Fast Particle modelling for JT60SA — next steps

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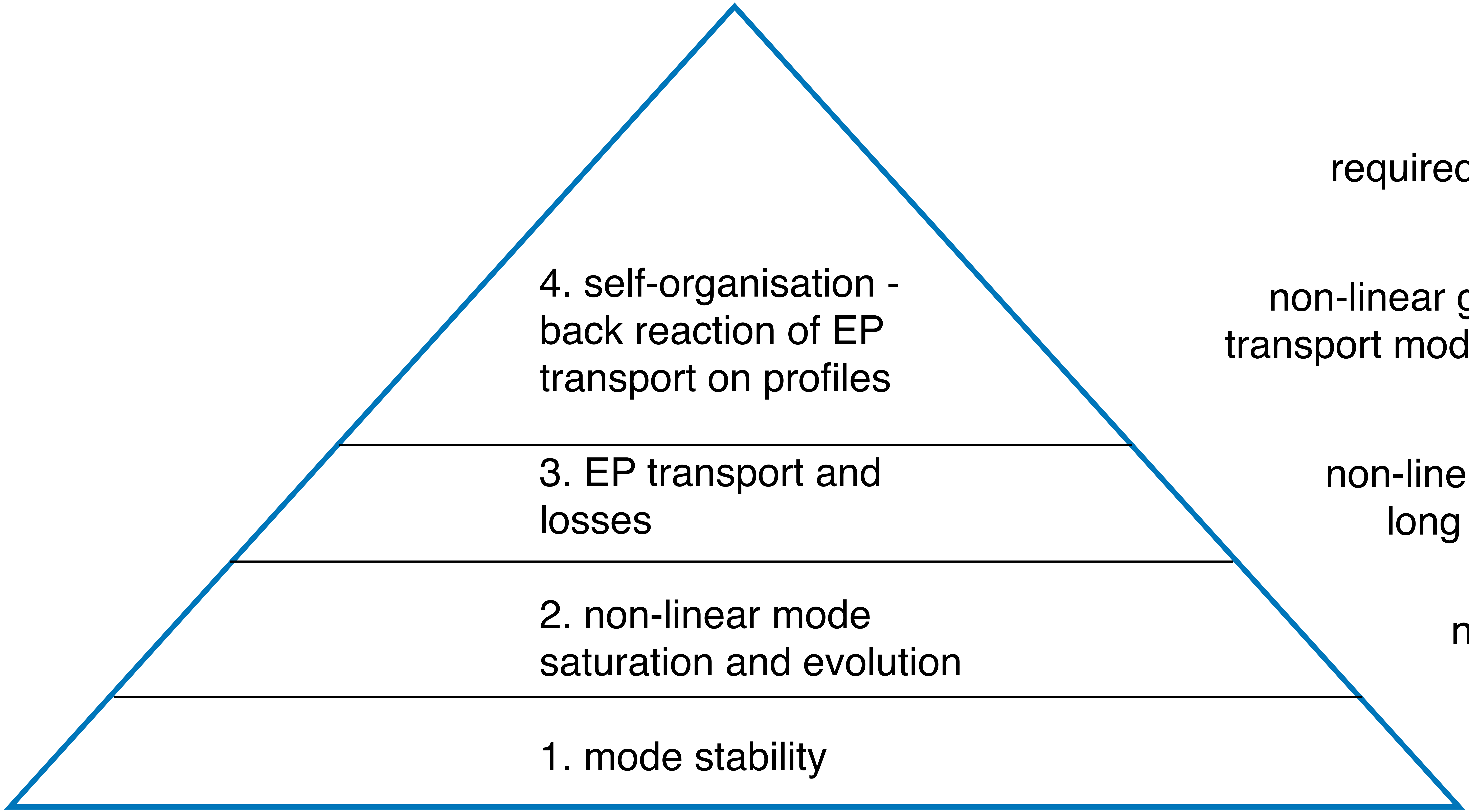
acknowledgements to ENR ATEP and TSVV#10 teams

needed for scaling from present day to future devices, in particular JT-60SA:



required model:

non-linear global kinetic equivalent transport model + background transport

non-linear/quasi-linear global kinetic + long time scales (source +sink)

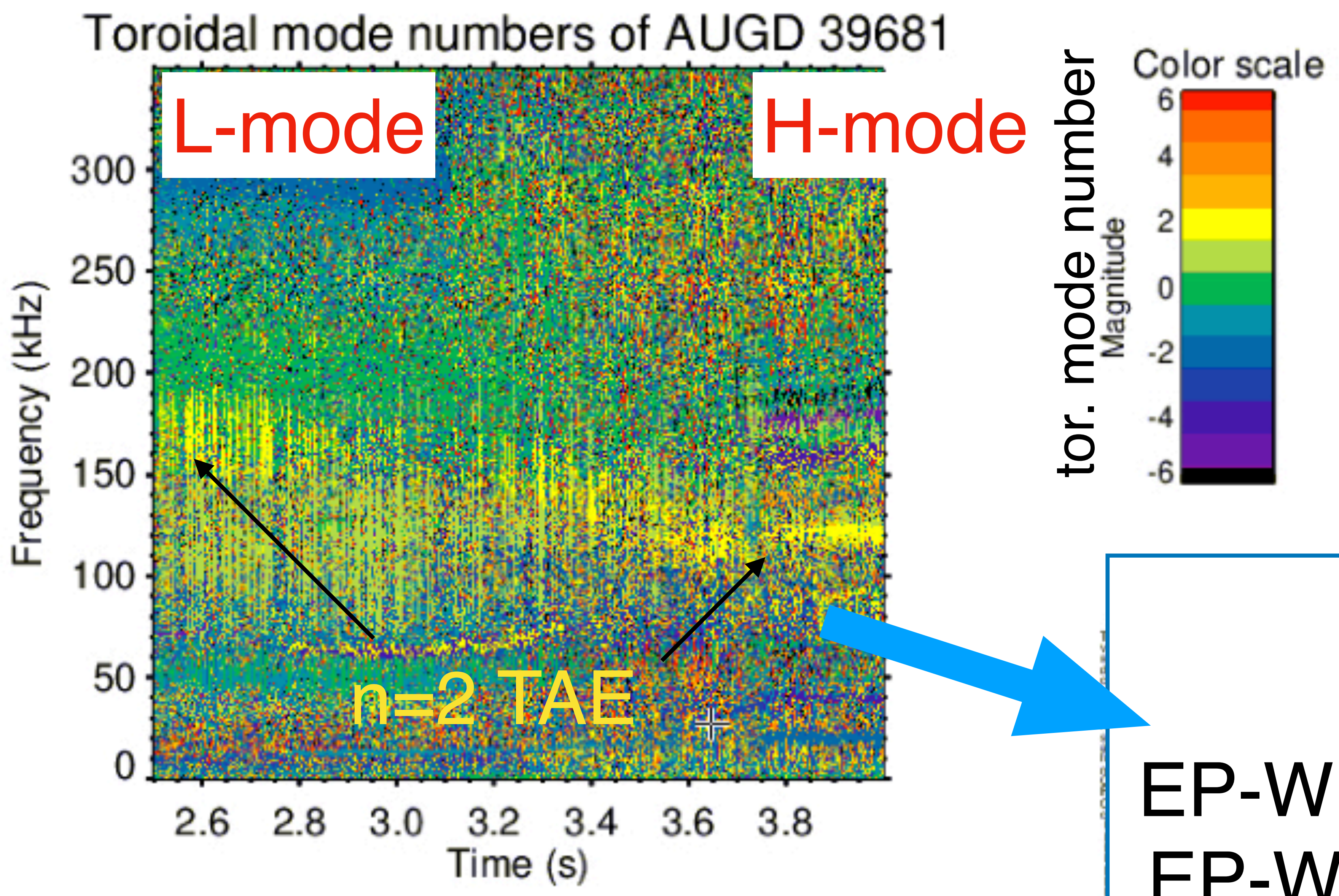
non-linear global kinetic

linear global kinetic

within TSVV#10 and ENR ATEP: develop and adopt to IMAS and set up consistent modelling hierarchy

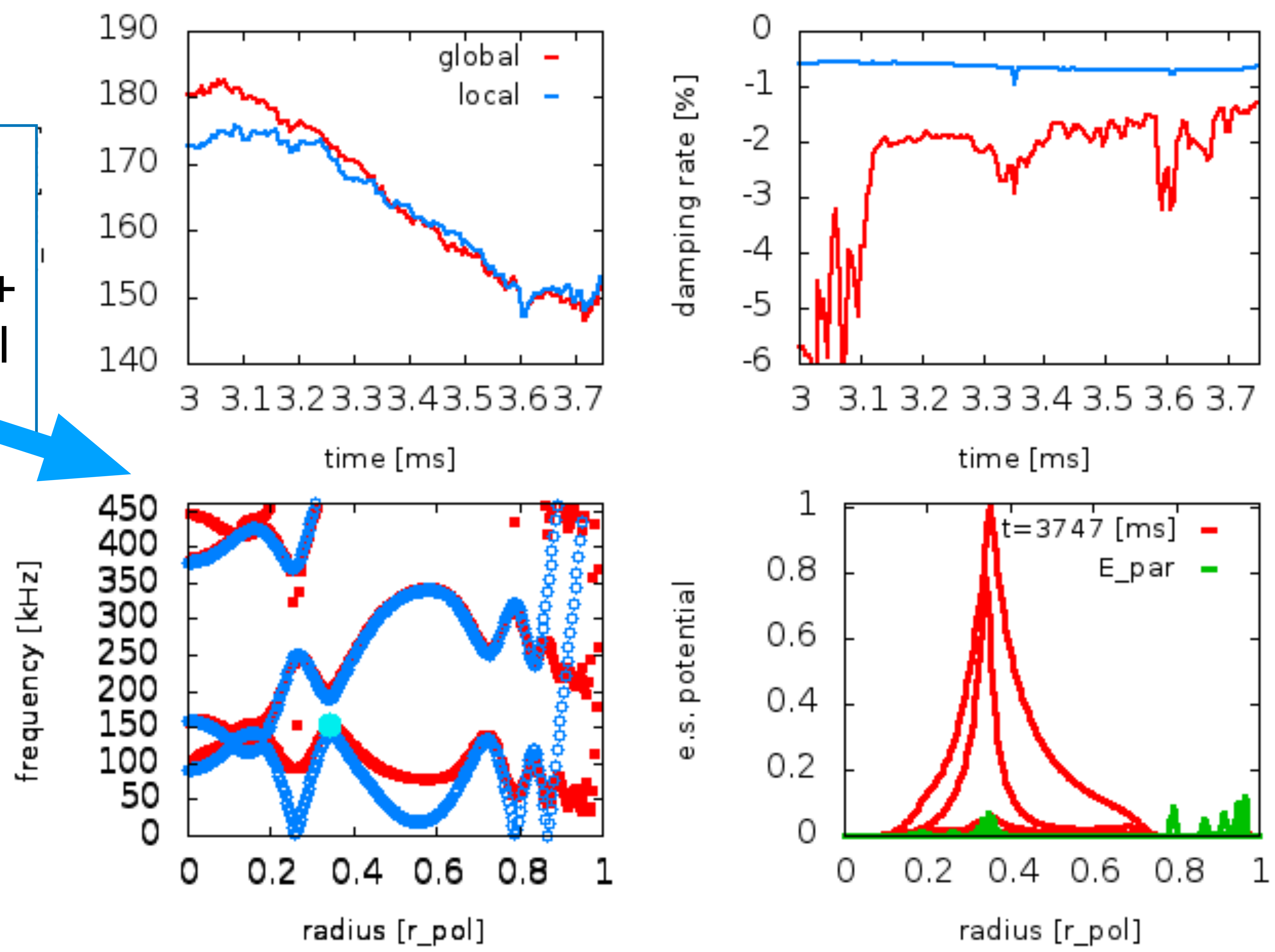
1. mode stability

automated application of EP stability workflow to 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

