Energetic Particle dynamics induced by off-axis neutral beam injection on ASDEX Upgrade, JT-60SA and ITER

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motivation

- JT-60SA has exclusive off-axis NNBI capabilities
- recent AUG experiments with exclusive off-axis PNBI allowed us to access regime of previously unexplored EP (energetic particle) physics
- ITER NNBI beams can be moved separately from on-axis to off-axis deposition - but only ~ 100 times in the lifetime of ITER
  reliable modelling is required to understand & predict consequences of EP-driven instabilities on heating and current profile (pre-fusion, fusion)

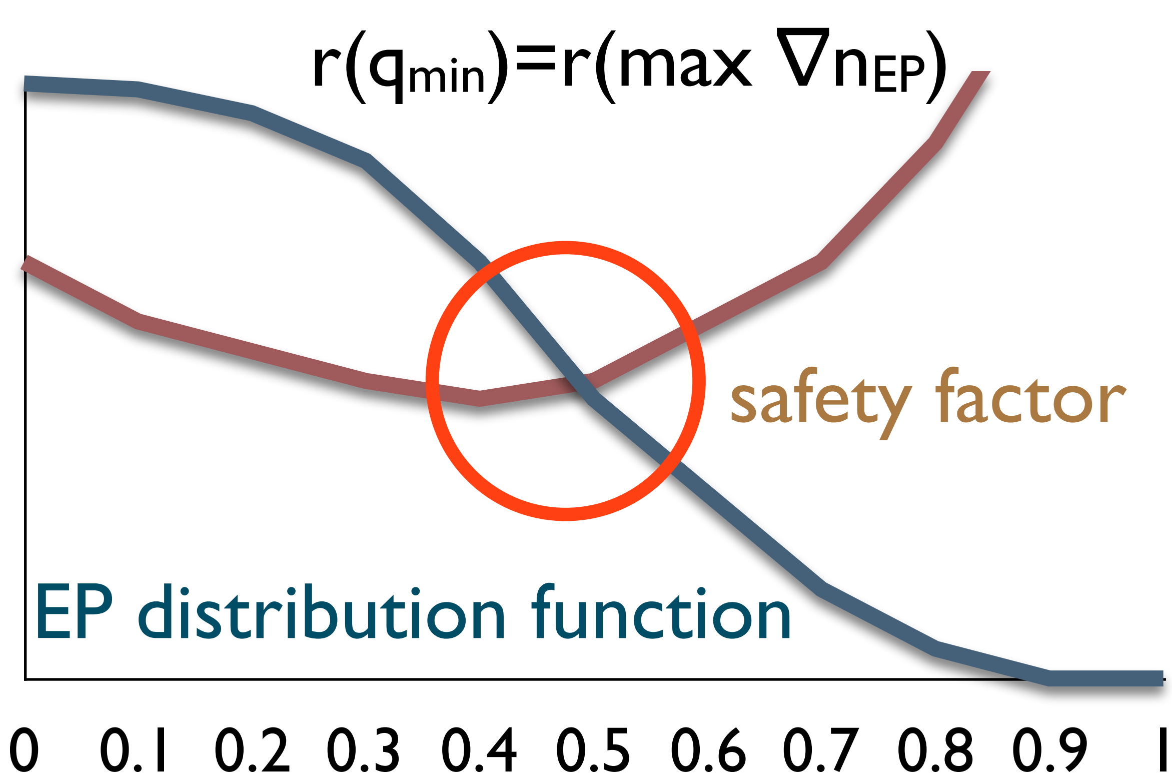
★ explore conventional and advanced regimes with off-axis NB current drive in step-ladder approach with the same framework/tools

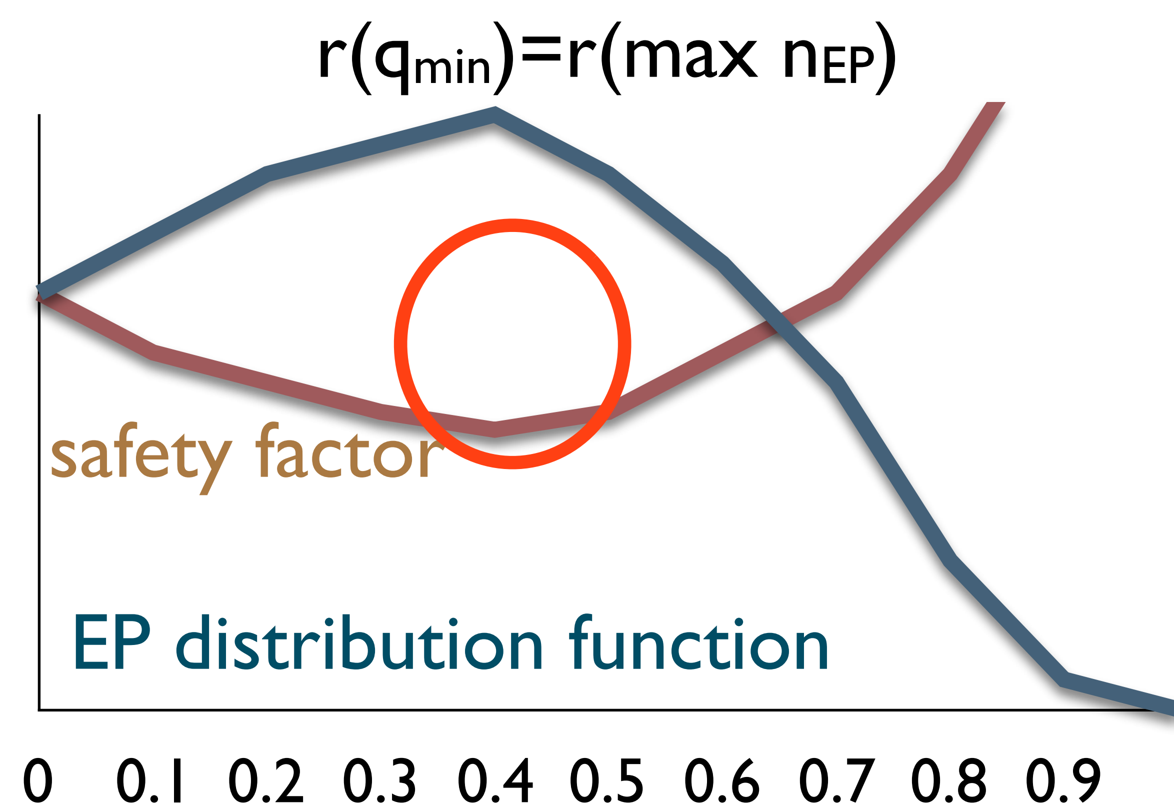
★ use AUG results as unique validation opportunity

IPP

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,…)



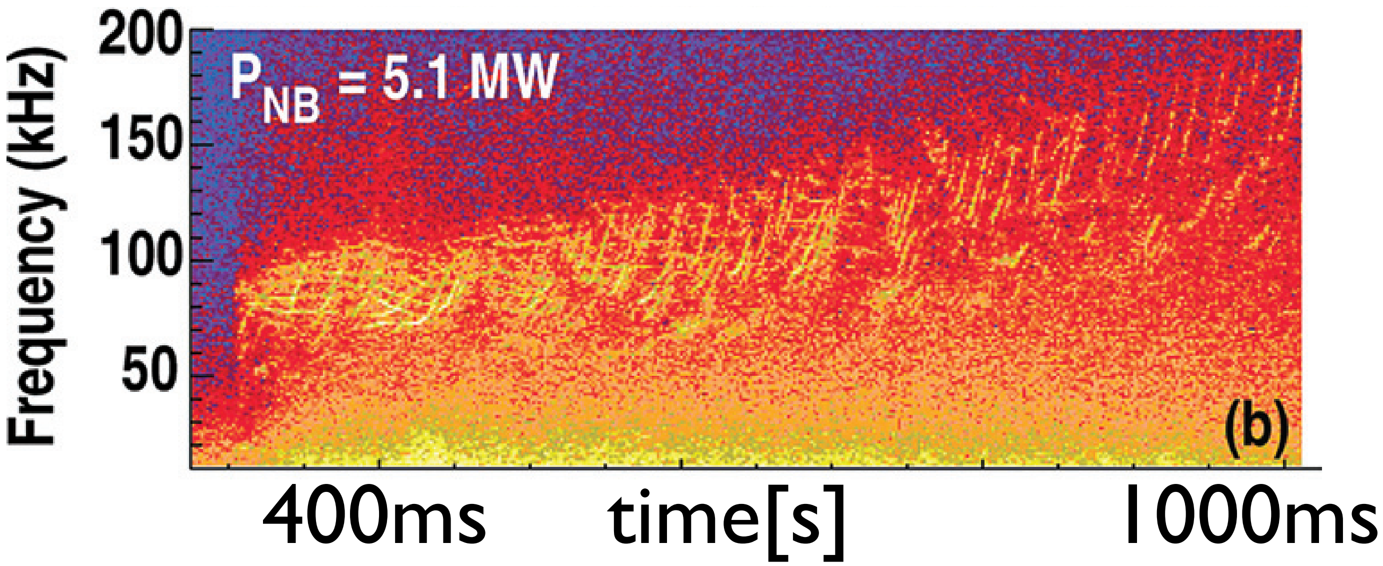


left: typical ramp-up profiles as traditionally used to study NBI EP transport in DIII-D/AUG
right: off-axis NBI scenarios relevant when current profile modifications or advanced/hybrid scenarios are under investigation

two (positive and negative) EP gradients arise - effect of EP driven modes on beam deposition and thus background heating (self organisation)?

