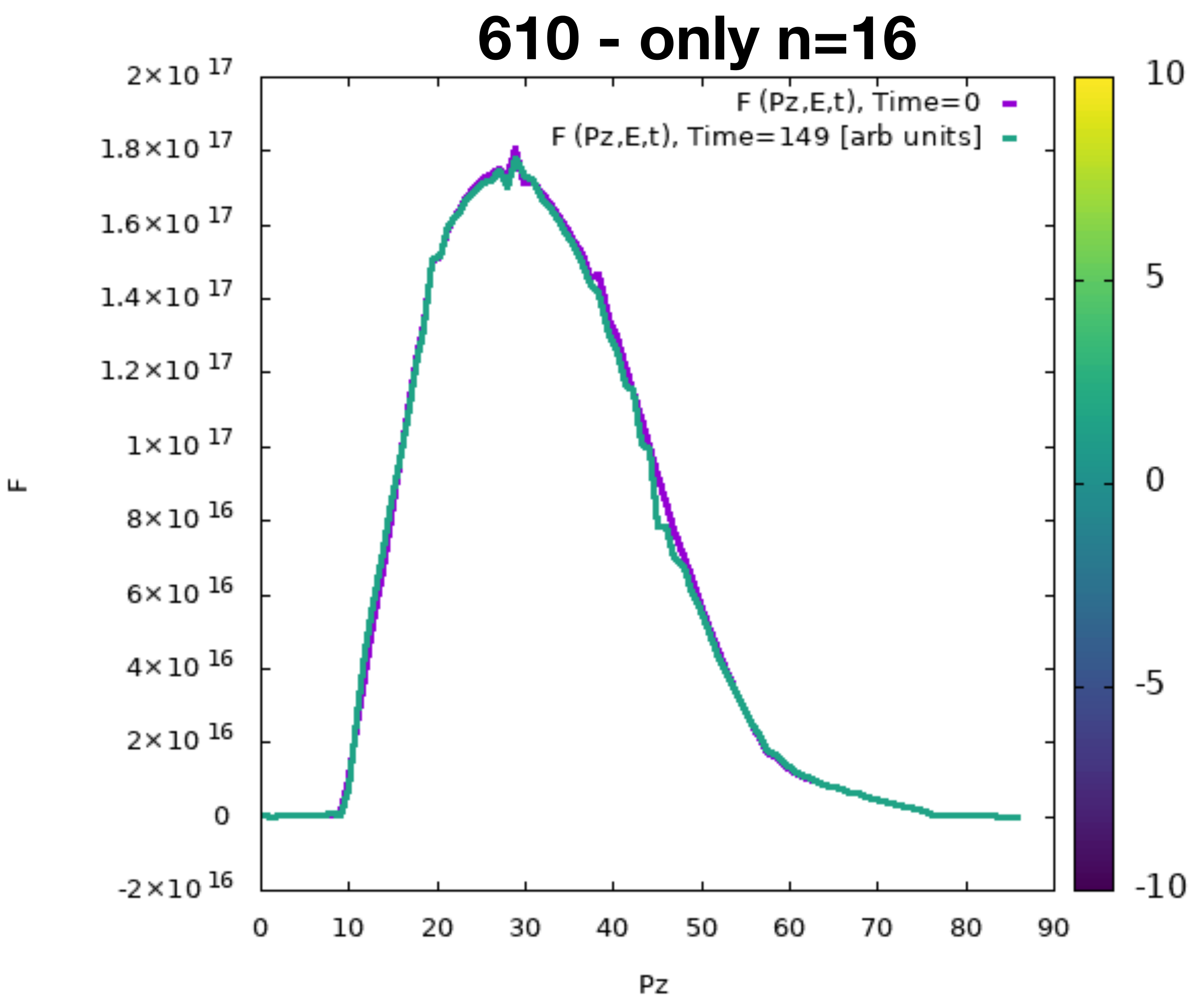


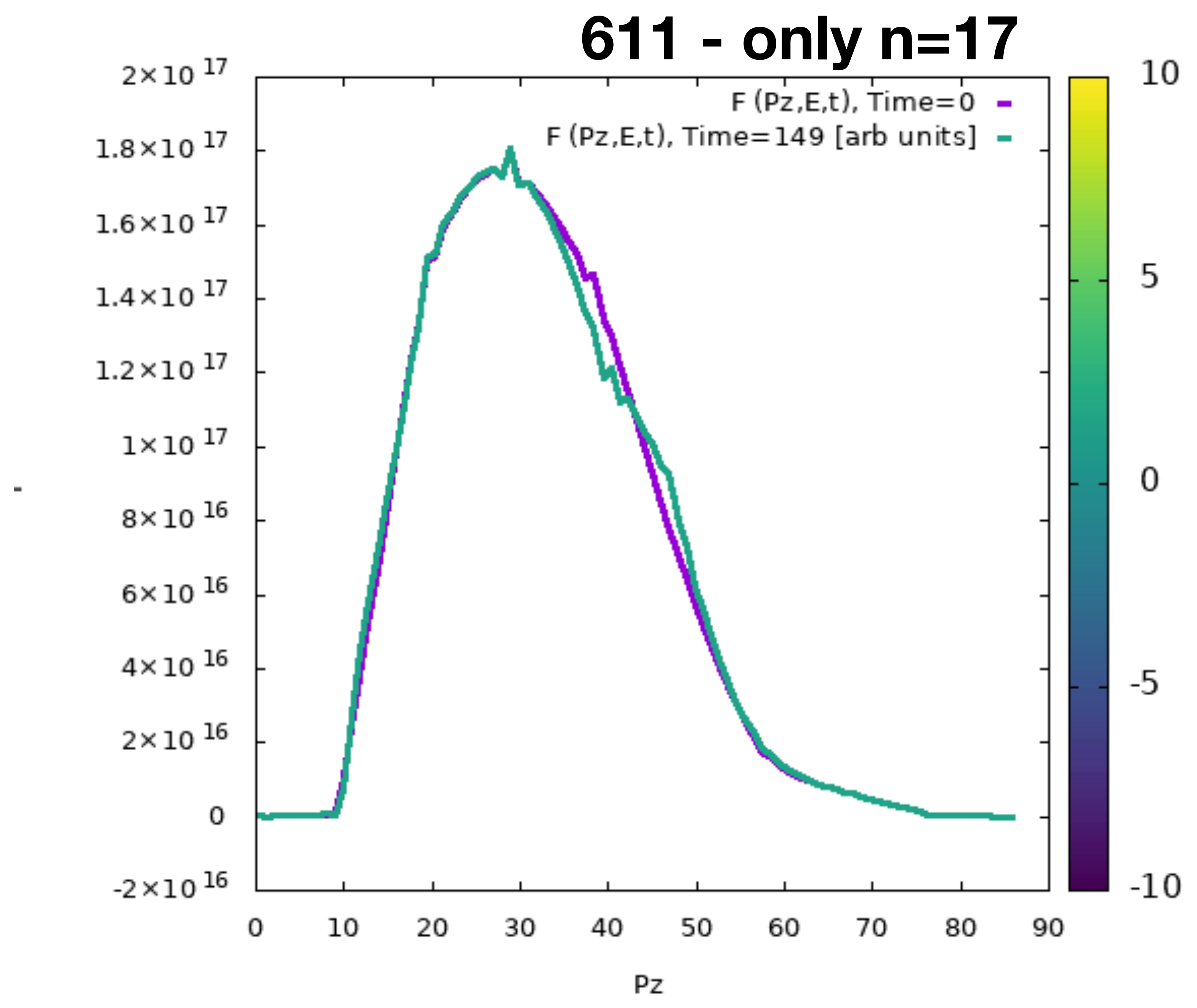
using ITER NBI on-on configuration

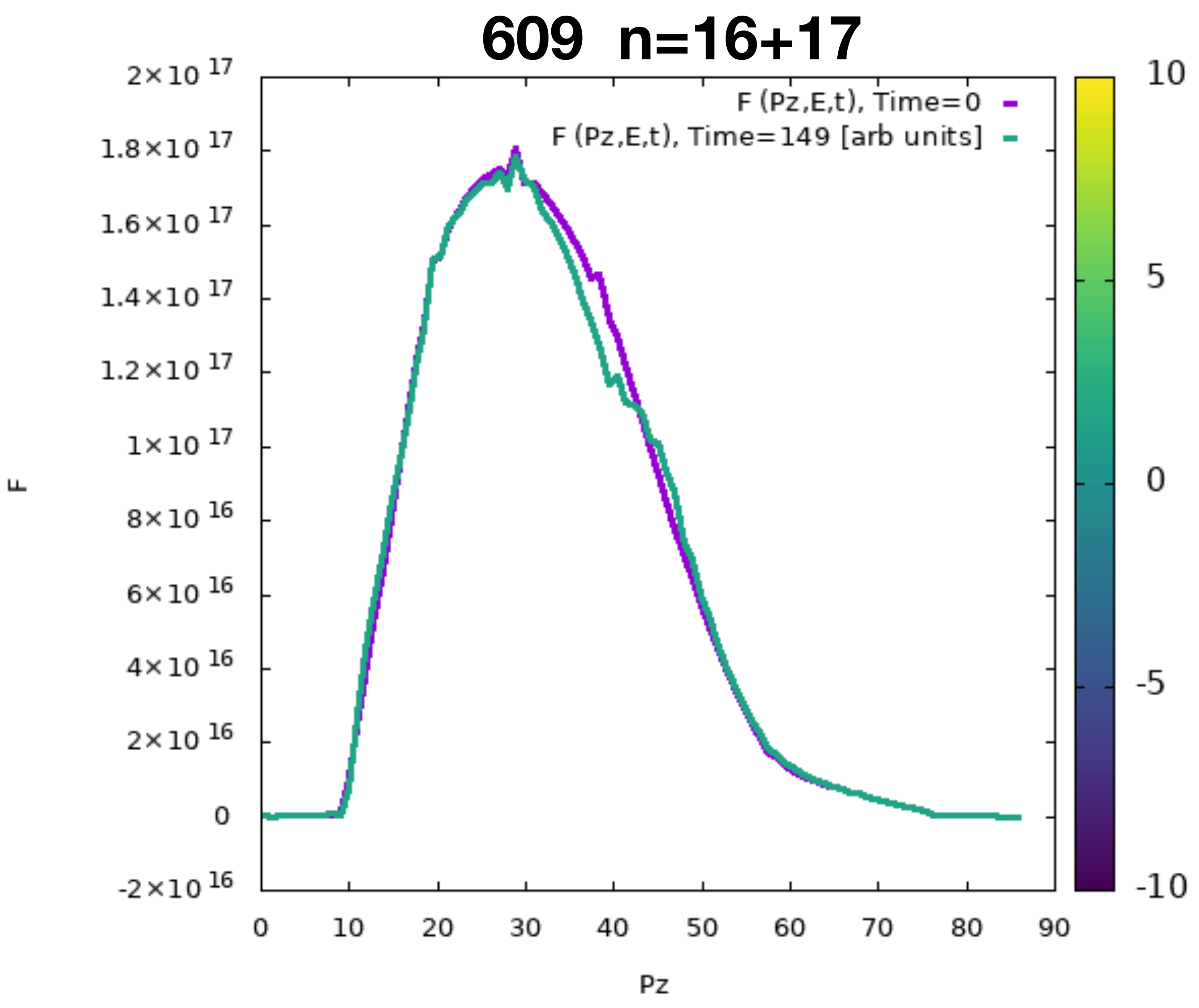


using ITER NBI on-off configuration