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

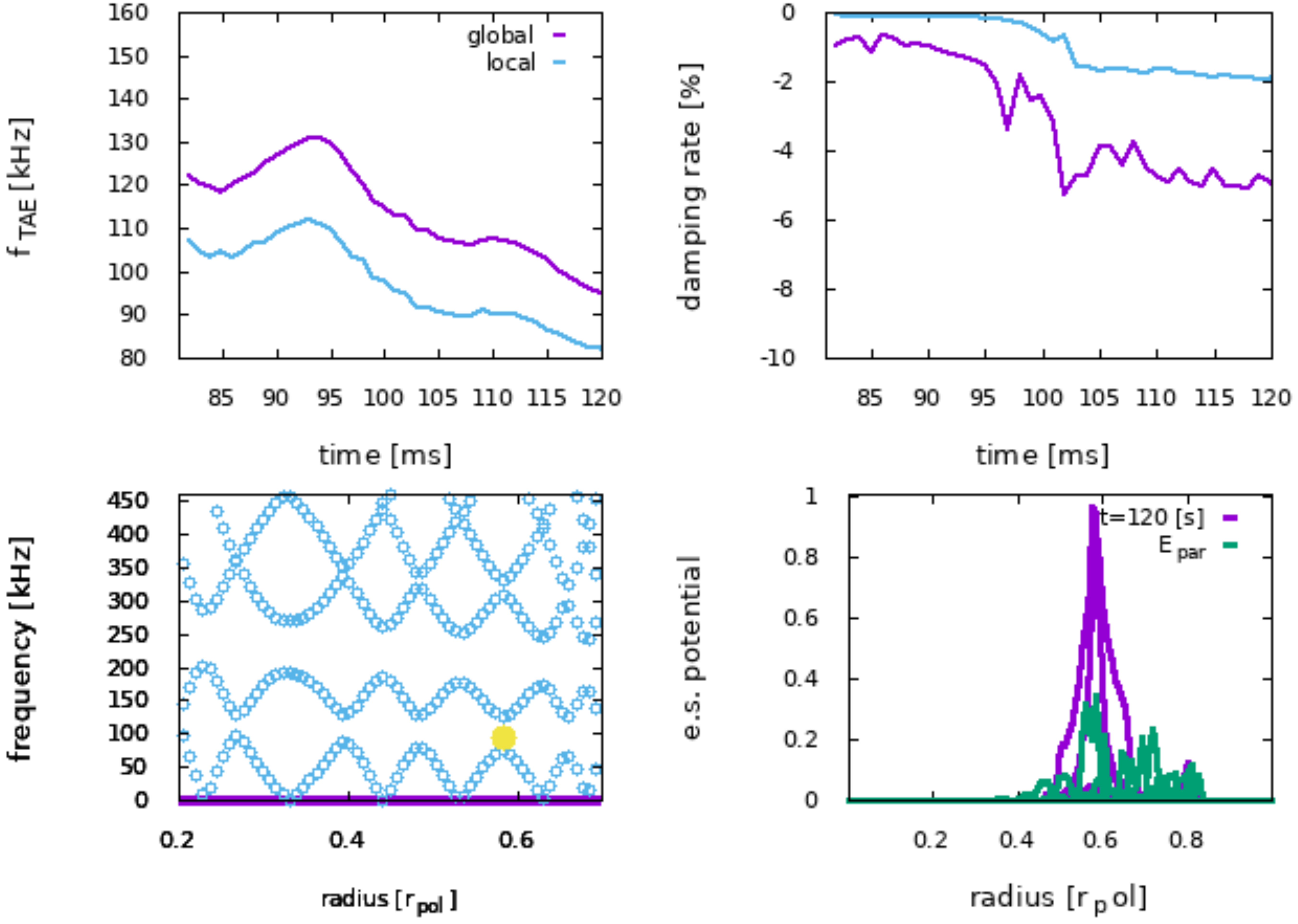


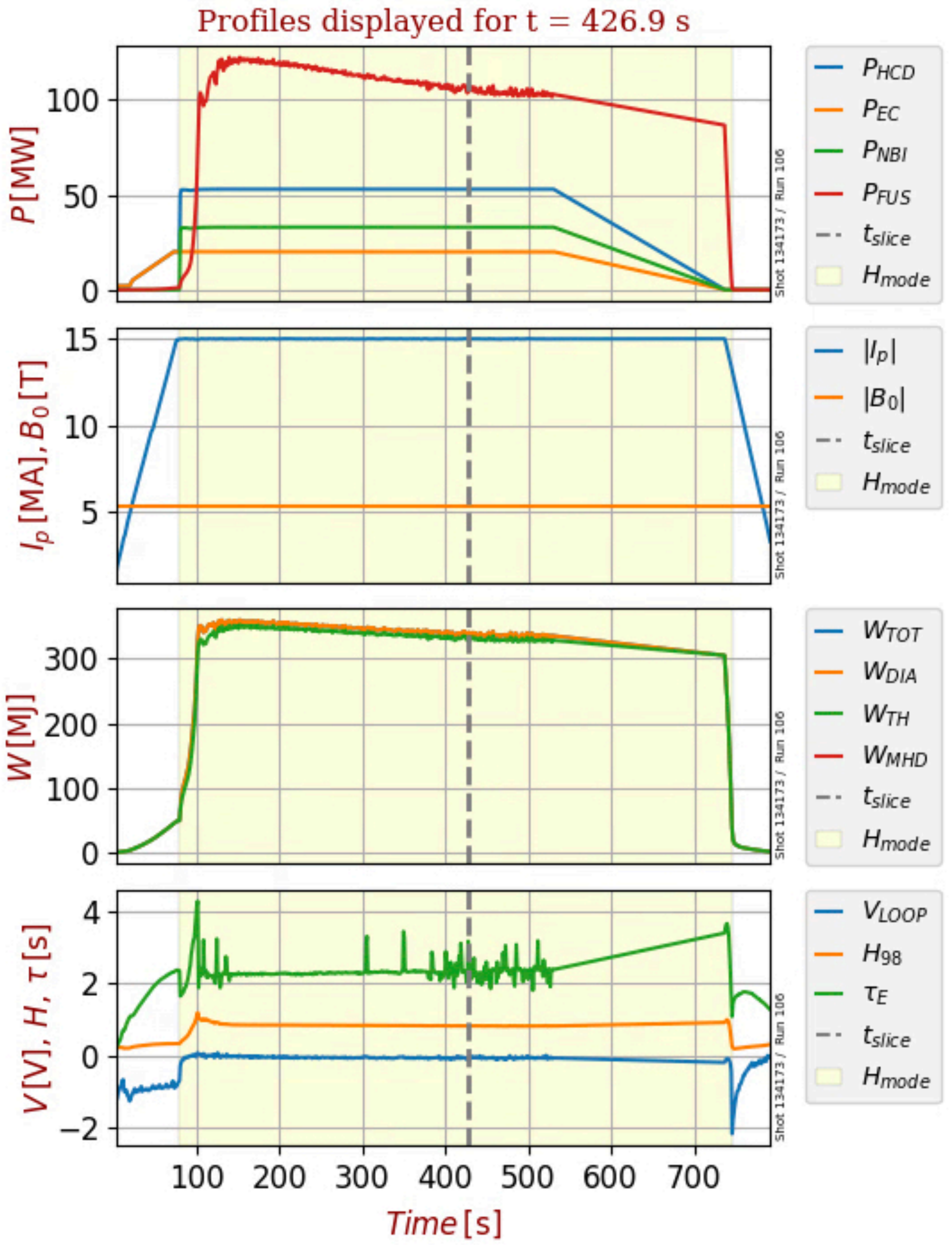
results:

- comprehensive, time-dependent information on linear properties, e.g. understanding of discrepancies between local and global model, sensitivity of damping rate,…
- ready for quasi-linear coupling to transport models in particular phase space zonal structure transport model [ENR ATEP project]
- systematic uncertainty quantification feasible
- ultimate aim: predictive scenario optimisation