previously: ramp-up phases in various experiments: near marginal vs bursting EP dynamics

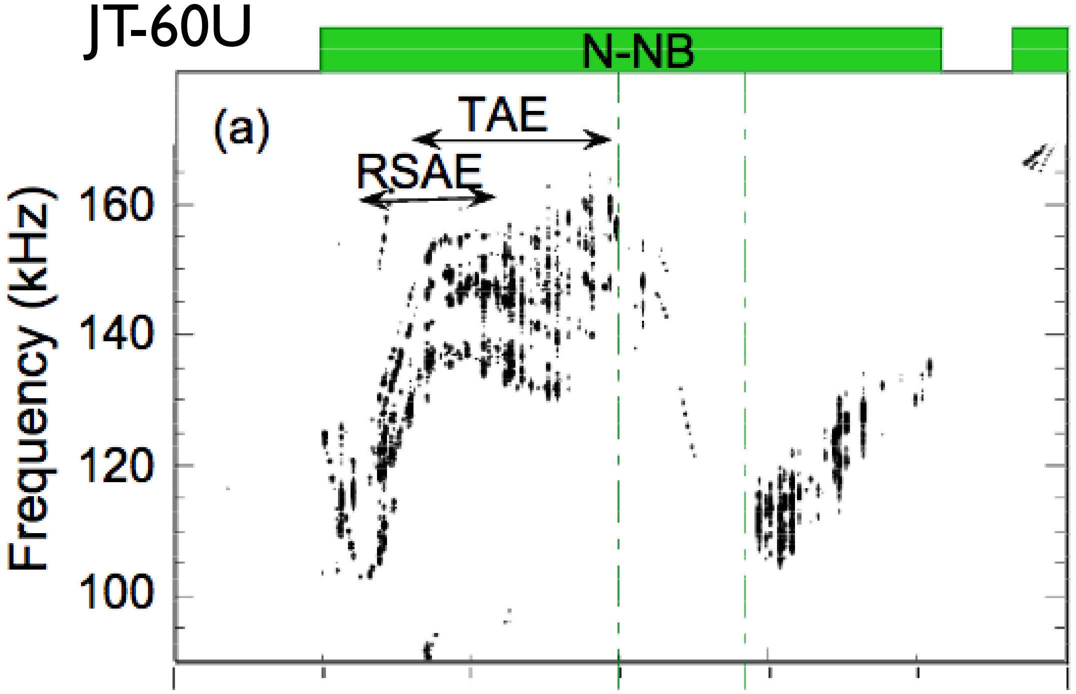
DIII-D(#142111):
[VanZeeland et al Phys. Plasmas 18, 056114 (2011)]



crucial parameters:

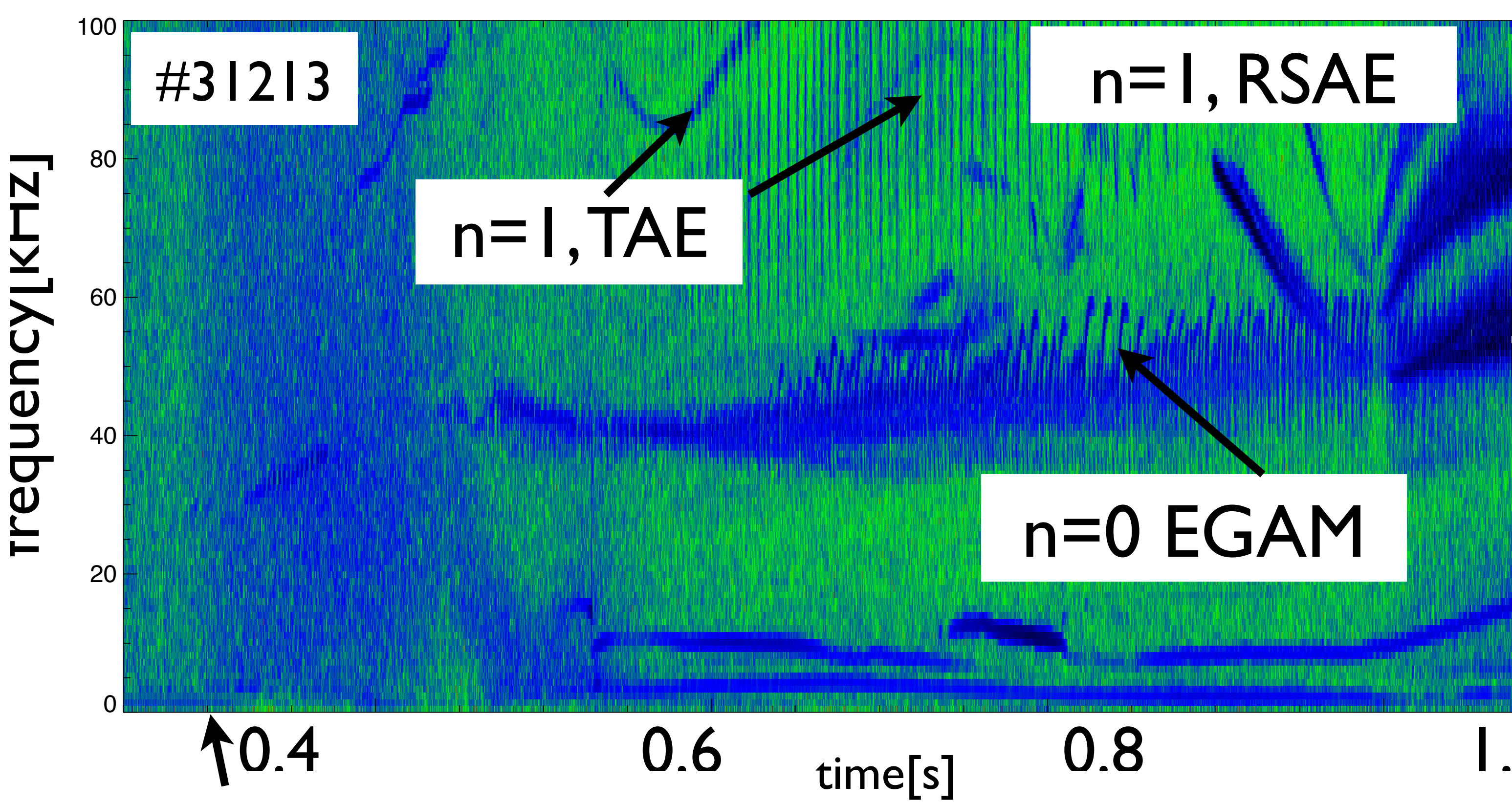
JT-60U/SA: v_f/v_{A0}~1.3 ; NB: 350/500keV
DIII-D: v_f/v_{A0}~0.4 ; NB: 80keV
AUG: v_f/v_{A0}~0.45; NB: 93keV

JT-60U



[Shinohara, 2001-2004; Takenaga, IAEA 2006]

AUG (Lauber 2014)