two mode system (n=16,17, see above): dB/B=0.5 *10^{-3}

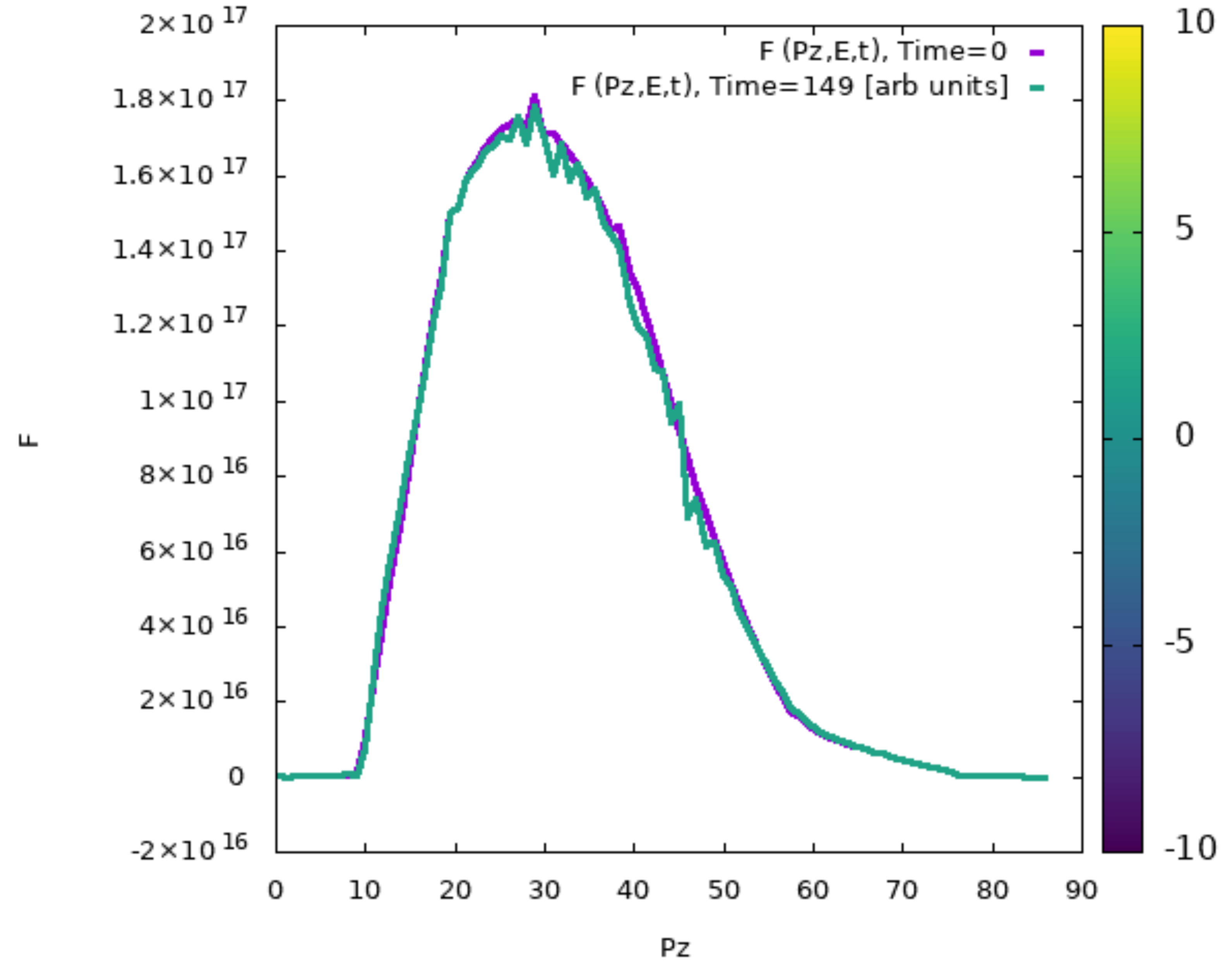




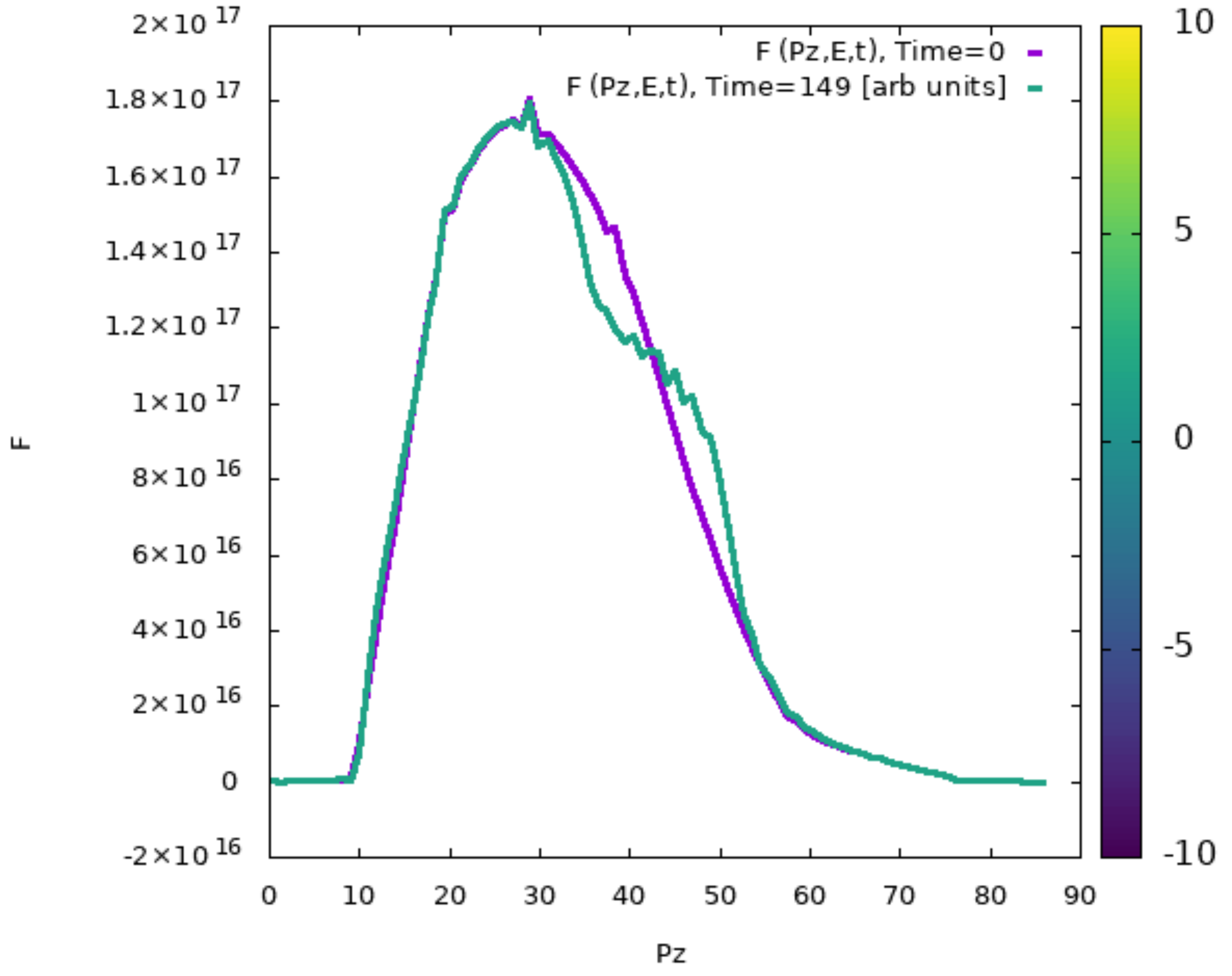