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

TAE n=18

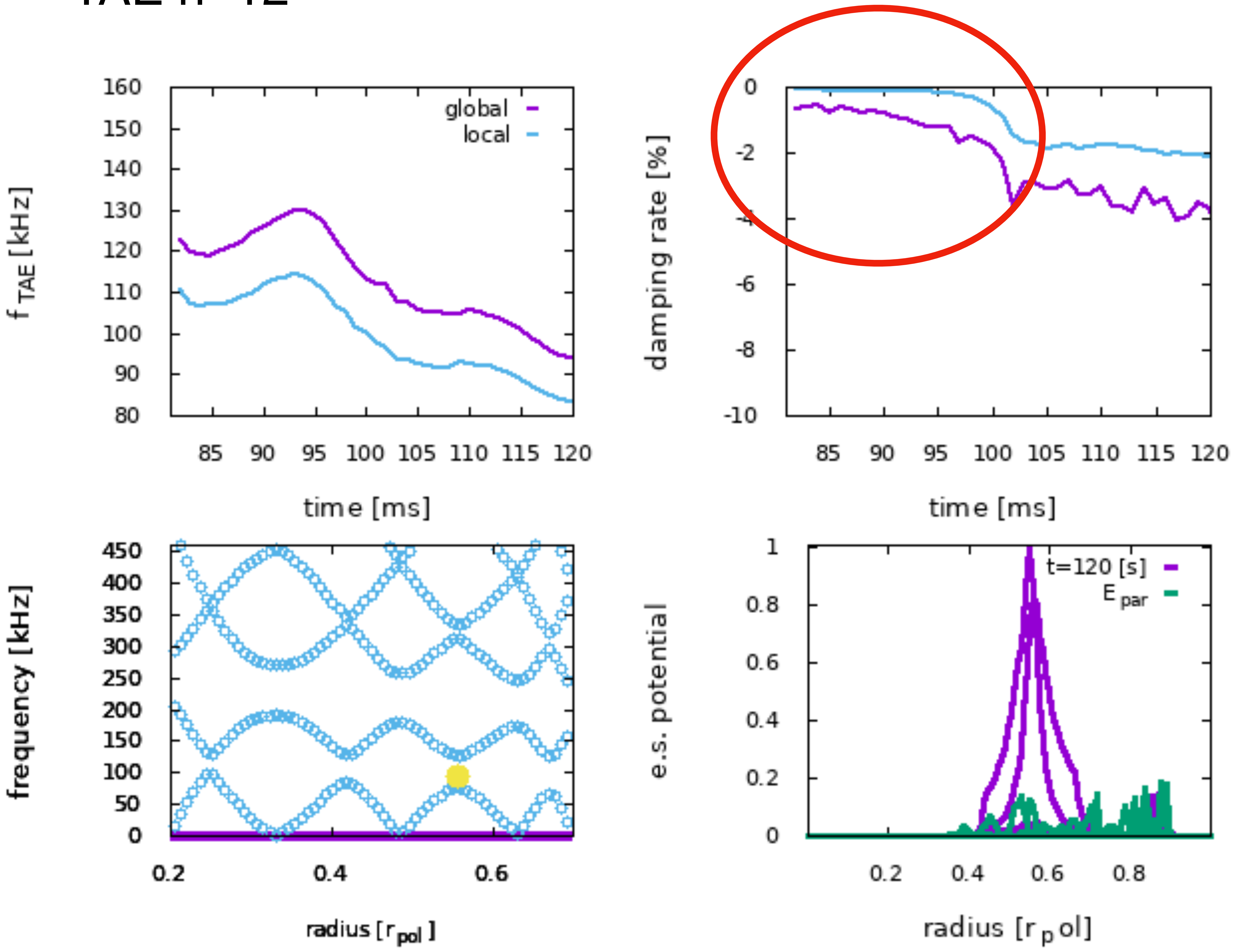




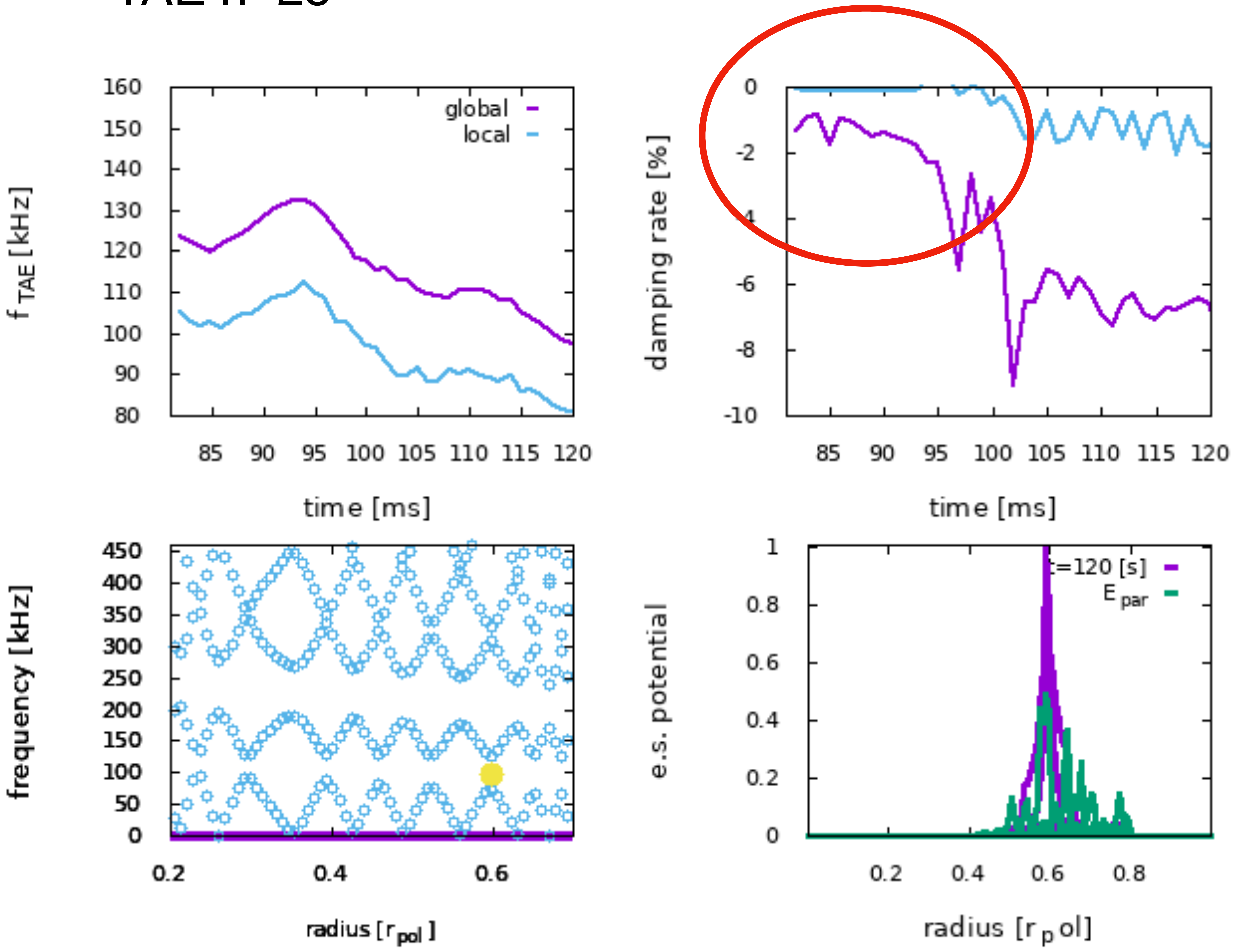
low damping rates during/at the end of the power ramp-up phase

automated application of EP stability workflow projected ITER scenarios: #134173, 106

TAE n=12

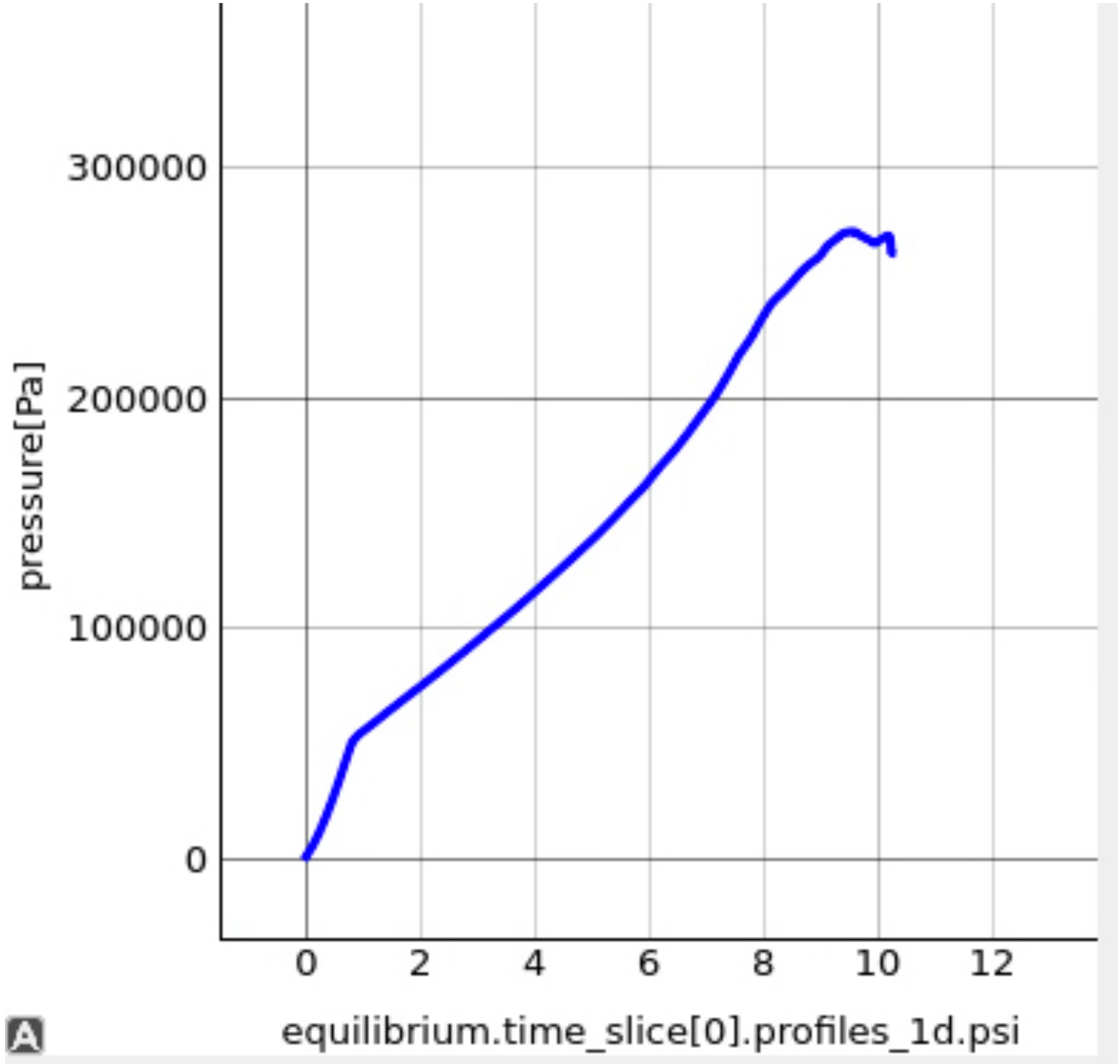


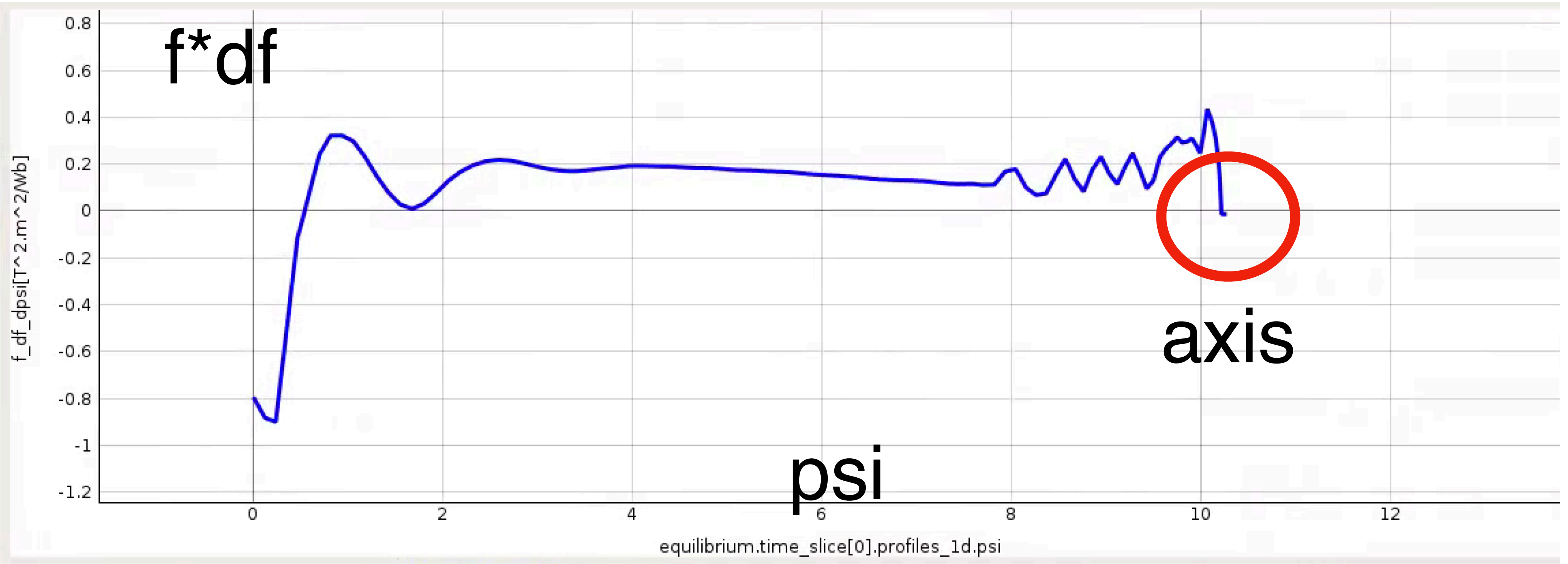
TAE n=25



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

JT-60SA: successful coupling to JINTRAC output (scenario 2, 70000,419) [L Garzotti] but: still equilibrium reconstruction issues remain