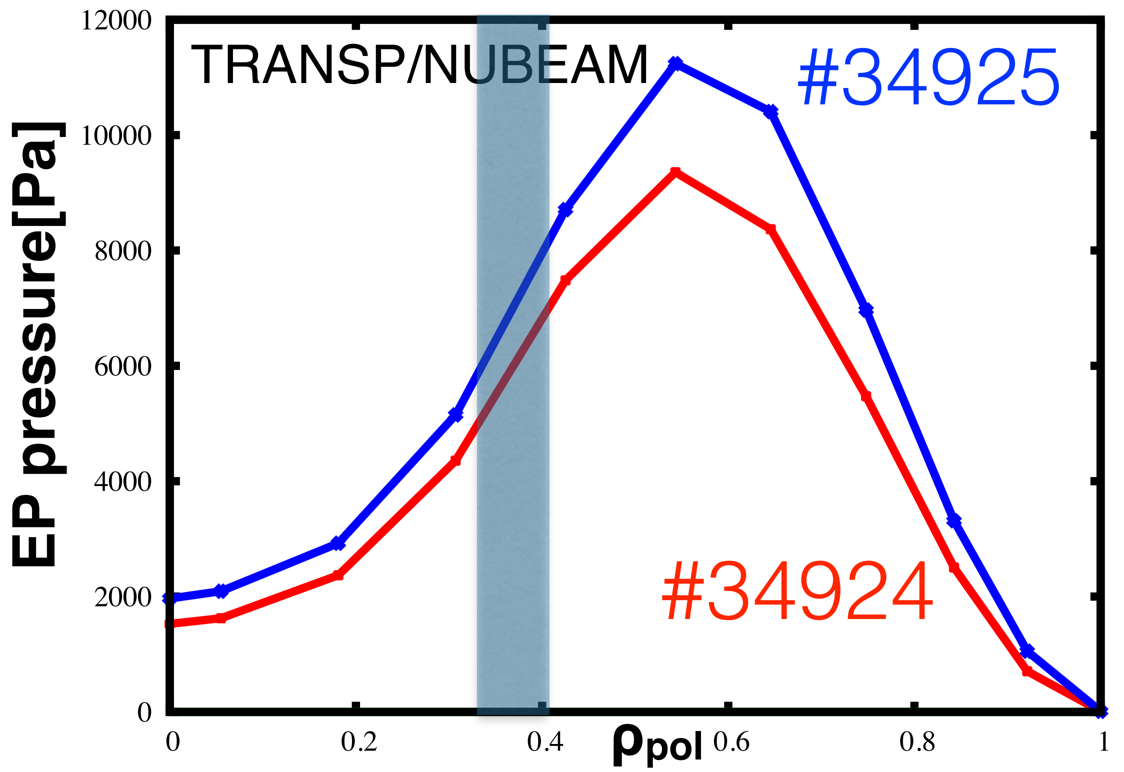


typical parameter space for important EP quantities (not representative for all scenarios)

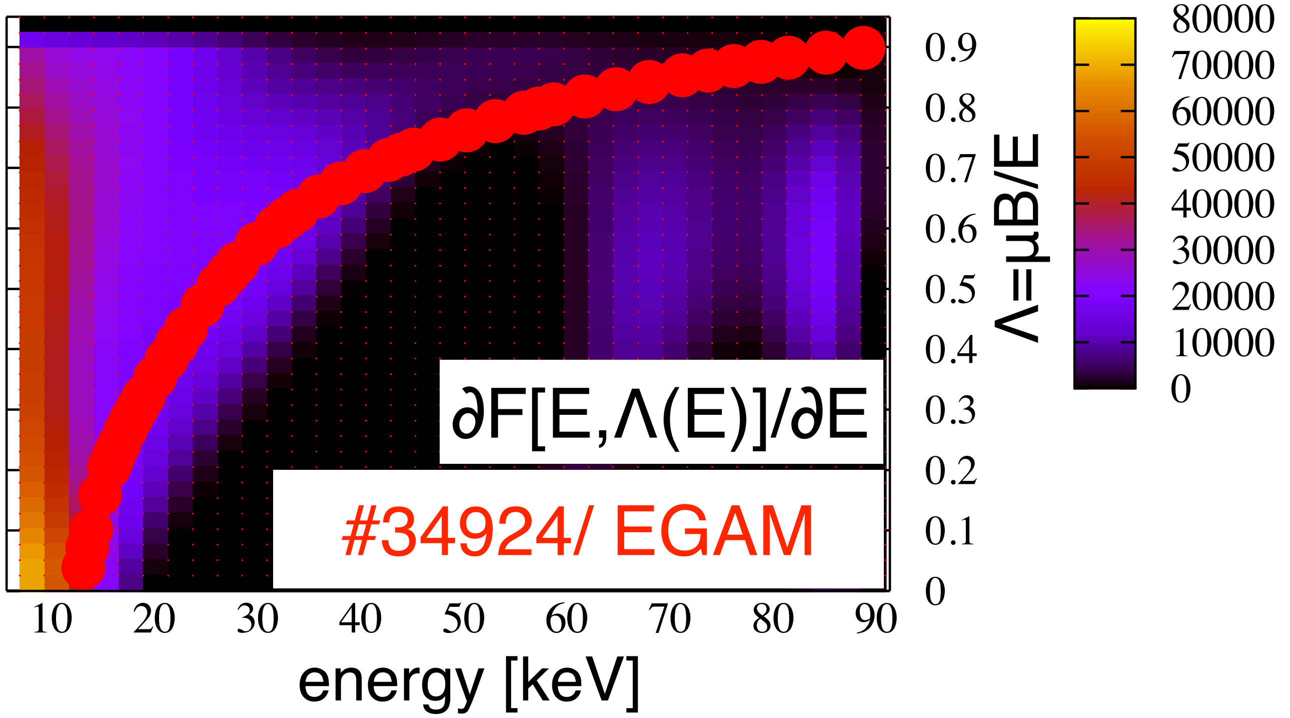
	v_{NBI}/v_{A0}	v_{NBI}/v_{th}	local β_{NBI}/β_{th}
ITER (beam)	>1 (pre-fusion)	40 (100 pre-fusion)	<0.5
ITER (α)	>1	~140	0.2-0.3
JT-60U/SA	1.3	<100	<1
DIII-D (NBI)	0.4	<30	<0.5
AUG (NBI)	0.45	<120	<1

1. AUG

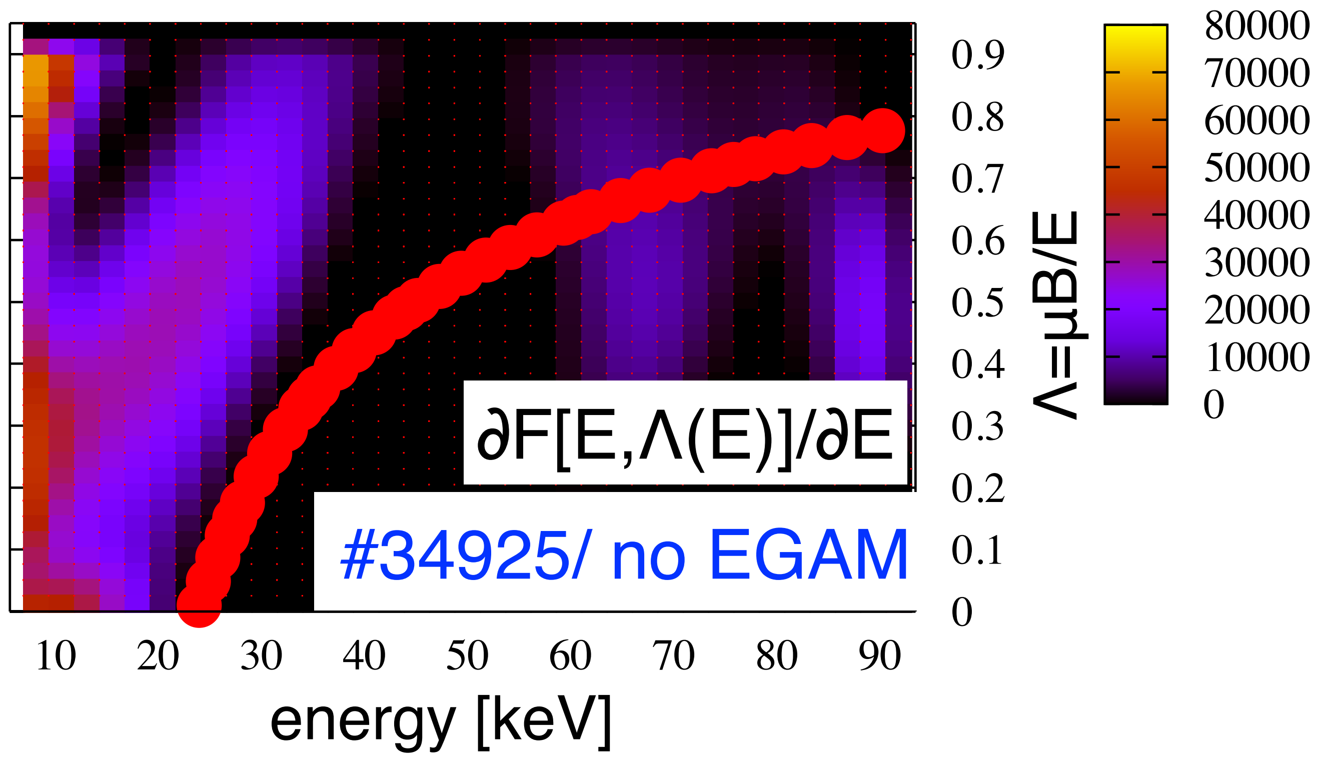
AUG experiments emphasise importance of accurate modelling of phase space gradients (∂F/∂E, ∂F/∂Λ) in off-axis NBI