two mode system (n=16,17, see above): dB/B=1 *10^{-3}

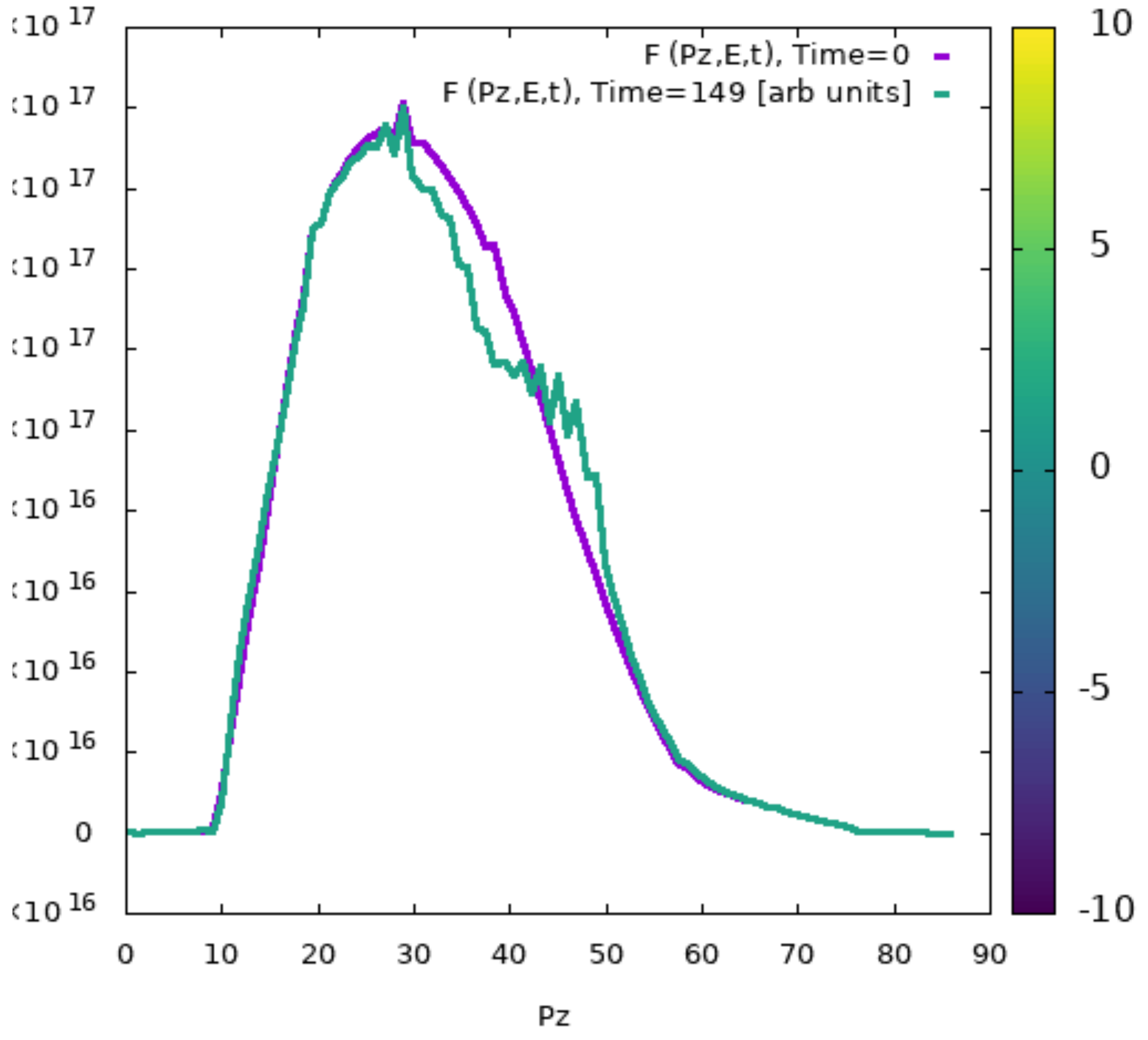
603 - only n=16



605 - only n=17

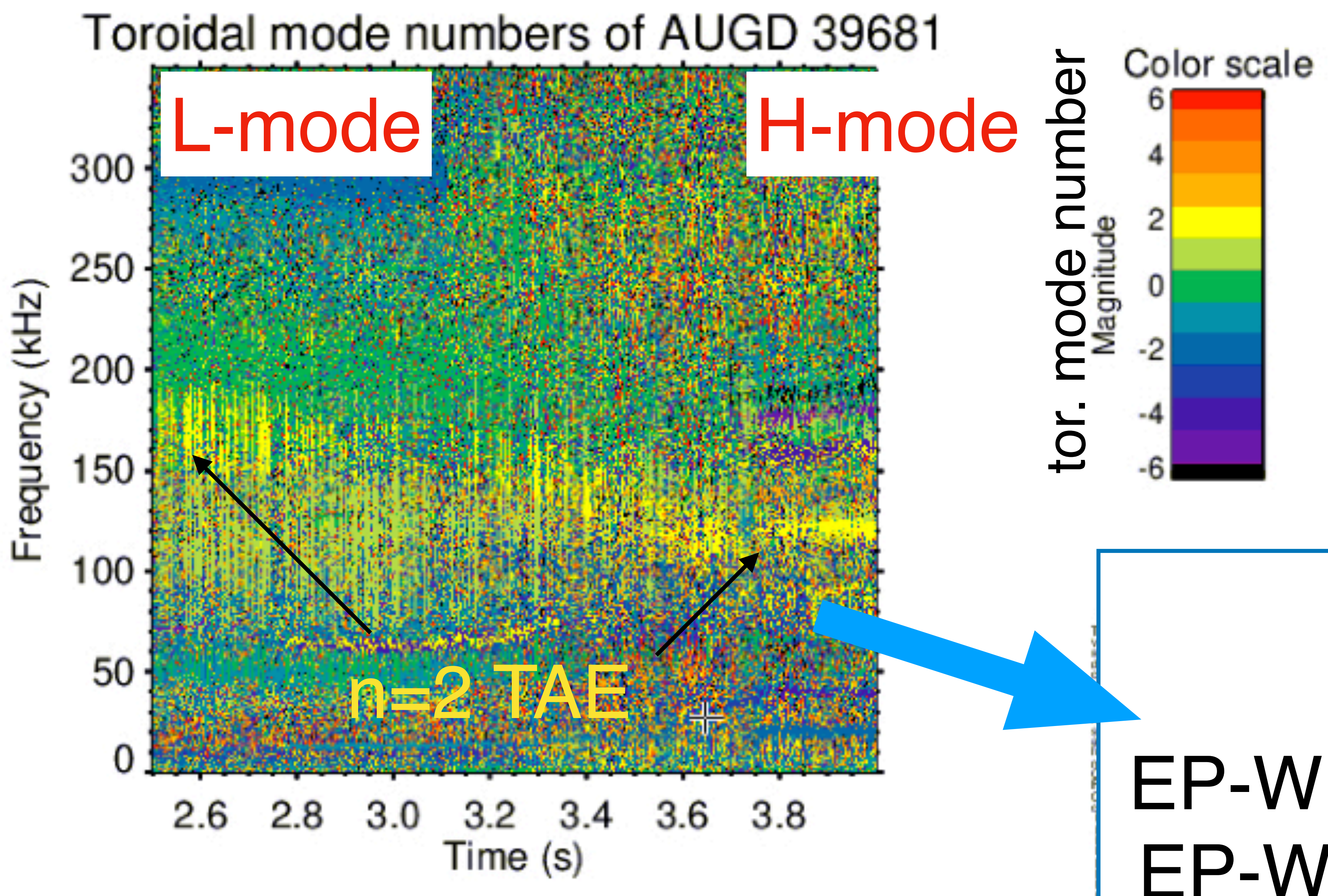


604 n=16+17