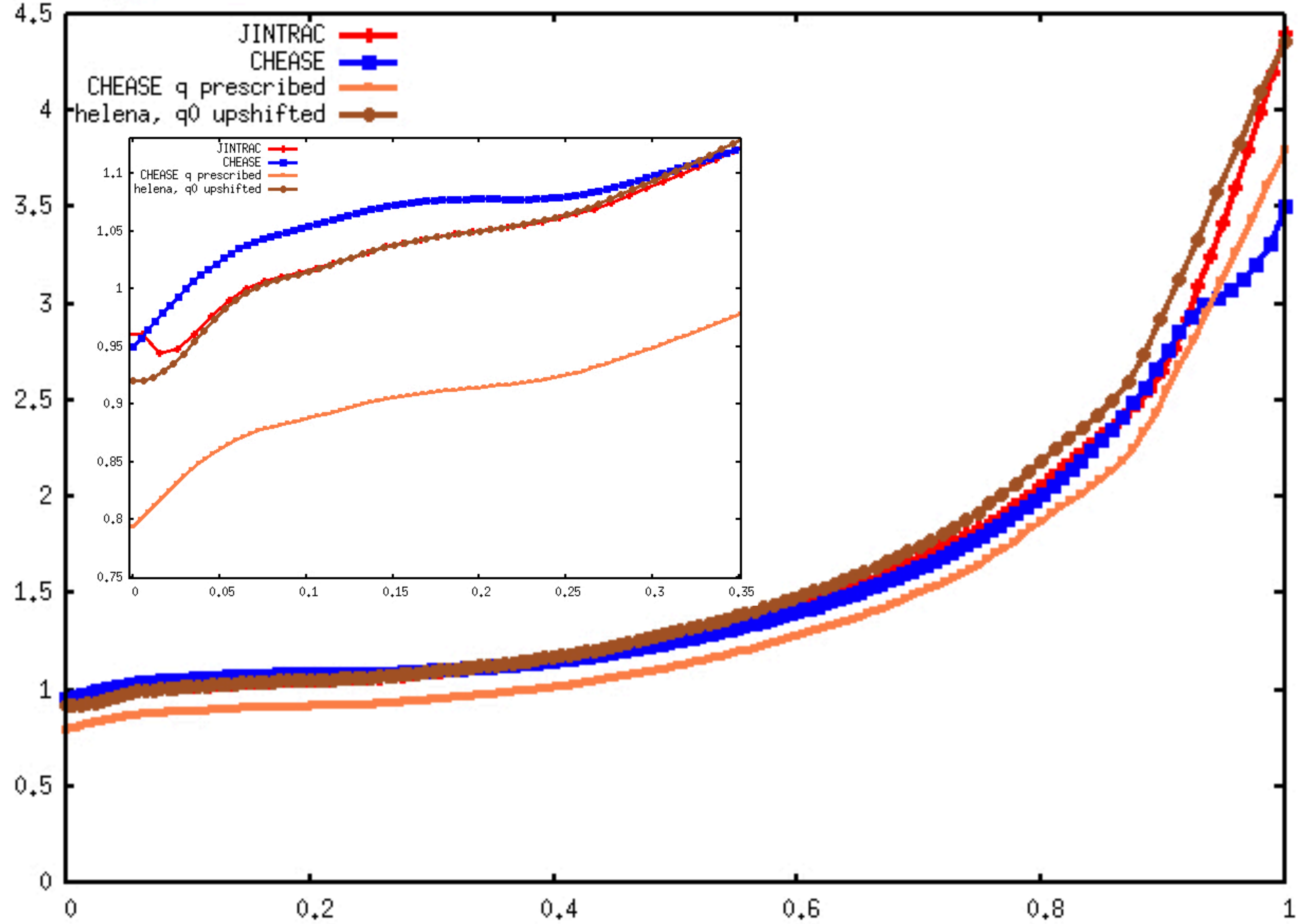




difficulty: profile input from transport codes to equilibrium codes

despite correctly filled equilibrium IDS (COCOS 11, seems to be correct with respect to signs)

equilibrium reconstruction issues remain



difficulty: profile input from transport codes to equilibrium codes:

- helena: crash
- helena: manipulate inner ffp data : works, no satisfactory match of resulting q profile
- CHEASE: using ffp and p: problems matching edge q
- CHEASE : using q and p (thx T. Hayward-Schneider): q downshifted

run/write internal EQ solver in JINTRAC with higher resolution?

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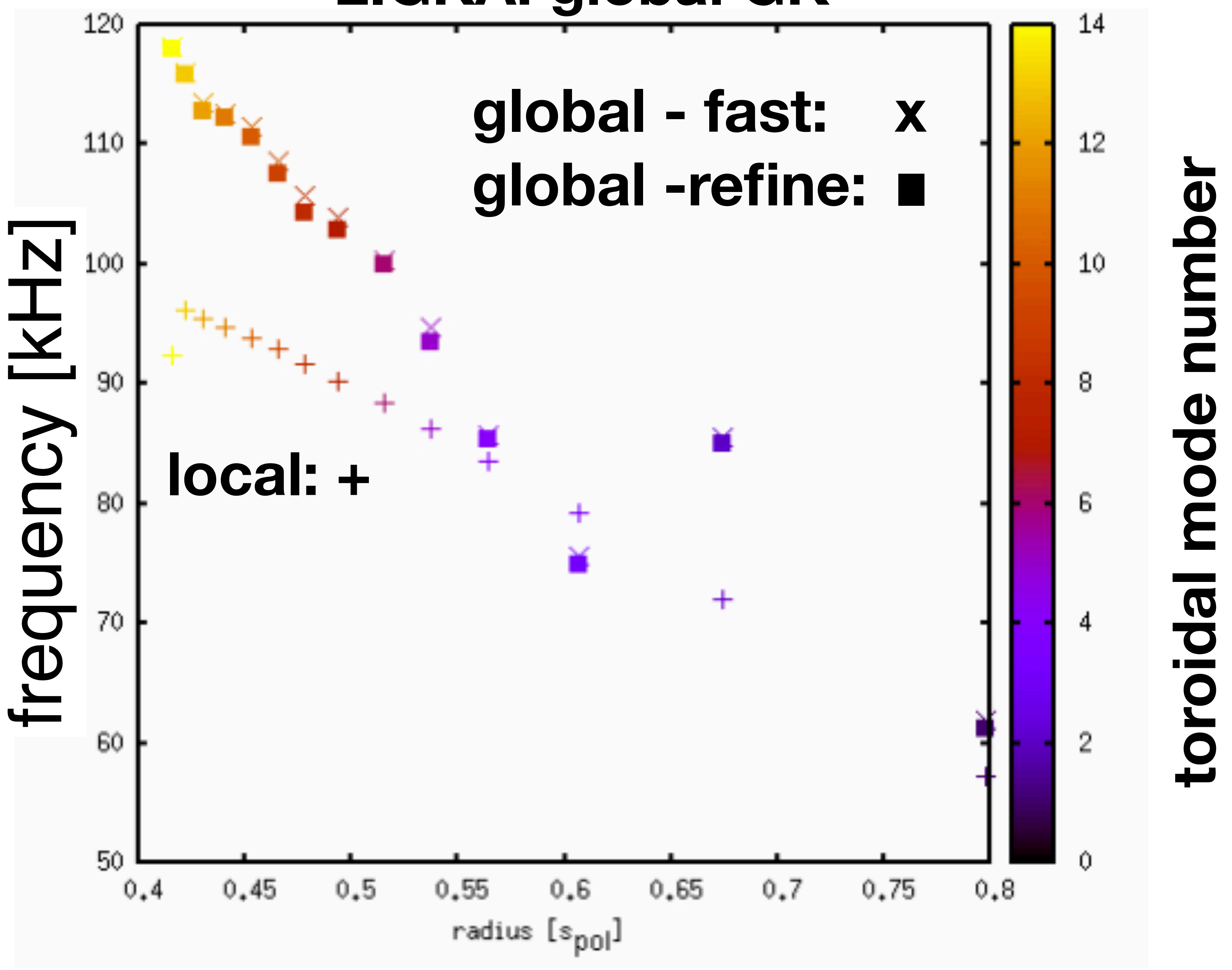
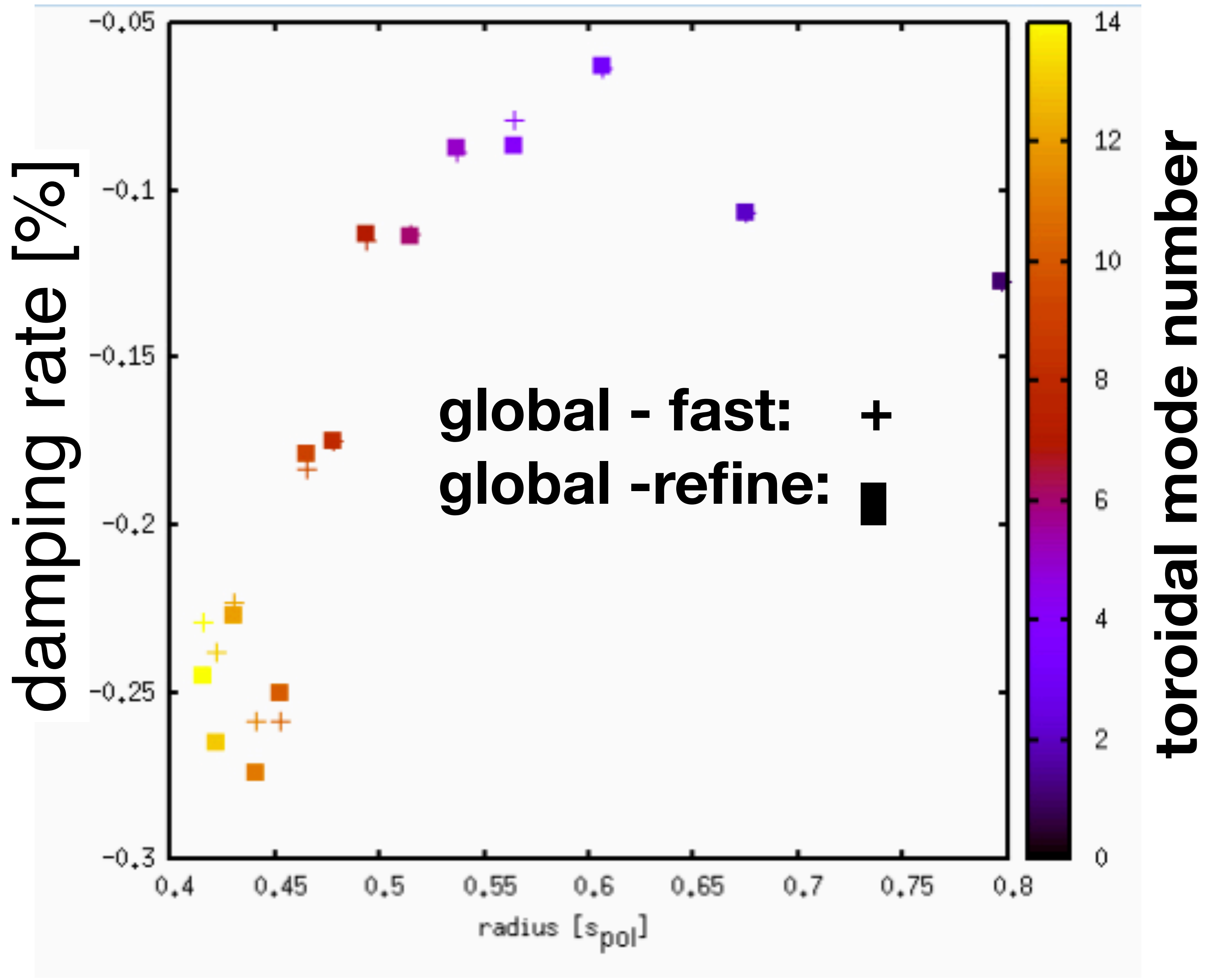
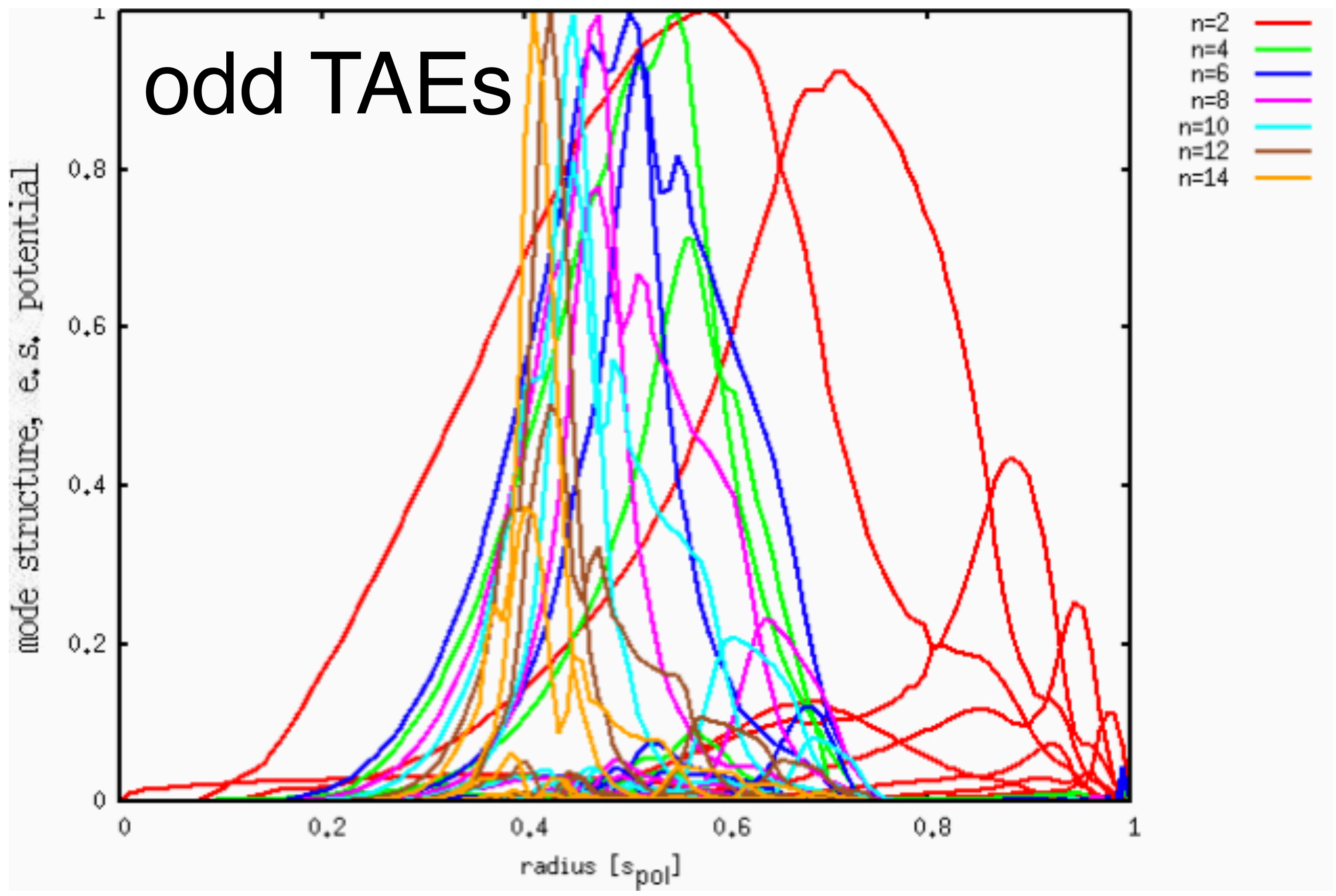
JT-60SA: successful coupling to JINTRAC output (scenario 2, 70000,419) [L Garzotti]