resonance with local f_{GAM}



resonance with local f_{GAM}



∂F[E,Λ(E)]/∂E< 0 is coloured as black with value 0

- 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
- under investigation for SA: under which conditions do EGAM/BAE resonances and steep ∂F/∂E NBI regions overlap? for elevated q~2 and moderate Ti it should be possible (working on F_{EP} representation… see below)

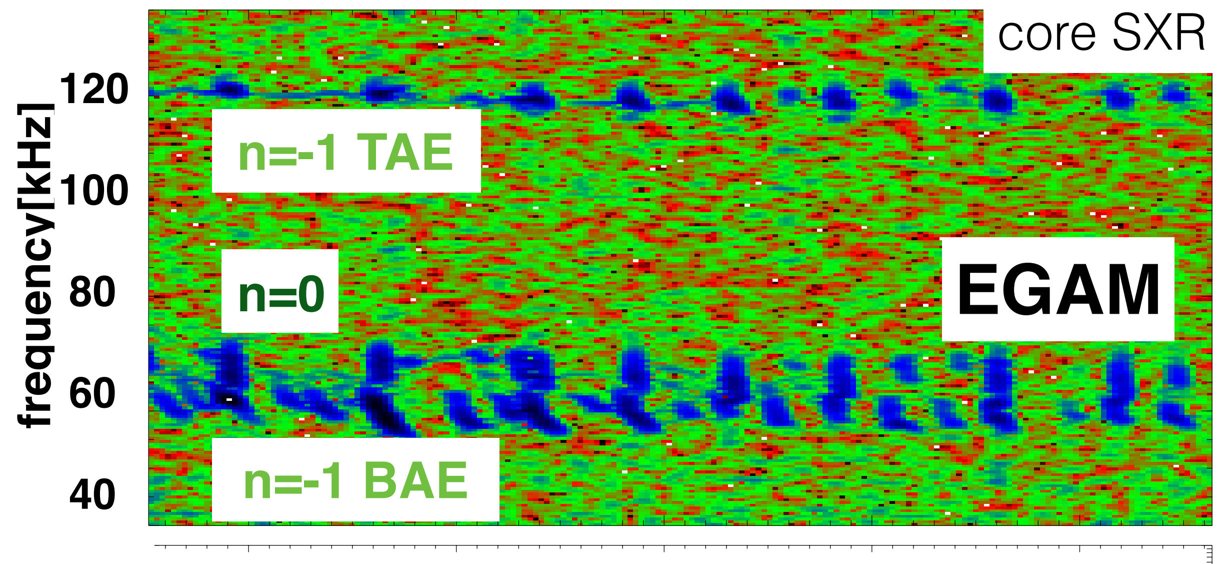
AUG: local and global LIGKA analysis

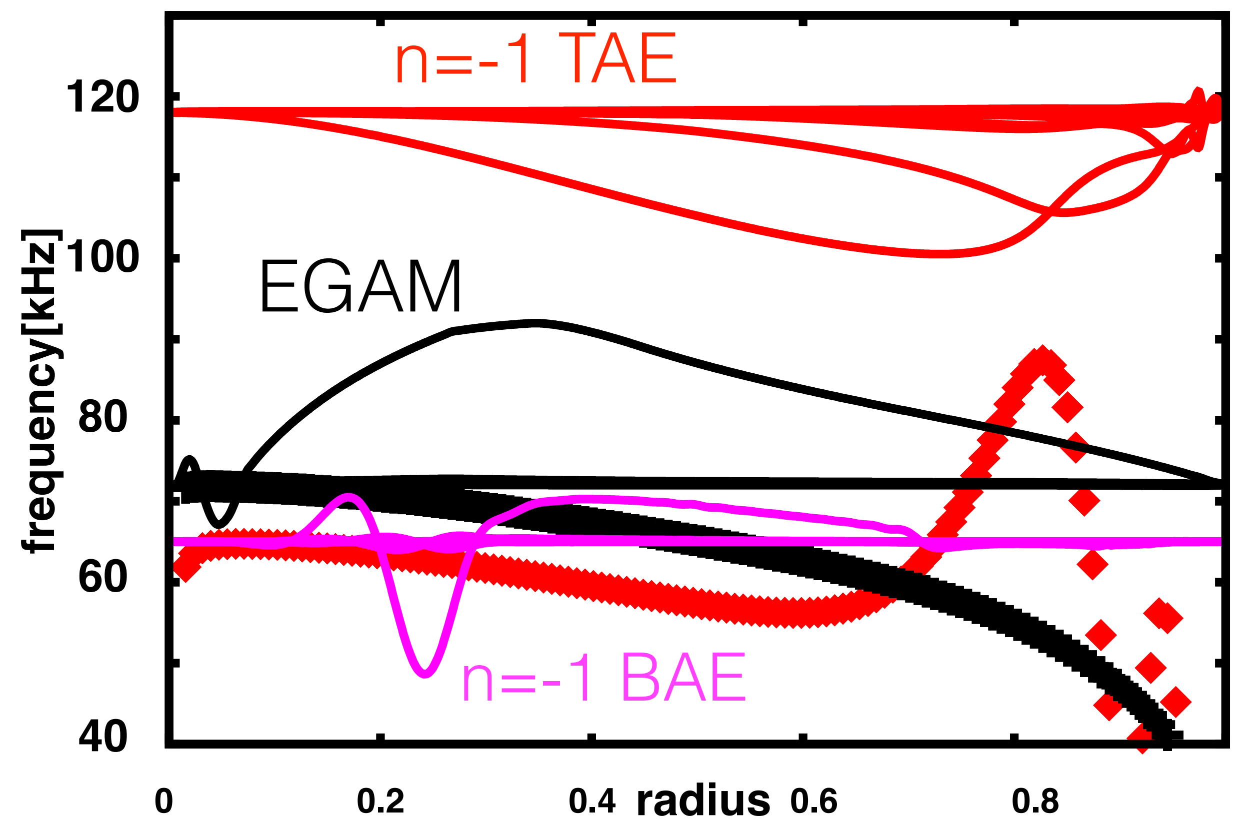
resonance analysis shows that:

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

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

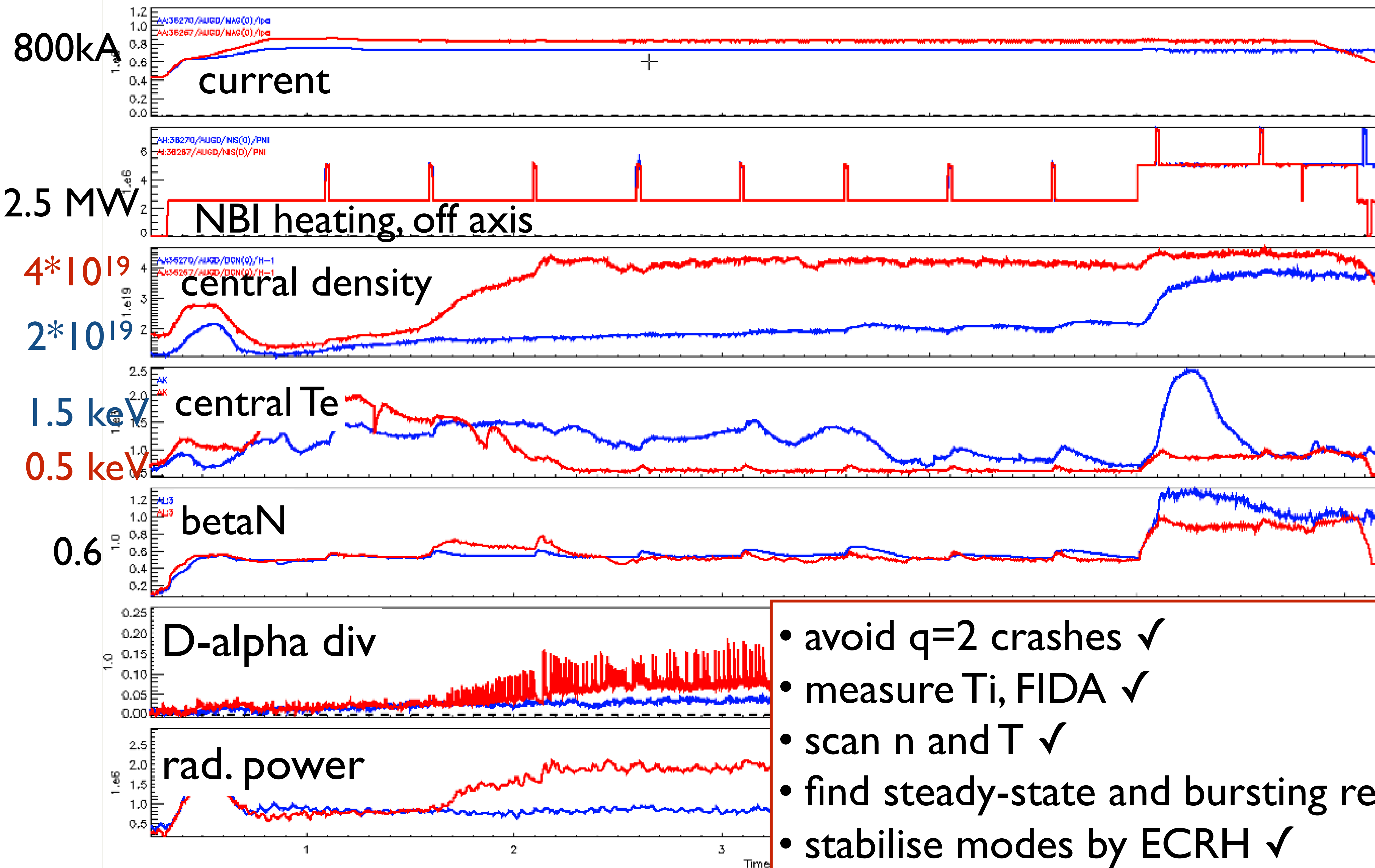
- BAE redistributes mainly in radial direction and thus triggers the EGAM (increased EP density) and TAE (higher order resonances)





Benchmark of HYMAGIC/MEGA/ORB5 ongoing [IAEA FEC 2020 G.Vlad, X Wang, F. Vannini]

new EP-AUG experiments [May 2019]: EP transport and EGAMs in H and L-mode

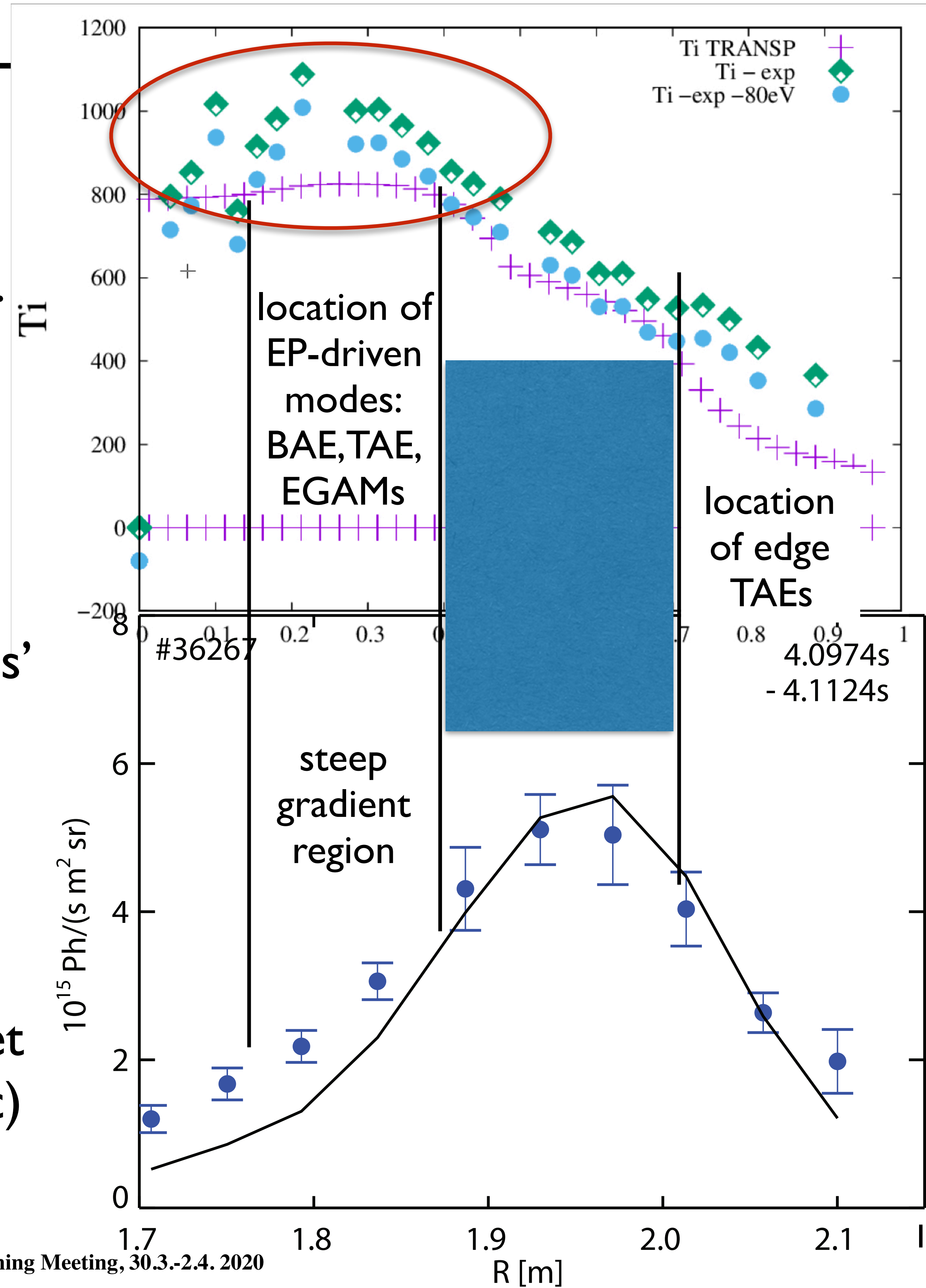


- avoid q=2 crashes ✓
- measure Ti, FIDA ✓
- scan n and T ✓
- find steady-state and bursting regimes
- stabilise modes by ECRH ✓