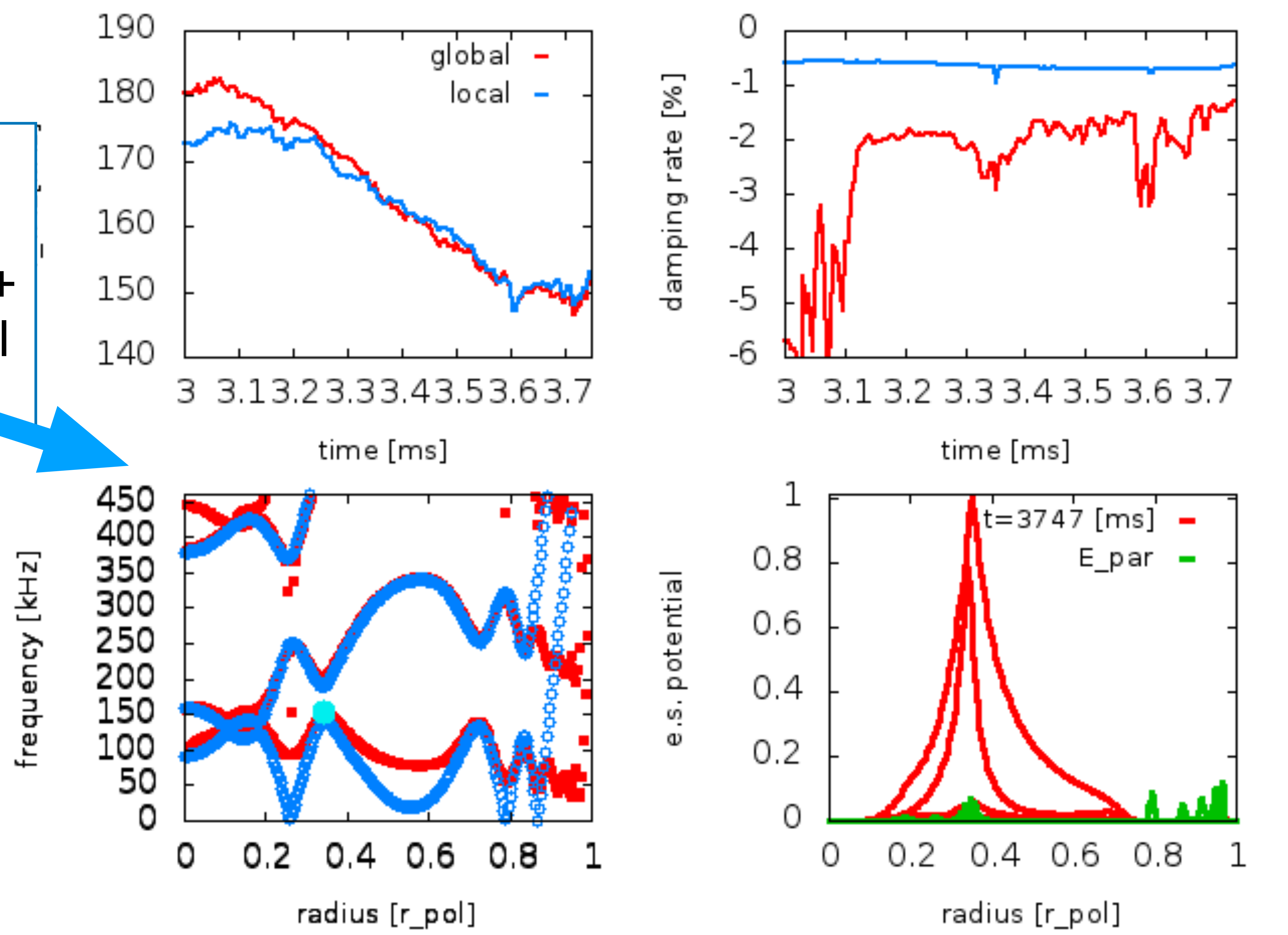
validation plans

exploit EP stability workflow: AUG data example: L-H transition in presence of TAEs



IDA +
TRVIEW +
EP-WF: LIGKA local +
EP-WF: LIGKA global