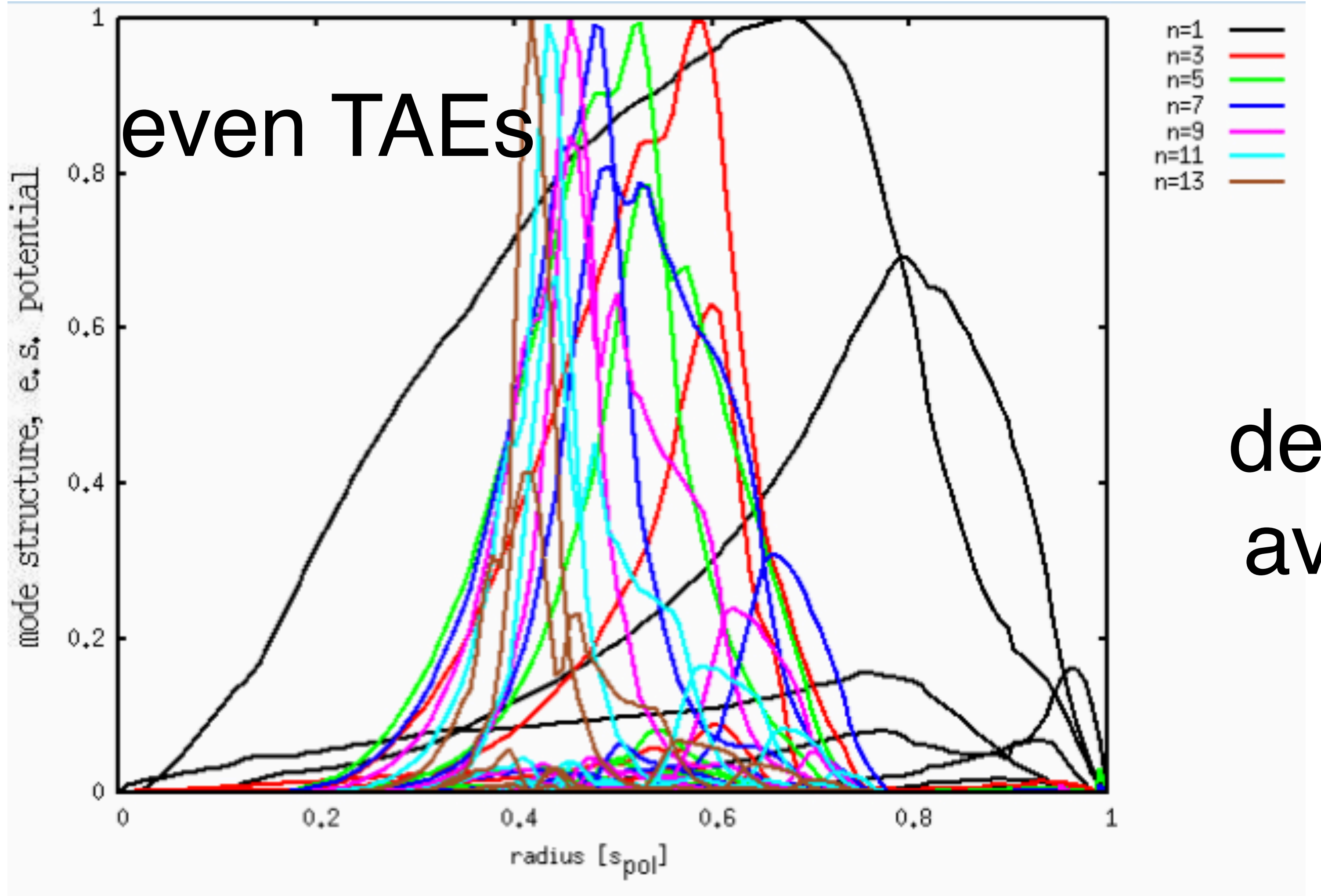
LIGKA: global GK



LIGKA: global GK







waiting for time-dependent runs to be available in IMAS on gateway…

2. non-linear mode saturation and evolution

not yet started - first choose optimal time point

work needed on ASCOT IMAS output

HAGIS2/ ORB5 IMAS interfaces exist, partially also interfaces to ITER H&CD WF, RABBIT

distribution IDS quantities needed:

```
distribution_outg%distribution(iinj)%markers(1)%coordinate_identifier(1)%description  = 'R'
distribution_outg%distribution(iinj)%markers(1)%coordinate_identifier(2)%description  = 'Z'
distribution_outg%distribution(iinj)%markers(1)%coordinate_identifier(3)%description  = 'Phi geom'
distribution_outg%distribution(iinj)%markers(1)%coordinate_identifier(4)%description  = 'Theta geom'
distribution_outg%distribution(iinj)%markers(1)%coordinate_identifier(8)%description  = 'Velocity'
distribution_outg%distribution(iinj)%markers(1)%coordinate_identifier(9)%description  = 'Parallel velocity'
distribution_outg%distribution(iinj)%markers(1)%coordinate_identifier(10)%description  = 'initial pitch'
distribution_outg%distribution(iinj)%markers(1)%coordinate_identifier(11)%description = 'Magnetic momentum'
distribution_outg%distribution(iinj)%markers(1)%coordinate_identifier(12)%description = 'Safety factor'
distribution_outg%distribution(iinj)%markers(1)%coordinate_identifier(13)%description = 'Magnetic field'
distribution_outg%distribution(iinj)%markers(1)%coordinate_identifier(14)%description = 'Toroidal momentum (kg m**2/s)'
distribution_outg%distribution(iinj)%markers(1)%coordinate_identifier(15)%description = 'Energy (eV)'
distribution_outg%distribution(iinj)%markers(1)%coordinate_identifier(16)%description = 'Lambda = mu*B0/E (-)'
```

to be stored in:
distribution_outg%distribution(iinj)%markers(itime)%positions(marker_number,identifier)
distribution_outg%distribution(iinj)%markers(itime)%weigths(marker_number)

250k-1M markers, depending on details of distribution function (e.g. number of beams etc)

3. EP transport and losses
and
4. self-organisation - back reaction of EP transport on profiles

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:

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

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]

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

$$+ \frac{\partial}{\partial w}(B_\parallel^* \overline{\delta\dot{w}\delta G_{\rm res}}) = 0 \qquad (12)$$

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

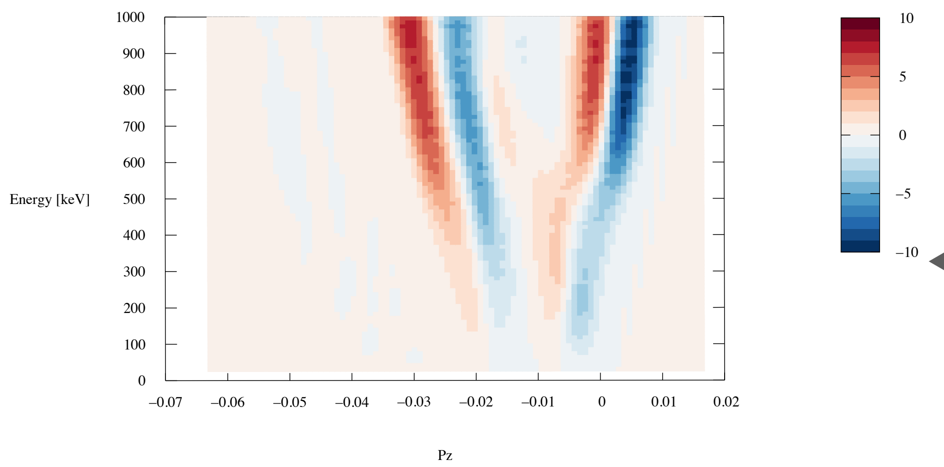
$$D_{\psi\psi} = \overline{\delta\dot{\psi}\delta\dot{\psi}}\tau_{ac} = \frac{1}{2}\sum_{\omega,\mathbf{k}_\perp} c^2 m_\beta^2 |\delta\hat{\Phi}|^2 \tau_{ac} \qquad (45)$$

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

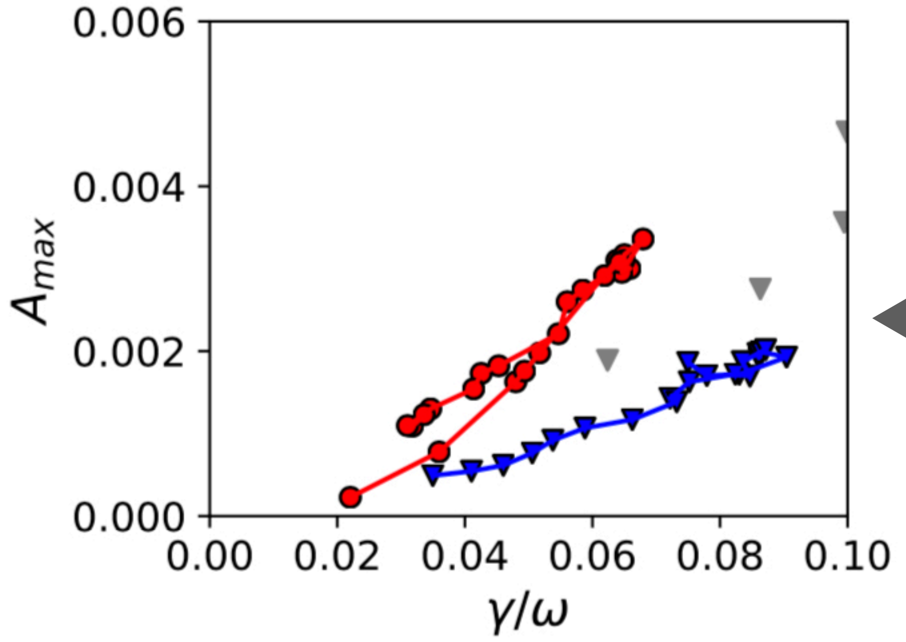
$$D_{\varepsilon\varepsilon} = \overline{\delta\dot{\varepsilon}\delta\dot{\varepsilon}}\tau_{ac} = \frac{1}{2}\sum_{\omega,\mathbf{k}_\perp}\left(\frac{\omega e}{m}\right)^2 |\delta\hat{\Phi}|^2 \tau_{ac} \qquad (47)$$