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

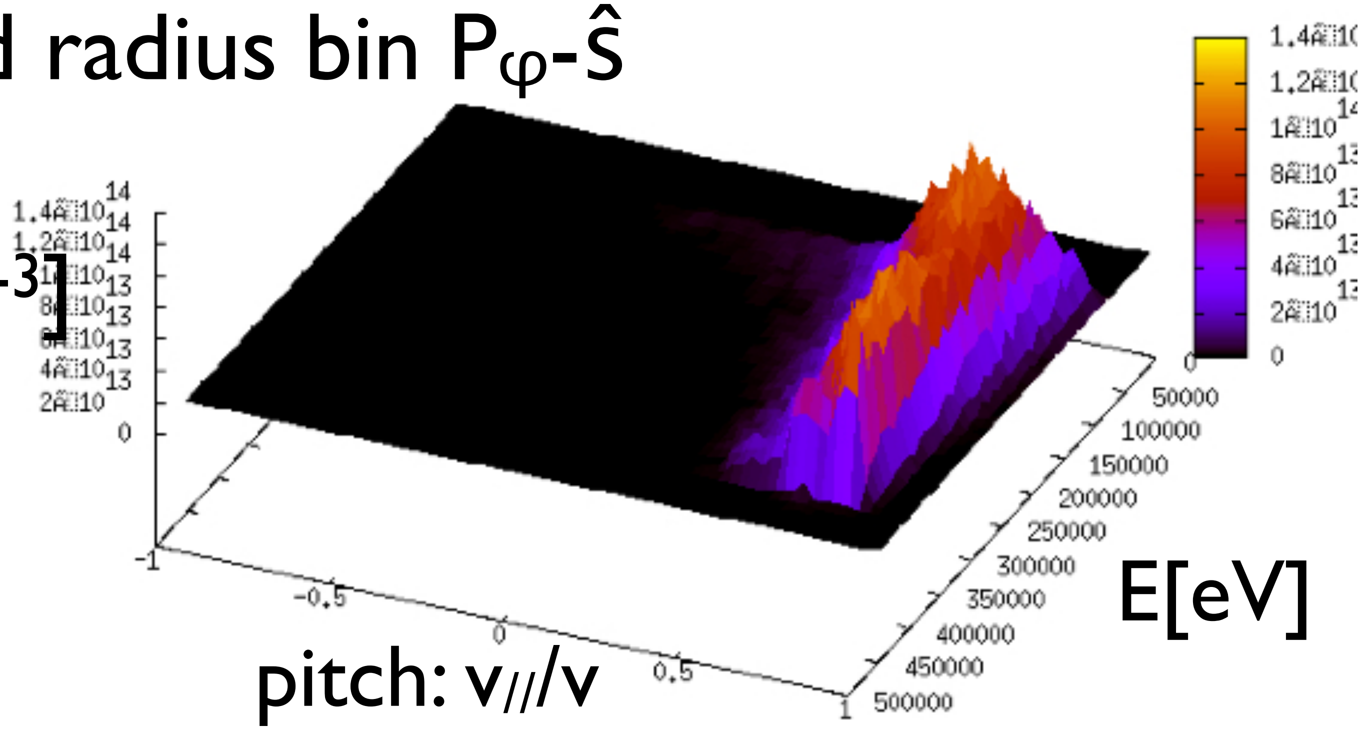


2. JT-60U/SA

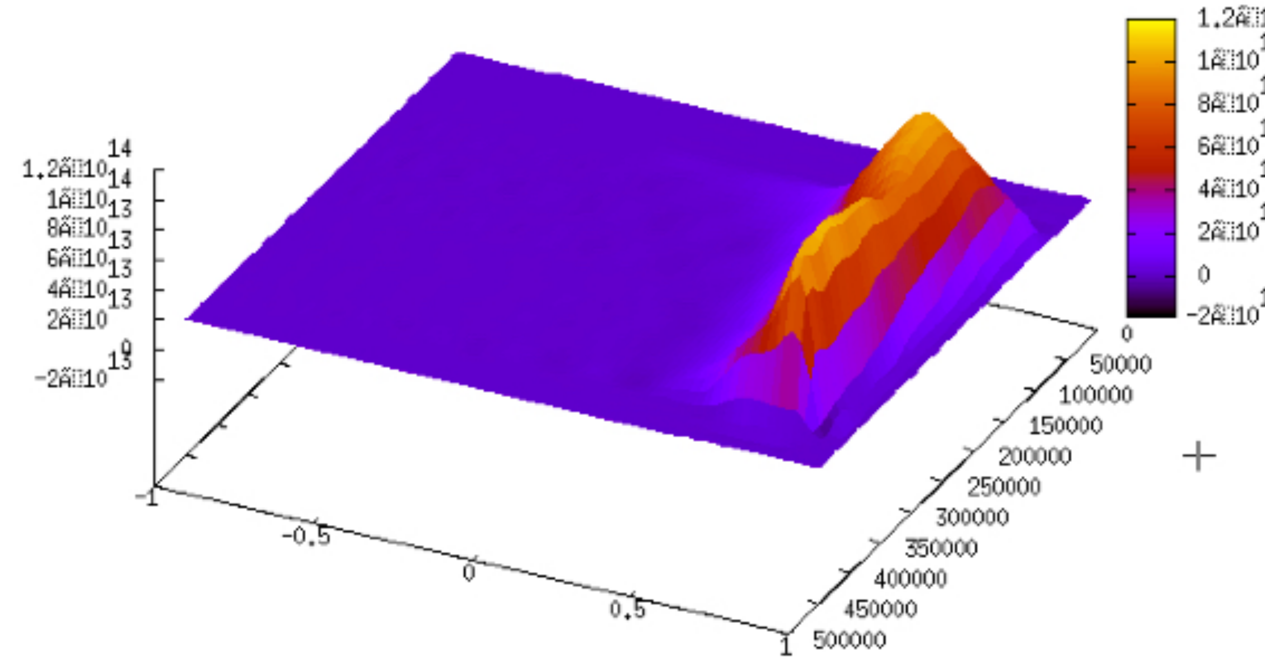
new interface LIGKA-PIC code output established [in collaboration with A. Bierwage]

processing MEGA particle data (~7M particles) ~30s

mid radius bin P_{φ}-$\hat{s}$



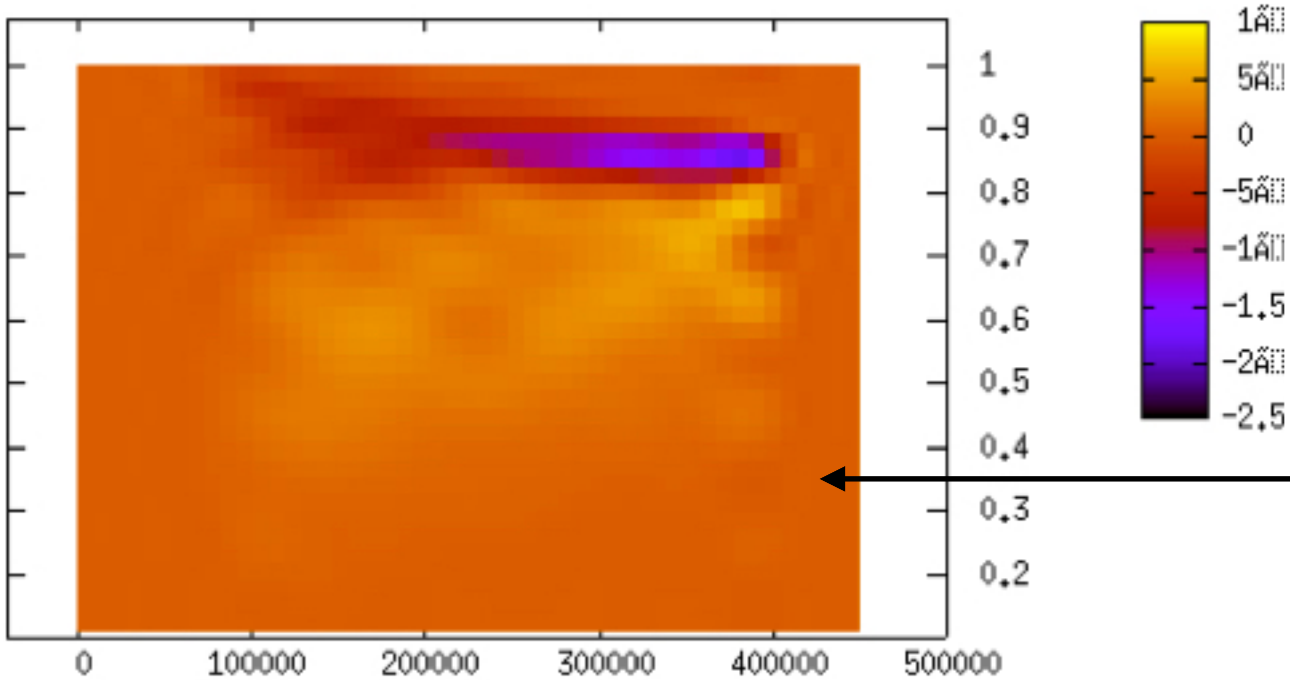
2d Chebychev polynomial fitting +smoothing