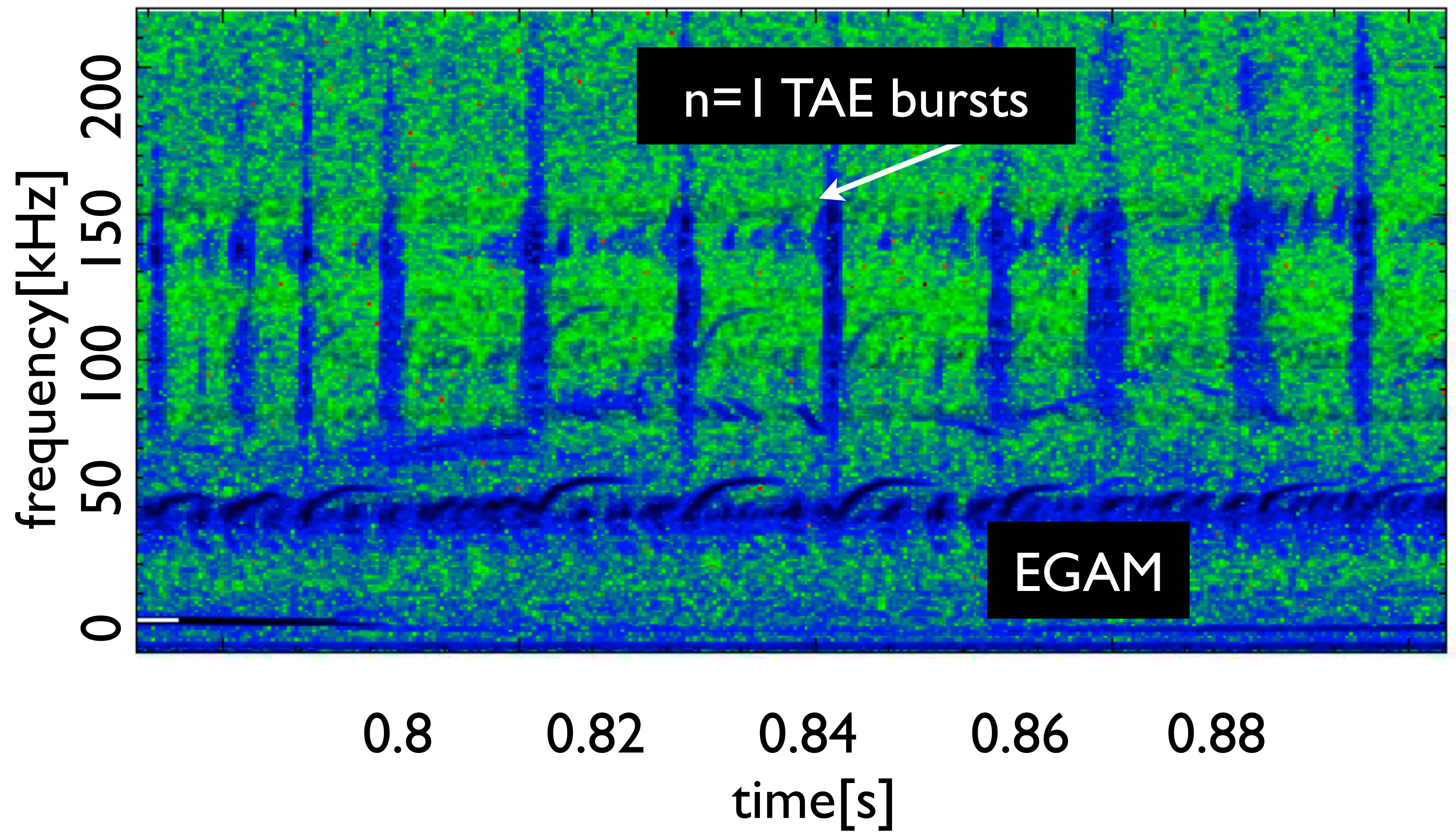
- automated processing of 160 time slices based on IDA equilibria and profiles
- fully implemented in IMAS, ensuring reproducibility