ATEP framework (ENR ATEP)
EP transport workflow schematics

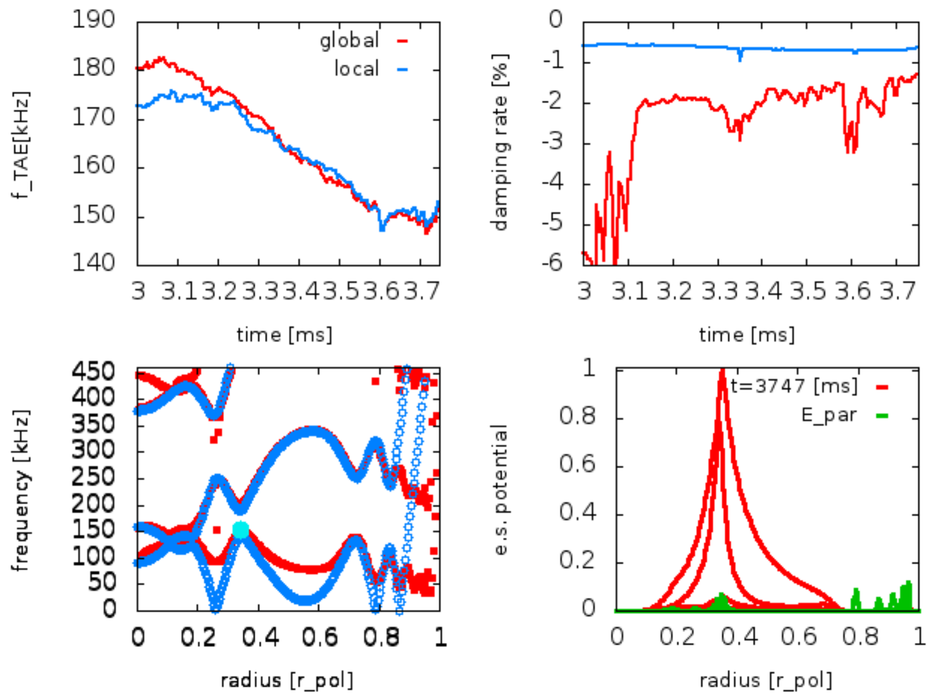
FINDER/HAGIS [Ph. Lauber, 2007,2022]



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



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



calculate PSZS

use NL code/model for intensity closure

calculate linear mode spectrum

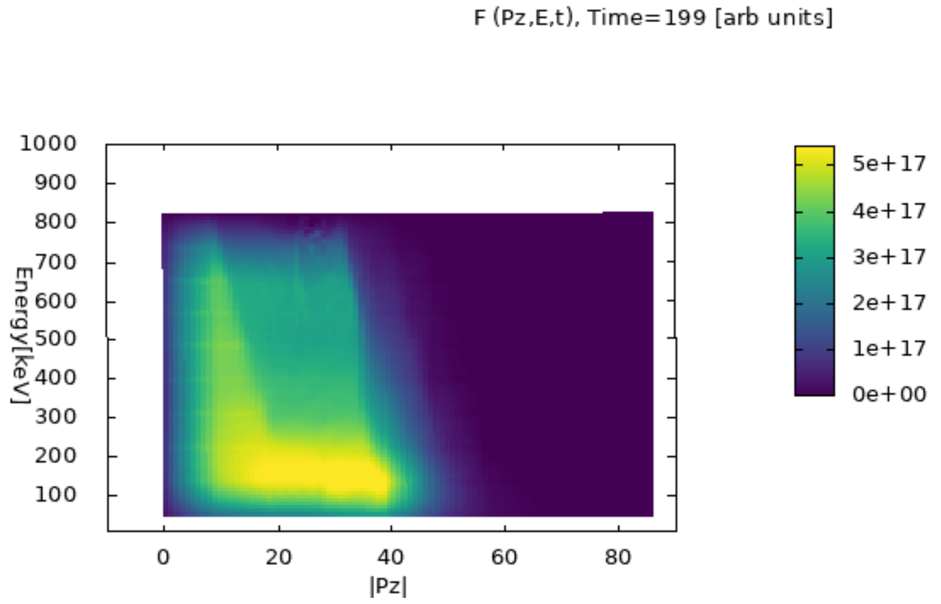
kick-model or QL transport model with intensity closure can be recovered under simplifying assumptions

calculate D(r,E)

or

advance F_{EP} and return updated distribution IDS, or its moments

ATEP code [Ph. Lauber, 2022]



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

t

t+1

core transport

equilibrium

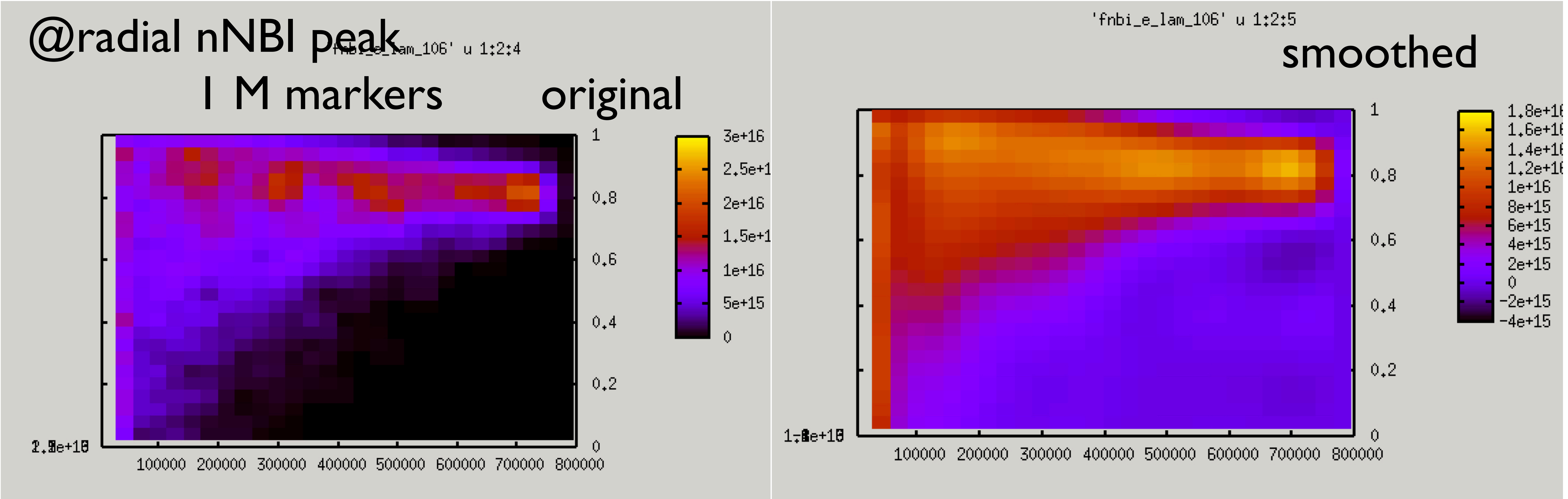
mhd_linear

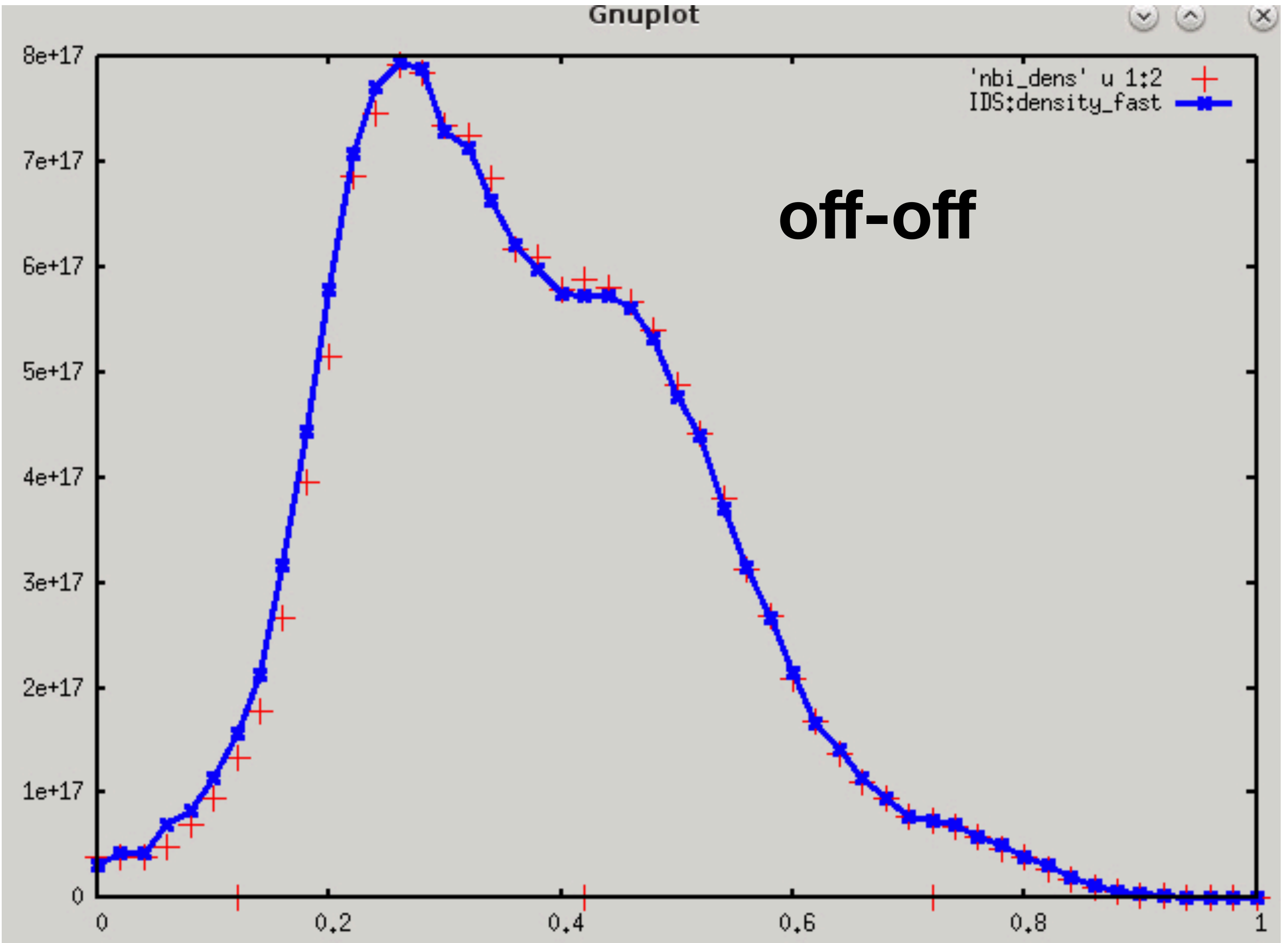
distributions

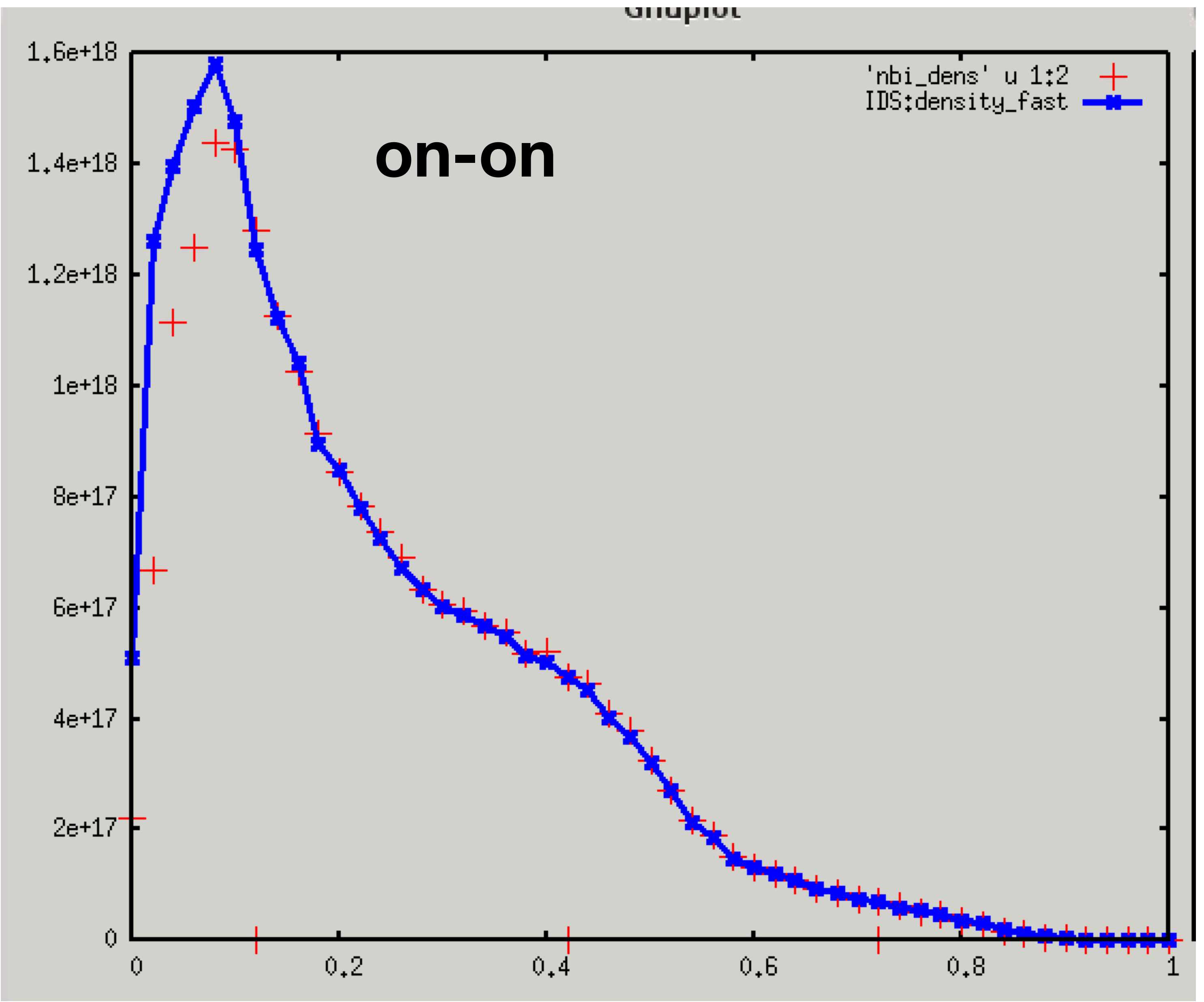
transport code

time

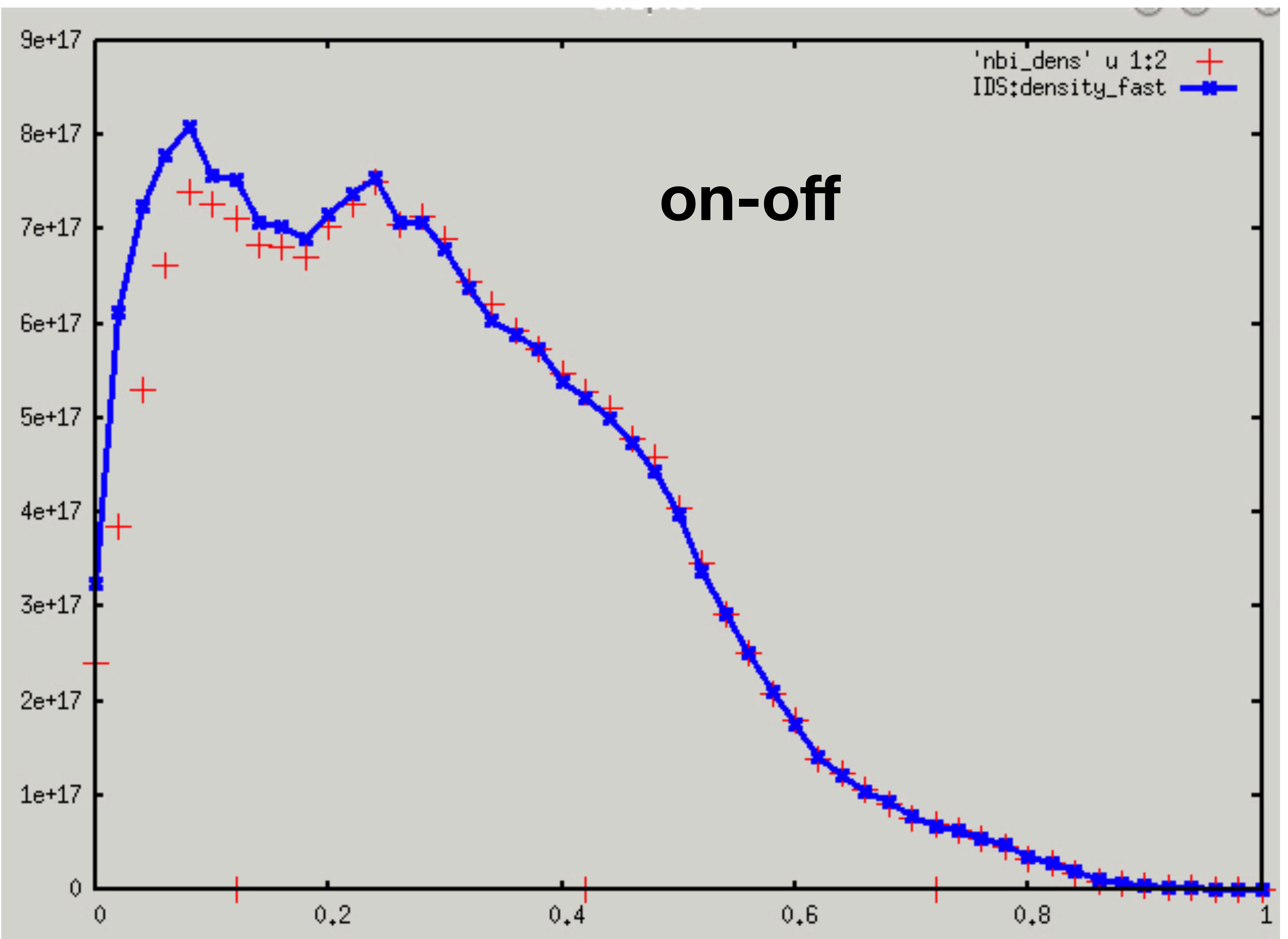
ITER: 100015: F_{EP} is available from H&CD WF [thx. M. Schneider]







distribution IDS
for 250k-1M markers
will be needed from
ASCOT



ATEP code: advance transport equation

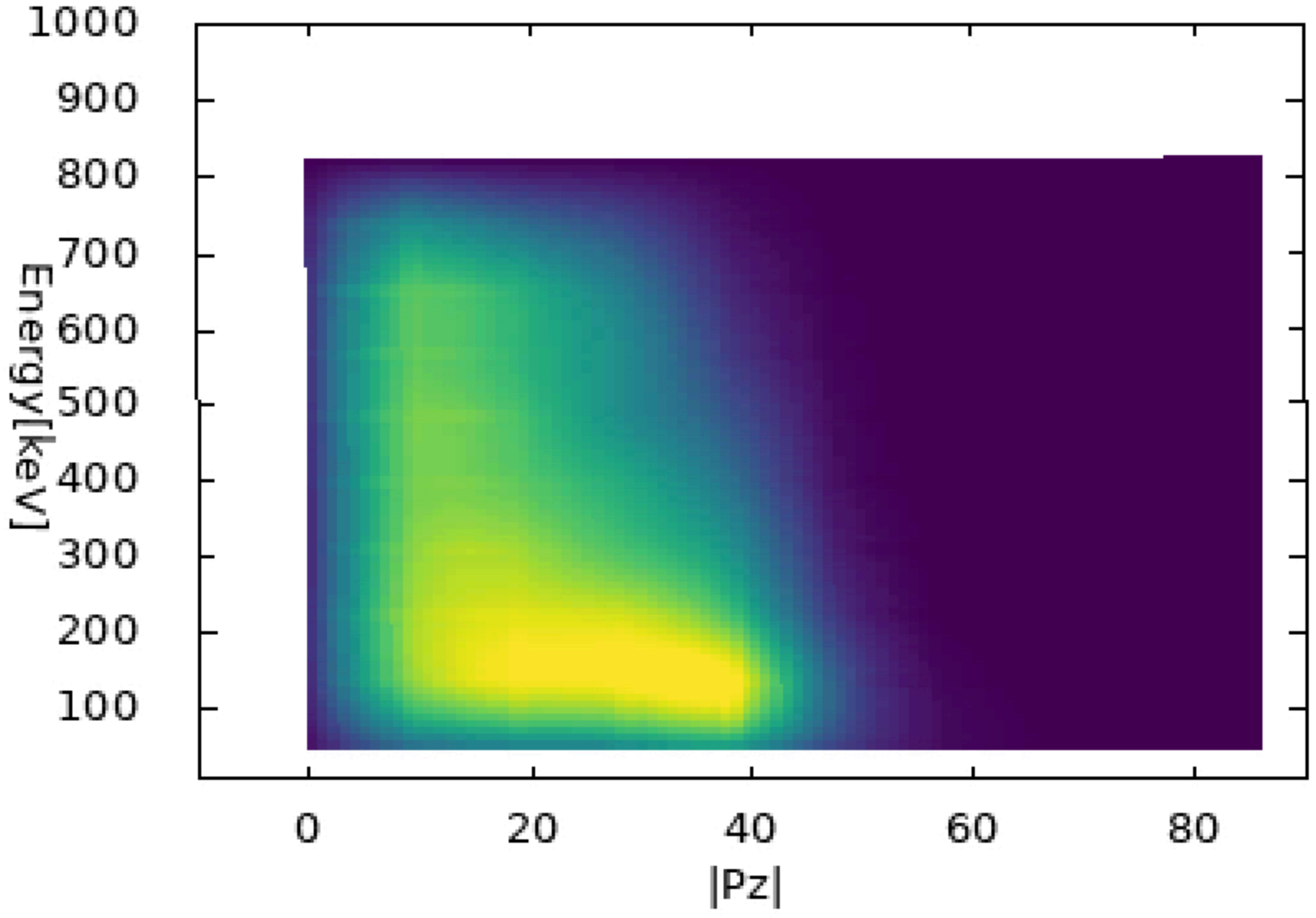
simple finite difference scheme to start with (final scheme to be decided when sources/collisions are implemented):