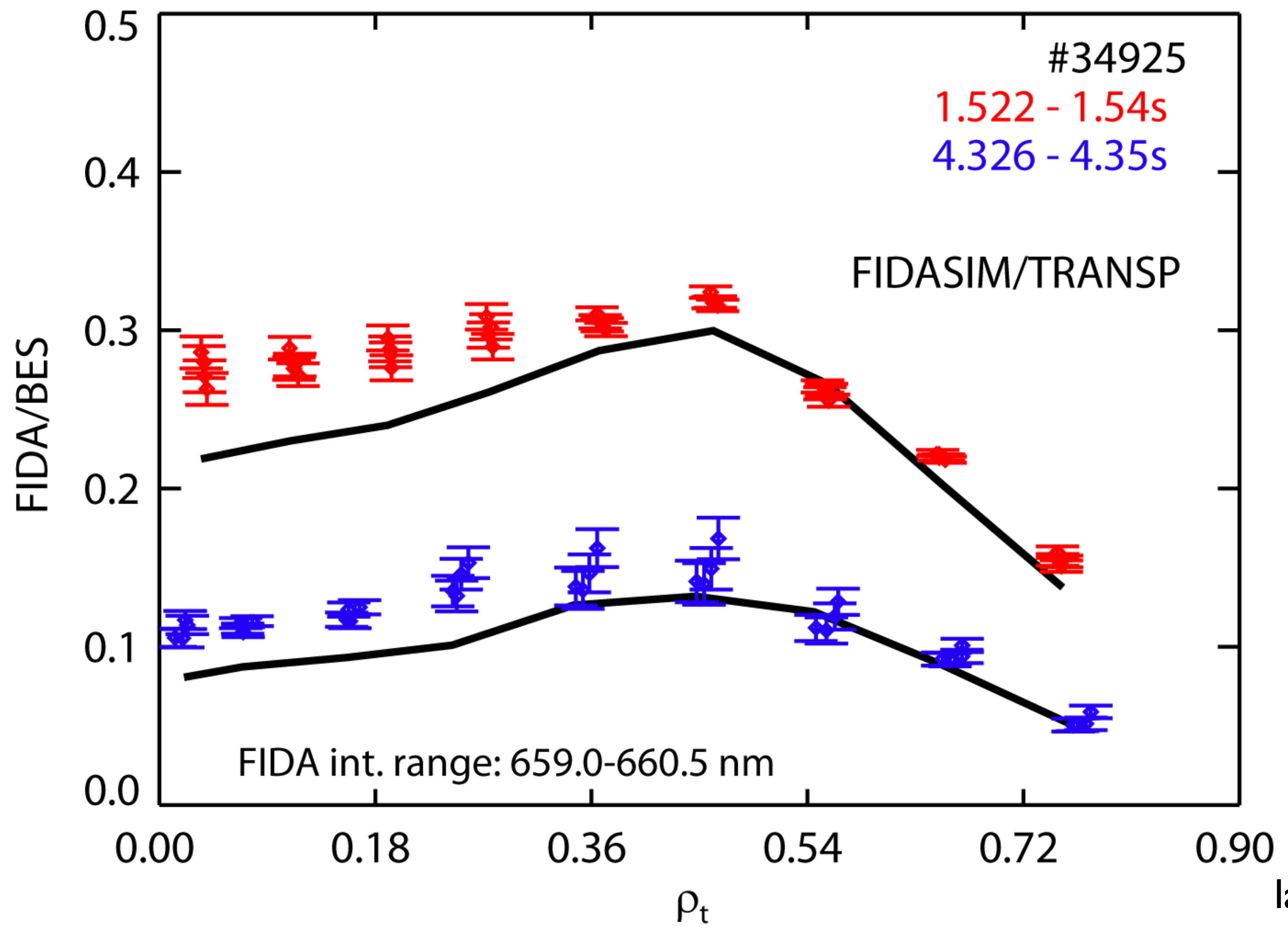
- analyse L-mode,H-mode and transition phase using
- also systematic uncertainty quantification feasible

AUG EP-'supershot' scenarios

[Lauber FEC 2018,2021; Horvath NF 56 2016]



- minimize ion and electron LD by:
- cold core plasma despite strong EP drive (NBI)
- let impurities accumulate in core, heat only off-axis
- EP pressure dominated plasma - very useful for validation [benchmark paper Vlad et al NF 2021, and at this workshop] of non-linear physics
- reaches for EP physics relevant parameters: $\beta_{EP}/\beta_{thermal} \sim 1$, $E_{NBI}/T_{i,e} \approx 100$



- off-axis peaked EP profile
- modes are driven by negative and positive EP gradients
- measurable inwards EP transport with change-exchange measurements

L. Horvath et al, Nucl. Fusion 56, 112003 (2016) link

Ph. Lauber er al, 27th IAEA FEC (2018) link

A. Di Siena, et al, Nucl. Fusion 58, 106014 (2018) link

I. Novikau, et al, accepted for publication in Comput. Phys. Commun. (2019) arXiv

F. Vannini, et al, Phys. Plasmas 27, 042501 (2020) arXiv - link

F. Vannini, et al, Physics of Plasmas 28, 072504 (2021)- link

I. Novikau, et al, Phys. Plasmas 27, 042512 (2020) link

M. V. Falessi, et al, J. Plasma Phys. (2020) link

Ph. Lauber er al, 28th IAEA FEC (2020) link

G. Vlad et al 2021 Nucl. Fusion 61 116026 link

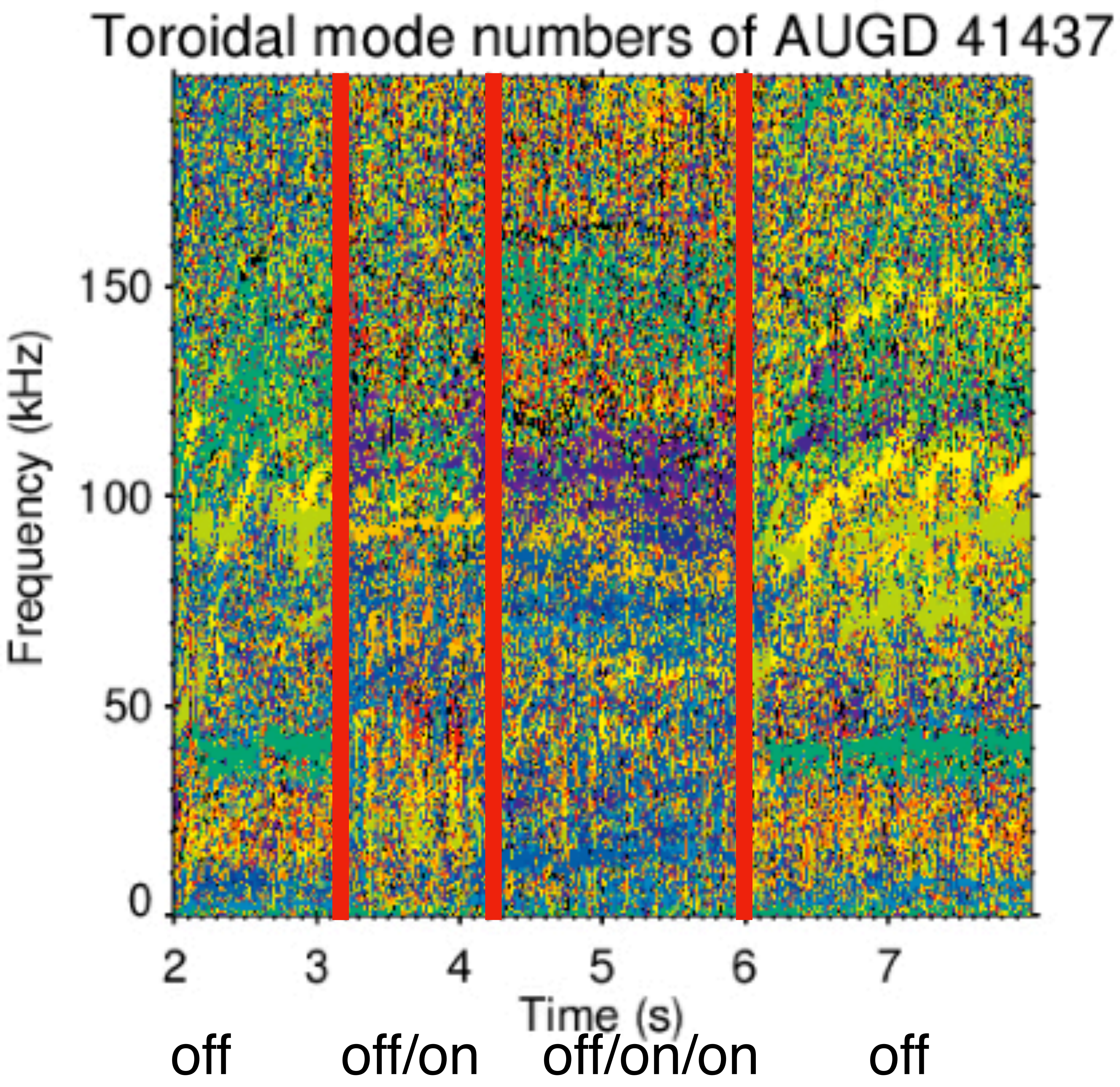
B. Rettino, 2022 Nucl. Fusion **62** 076027