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

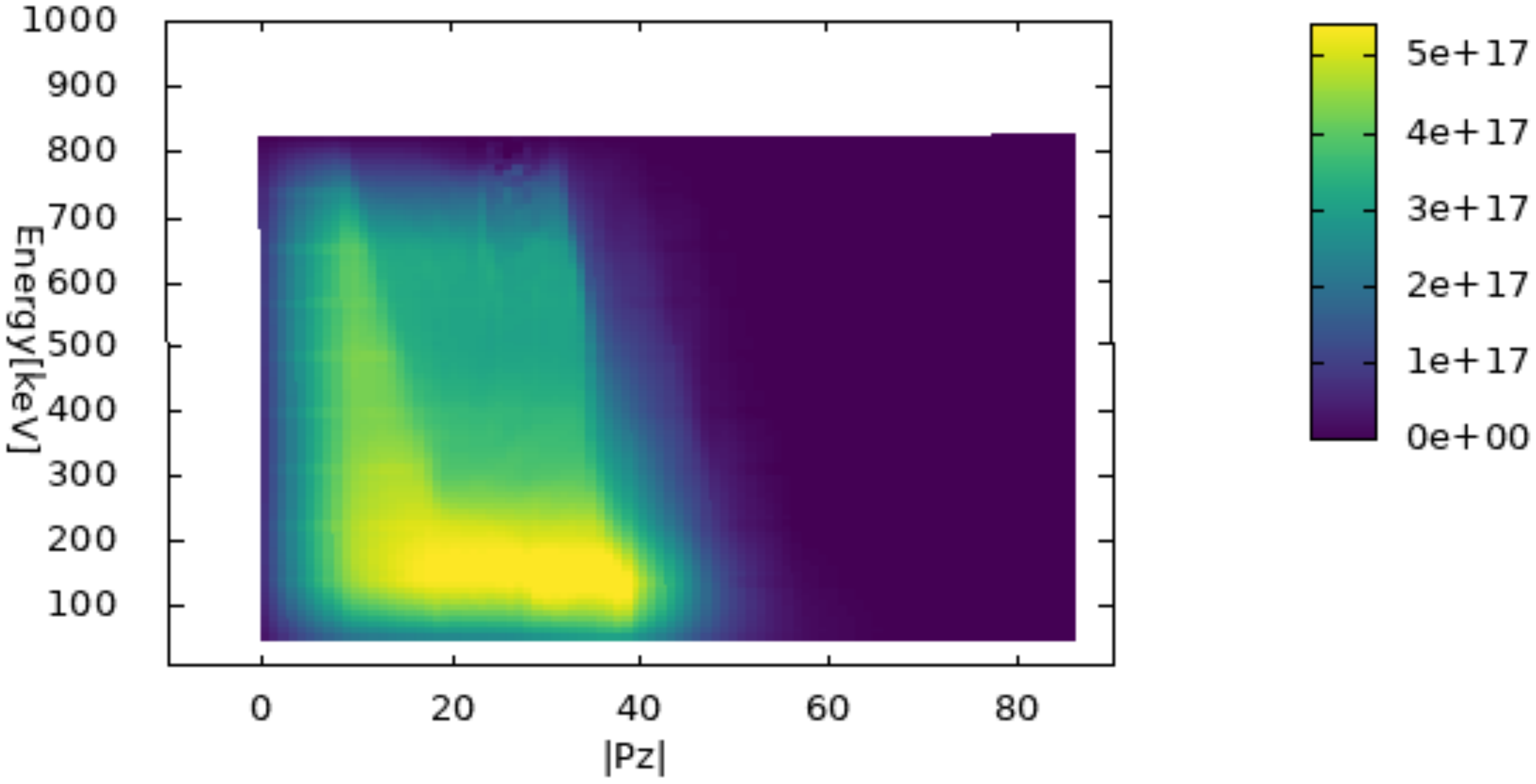
note: $\frac{\partial^2 Pz}{\partial t \partial P_z} F_{EP}$ **term excluded so far: dPz/dt assumed constant -> kick model limit**

runtime: several seconds

FEP at start (integrated over Λ):

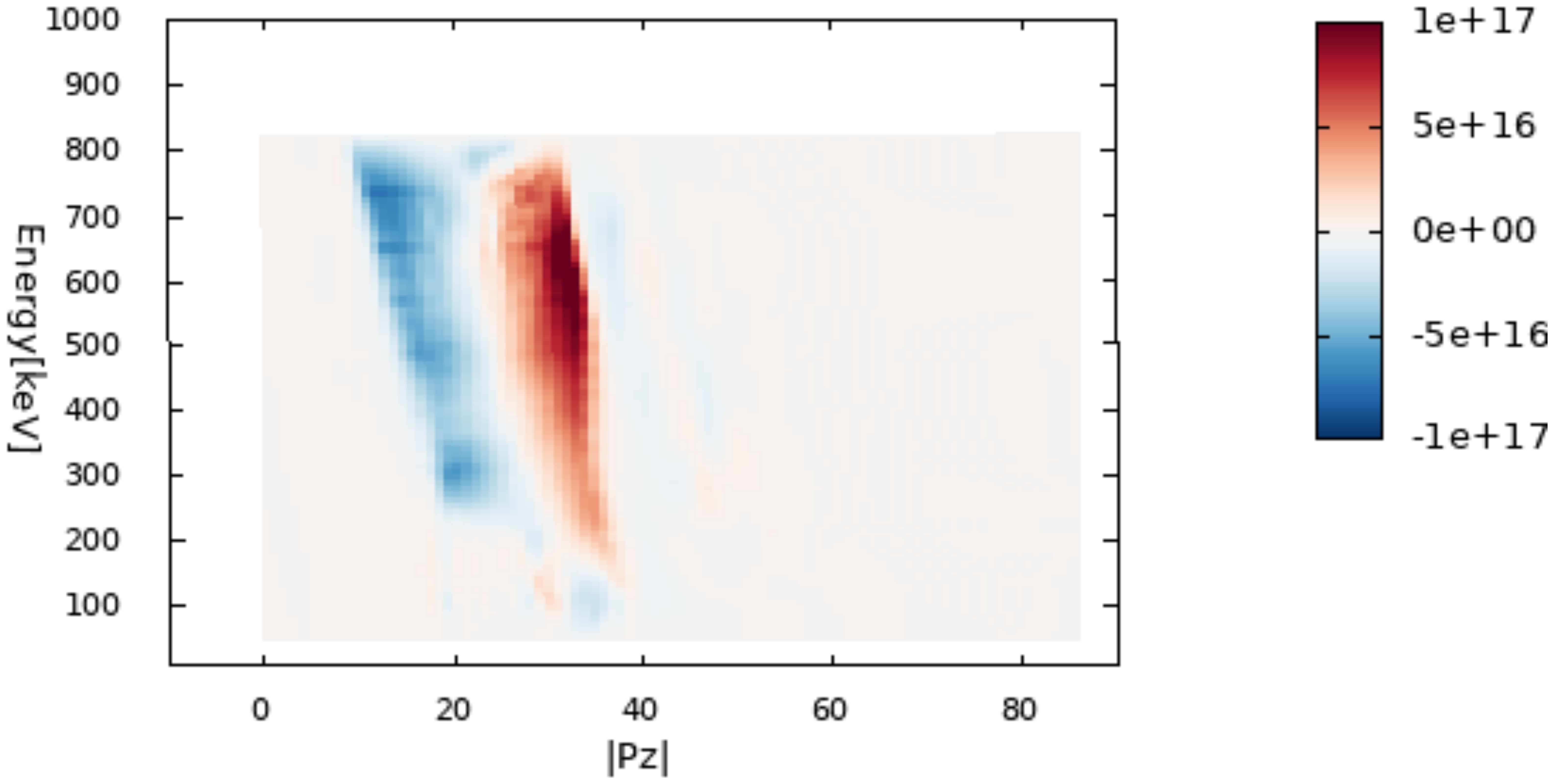


F (Pz,E,t), Time=199 [arb units]

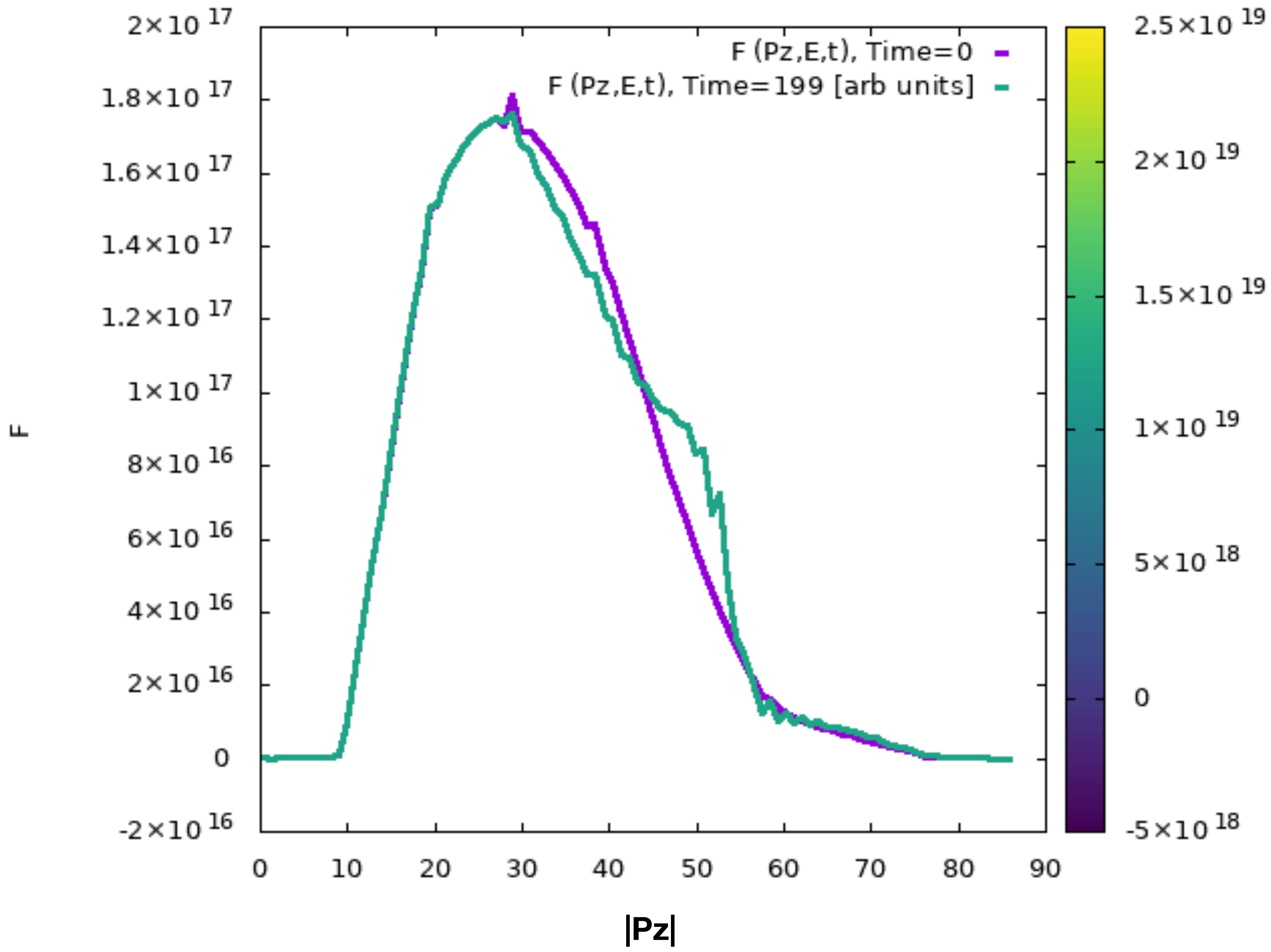


ATEP code: advance transport equation

F(t) - F(t=0), Time=147 [arb units] (integrated over Λ):



ATEP code: advance transport equation: 1d projection



using ITER NBI off-off configuration, on-on, on-off also done
should be straightforward to extend to JT-60SA

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outlook 2022/23

- obtain the plasma scenarios from JETTO/ETS (preferably in IDSs)/extend scenario database
- work on consistently filled IDSs (core_profiles, equilibrium, distributions)
- adopt ASCOT F_EP via IMAS, obtain/calculate (collaboration with ETS / JINTRAC teams) the NBI energetic particle deposition profiles and distributions, use separately P-NBI and N-NBI
- estimate drive/damping contribution from NBI ions using CASTOR-K hybrid MHD drift kinetic code. Estimate also thermal ion damping
- time-dependent runs: find ‘least damped’ time slices, attempt non-linear GK runs
- start to apply transport models for various beam geometries
- <u>further needs:</u>
- set of standardised tools to process noisy FEP [ITPA, Bierwage et al 2021] - solution available (part of ATEP code), to be tested on wide number of cases
- IDA-type analysis tools for JT-60SA very valuable: error analysis and UQ urgently needed for predictive studies