F. Vannini 2022 Nucl. Fusion 2022 accepted

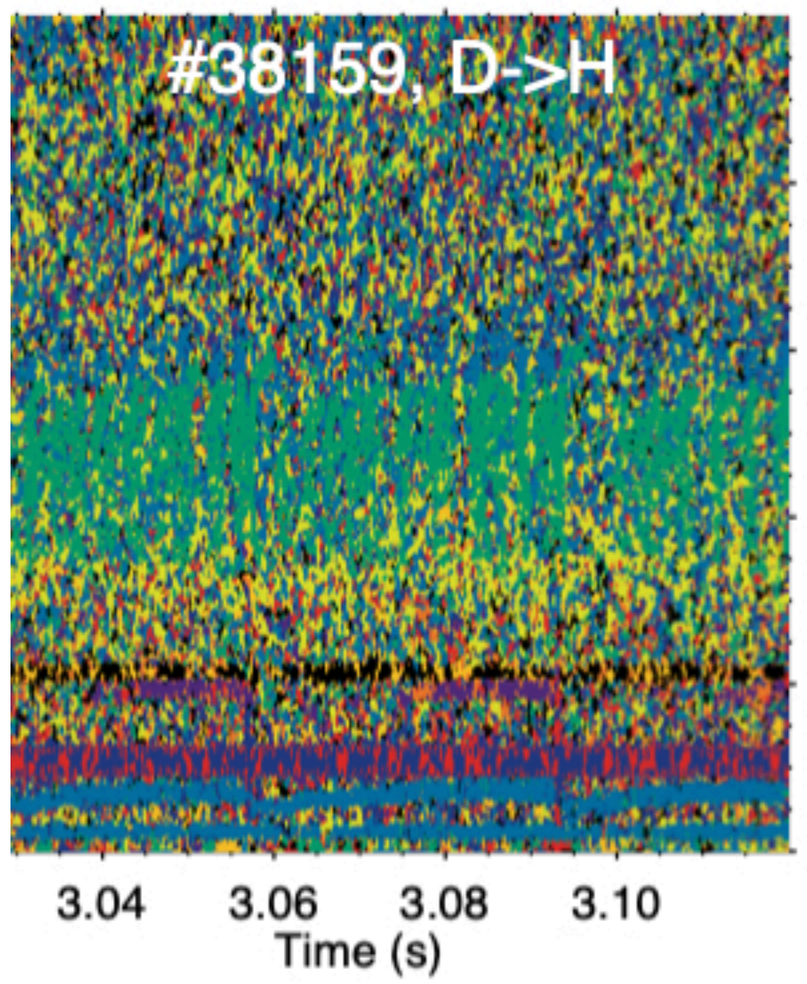
recently in AUG : isotope scans for hydrogen and helium plasmas performed

- **exhaustive data for FOW/FLR effect studies**
- **higher L-H transition threshold in H allows for improved profile measurements in L-mode**
- **various combinations of on and off-axis beams with modes propagating in both electron and ion diamagnetic directions**
- **non-linear mode-mode interaction documented via bi-coherene analysis [Lauber FEC 2018]**

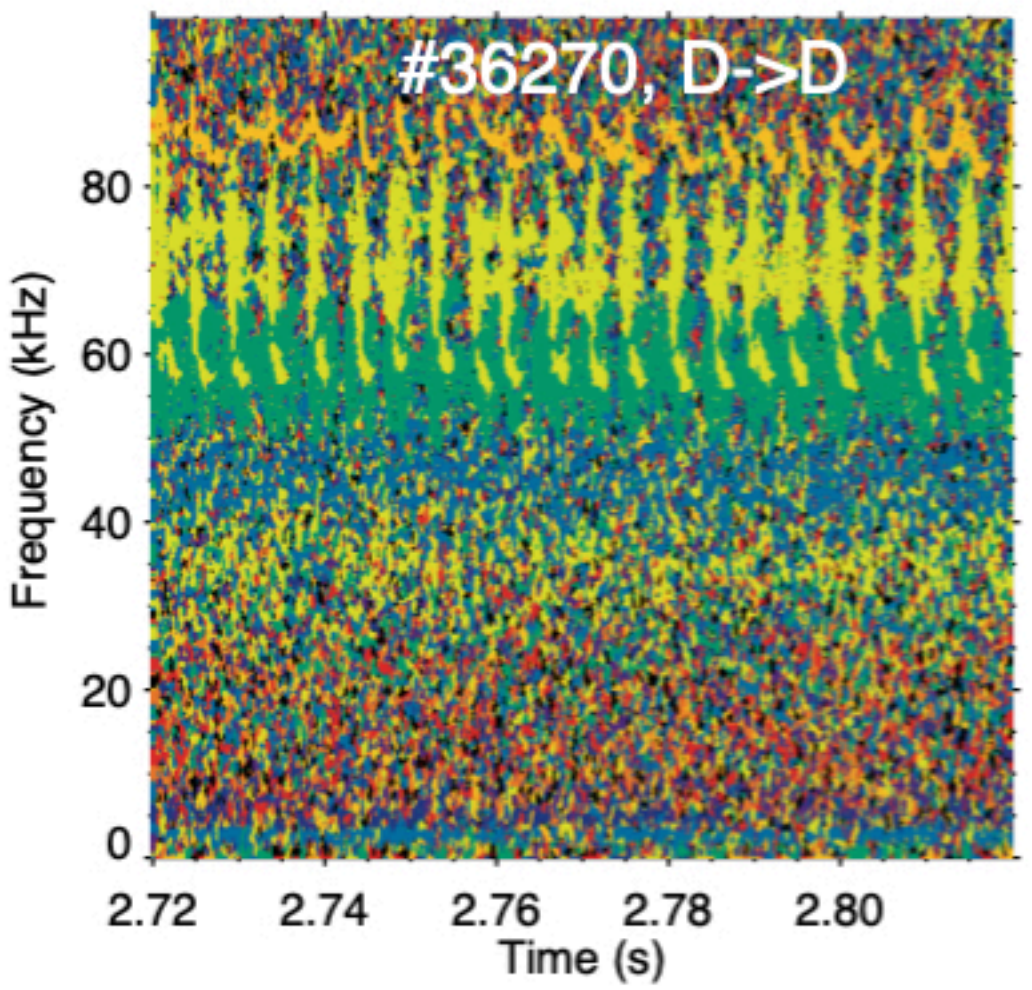
helium plasma, D beams



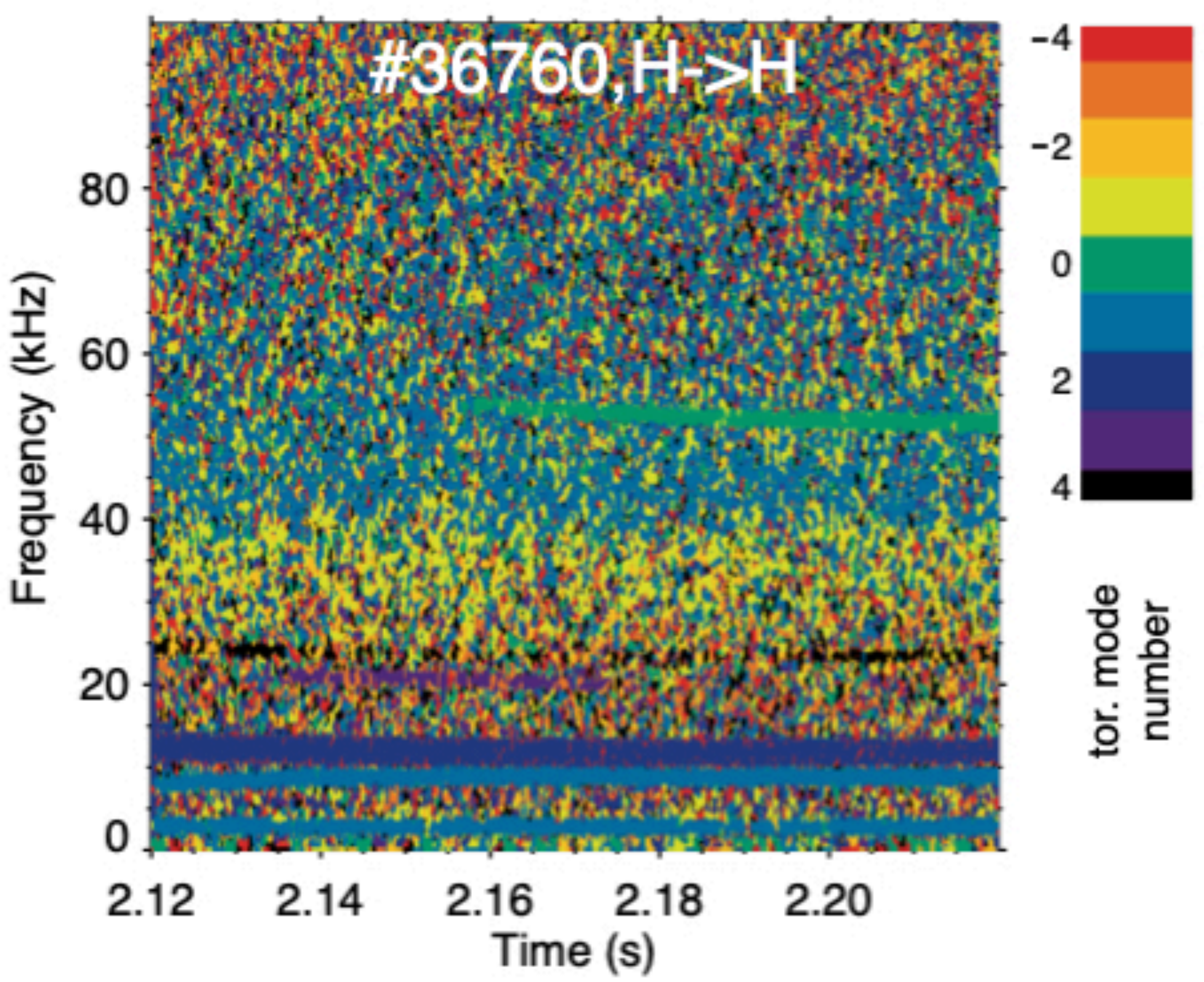
hydrogen plasma, D beams



deuterium plasma, D beams

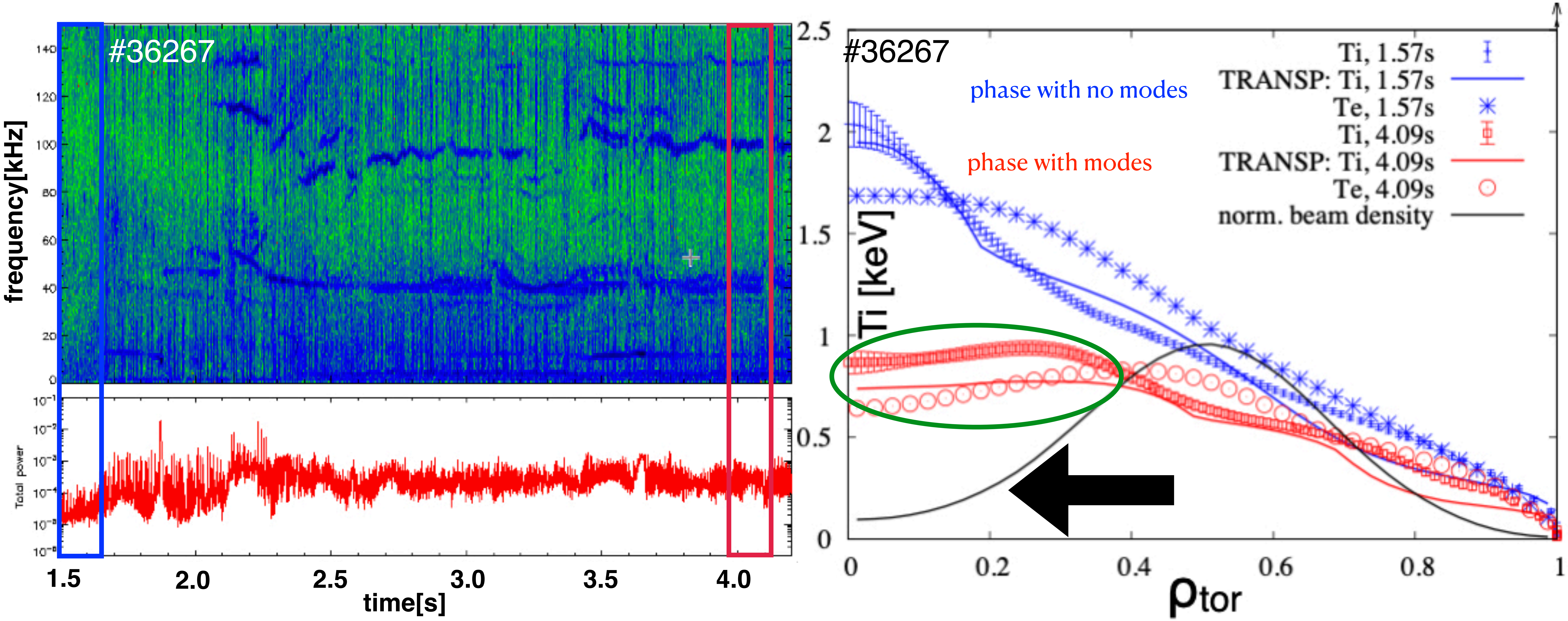


hydrogen plasma, H beams



Evidence for anomalous core background ion heating due to Alfvénic modes?

assess effect of EP re-distribution on Ti profiles - is the EP transport enough to explain the Ti difference?



other cases/experiments very welcome - TCV, JET, JT-60SA, ITER ongoing

summary & outlook

- IMAS-based PSZS transport model has been setup via coupling linear GK and non-linear drift-kinetic codes
- general F_{EP} generated from 'neoclassical' marker data can be used
- evolved PSZS transport equation in COM space in kick-model limit - mapping to real space available
- dedicated experiments at AUG address strongly non-linear EP regimes and diagnose related EP transport

next steps:

- calculate D(s,E) - couple to RABBIT/transport codes
- add amplitude dependence of PSZS i.e. d (dP/dt)dPz * F_{EP} term -> similar to RBQ model
- add various intensity closure models - analytical theory/ORB5/…
- add collisions and sources - bounce averaged collision operators - compare with models/codes e.g. CKA-EUTERPE [Brizard, Slaby/Kleiber, Hoppe,…]
- check diffusive vs convective cases, different mode spectra, overlap criteria
- separate scales according to PSZS theory → use to evolve to non-linear equilibria
- include (PS)ZSs due to turbulence, explore interaction in various limits

- speed up, hopefully export support next year via Eurofusion, integrate in workflow framework