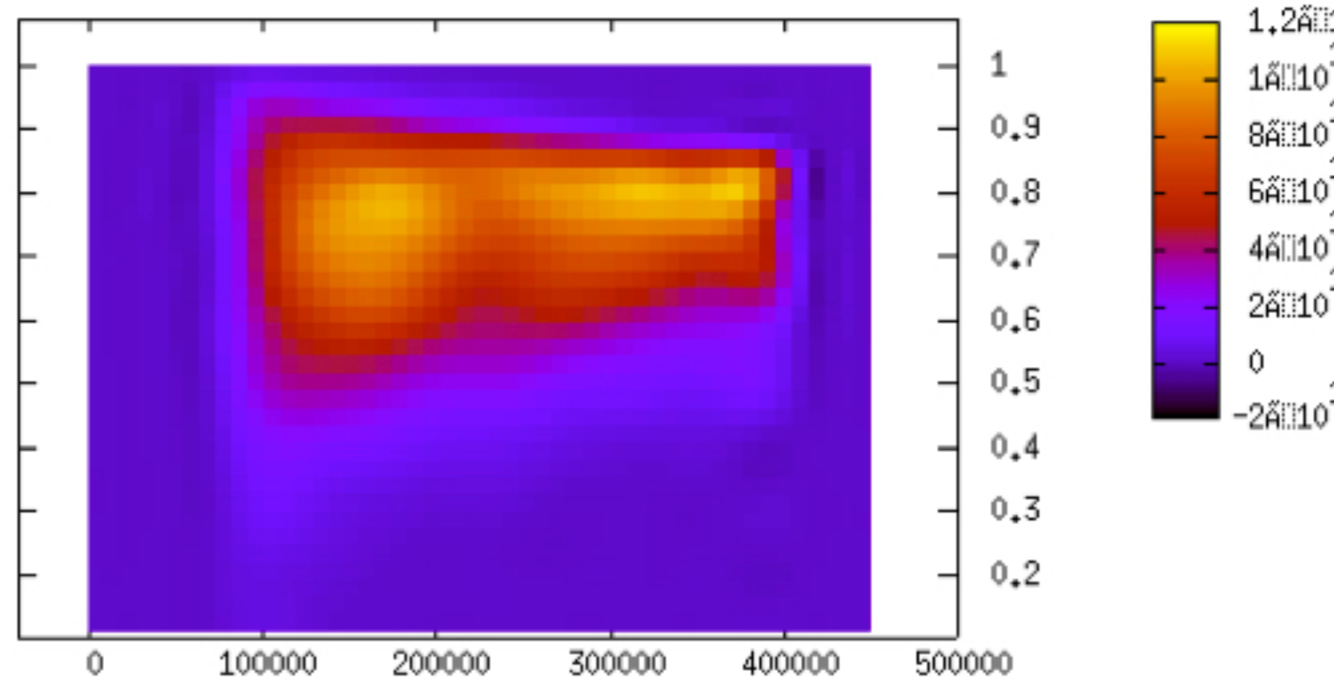
- then normalise splined data to total local density

taking derivatives in now possible:

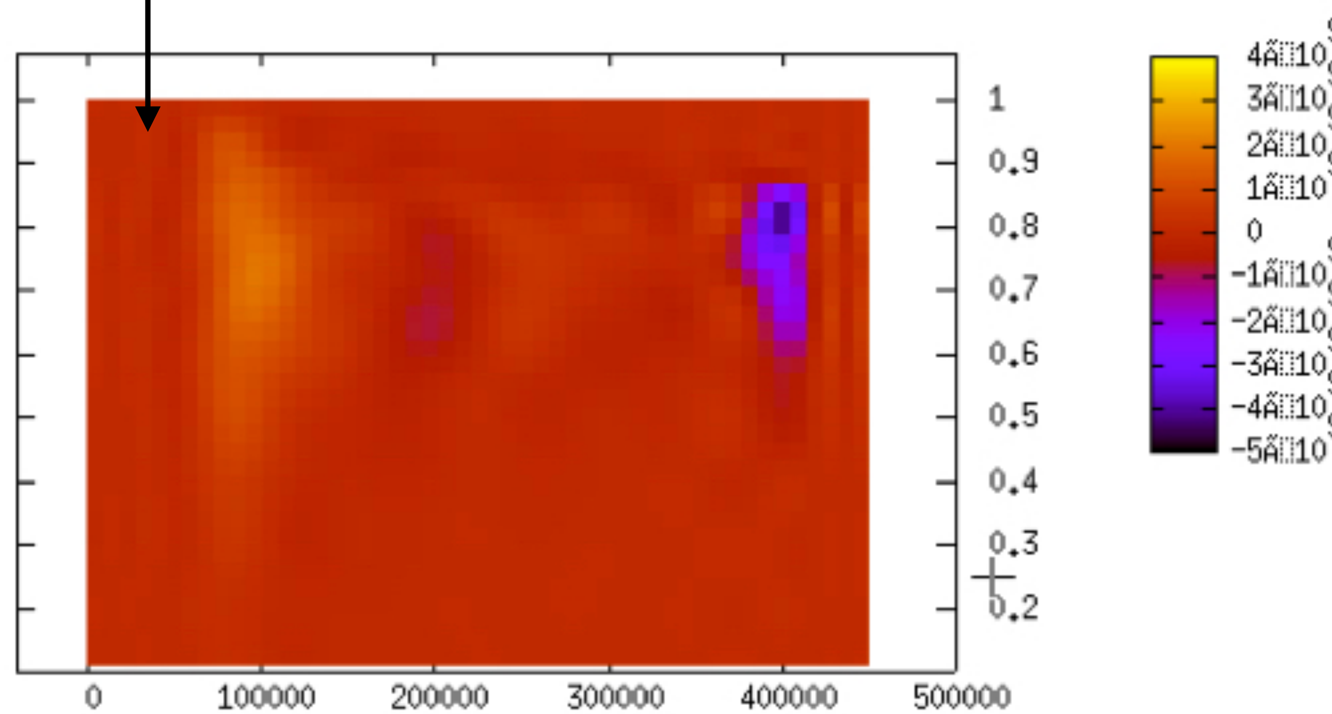
dF/dλ



F_smooth

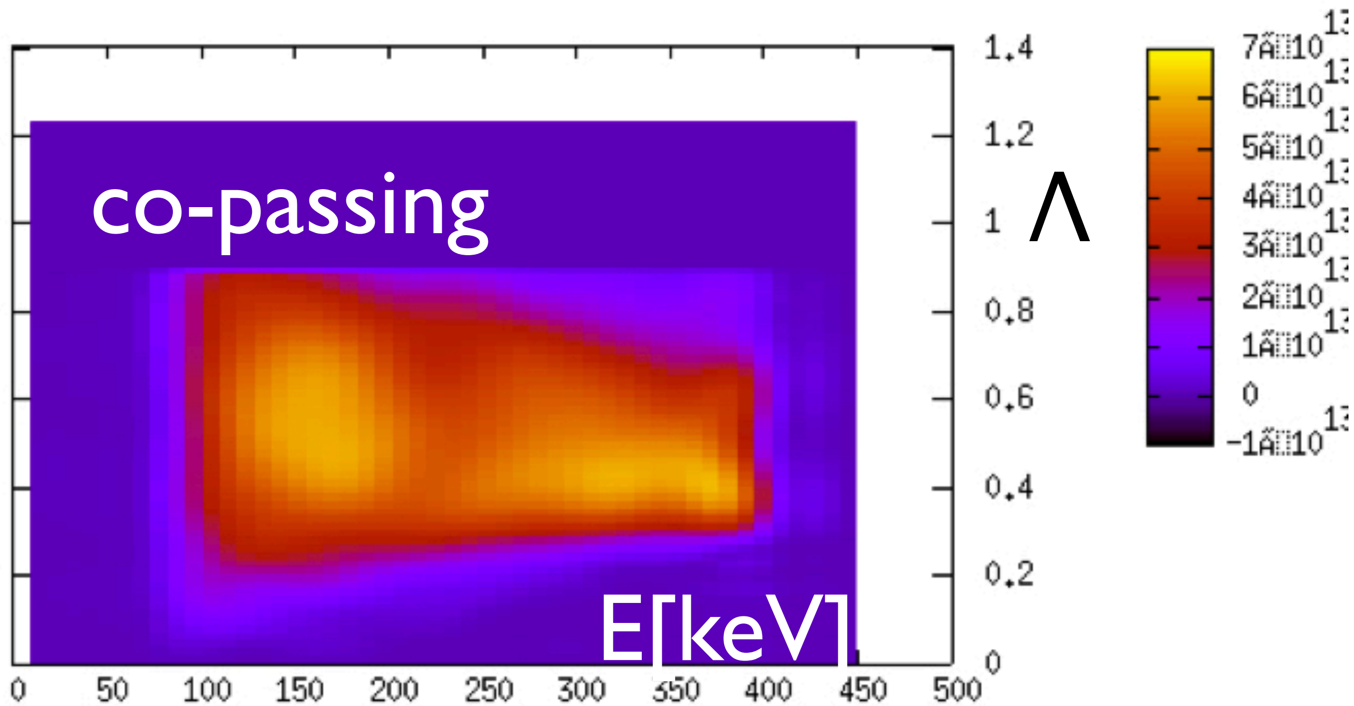


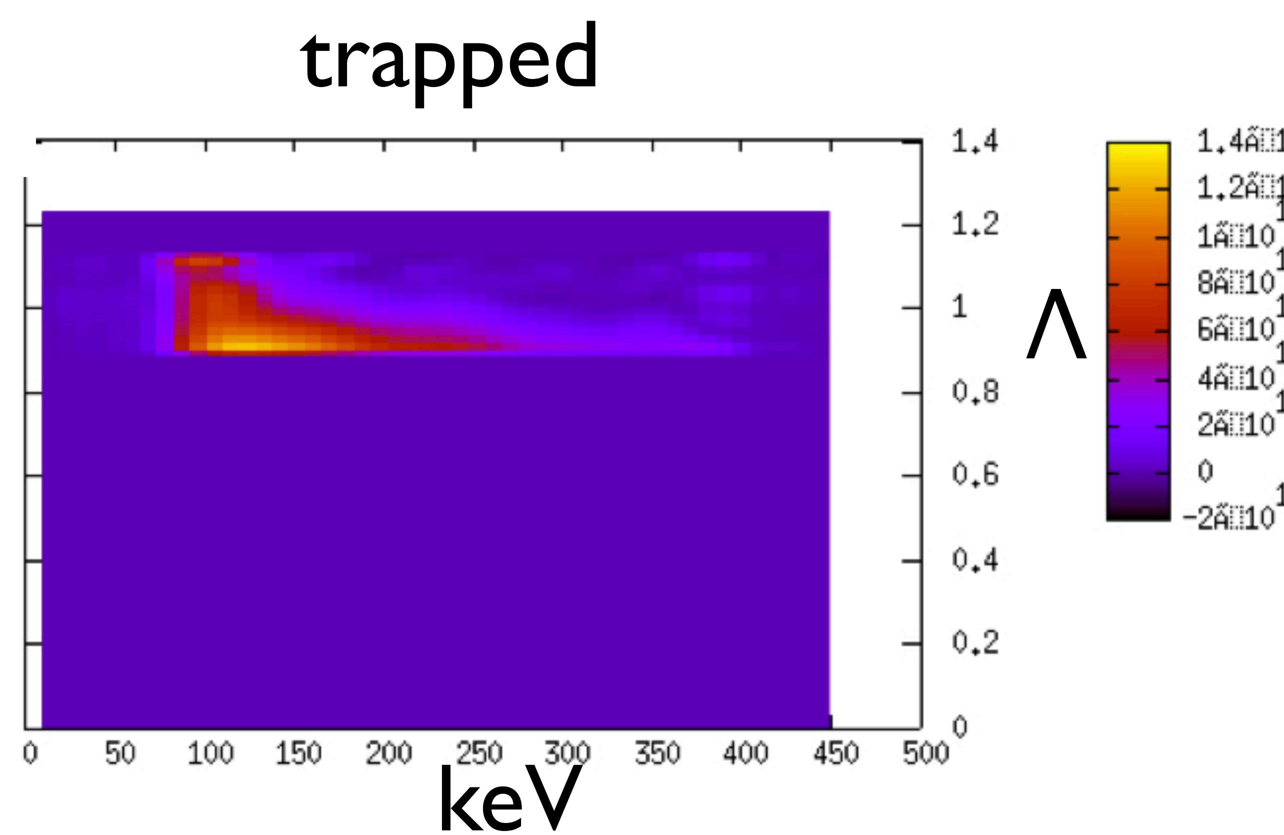
dF/dE



successful test on JT-60U case [Bierwage, Nature Comm, 2018, ALE Bierwage&Lauber, 2018]

map to E-Λ-space:

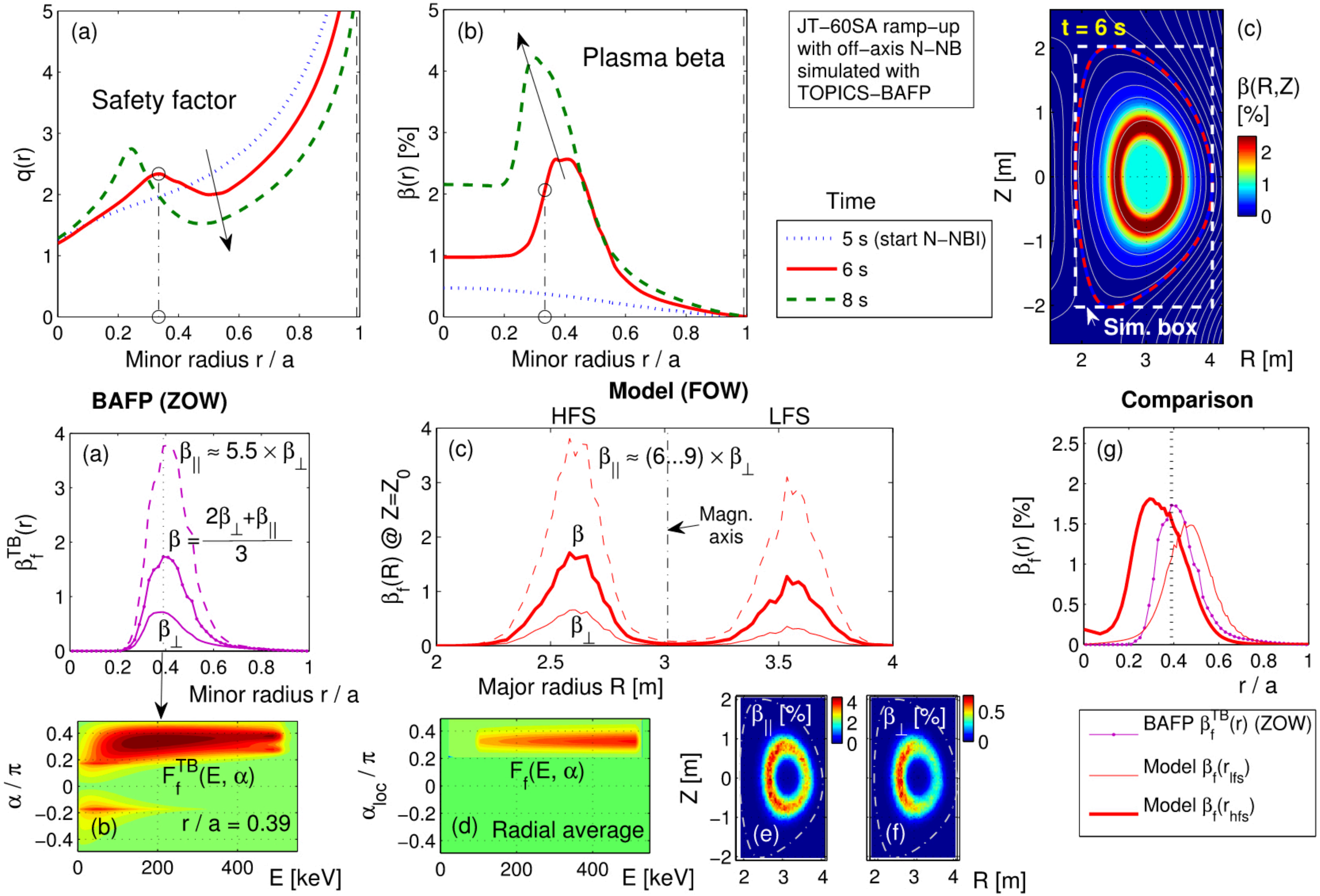




- divide in co/cp/trapped particle and normalise separately again

next: compare LIGKA results on MEGA results (data in DMS since last week)

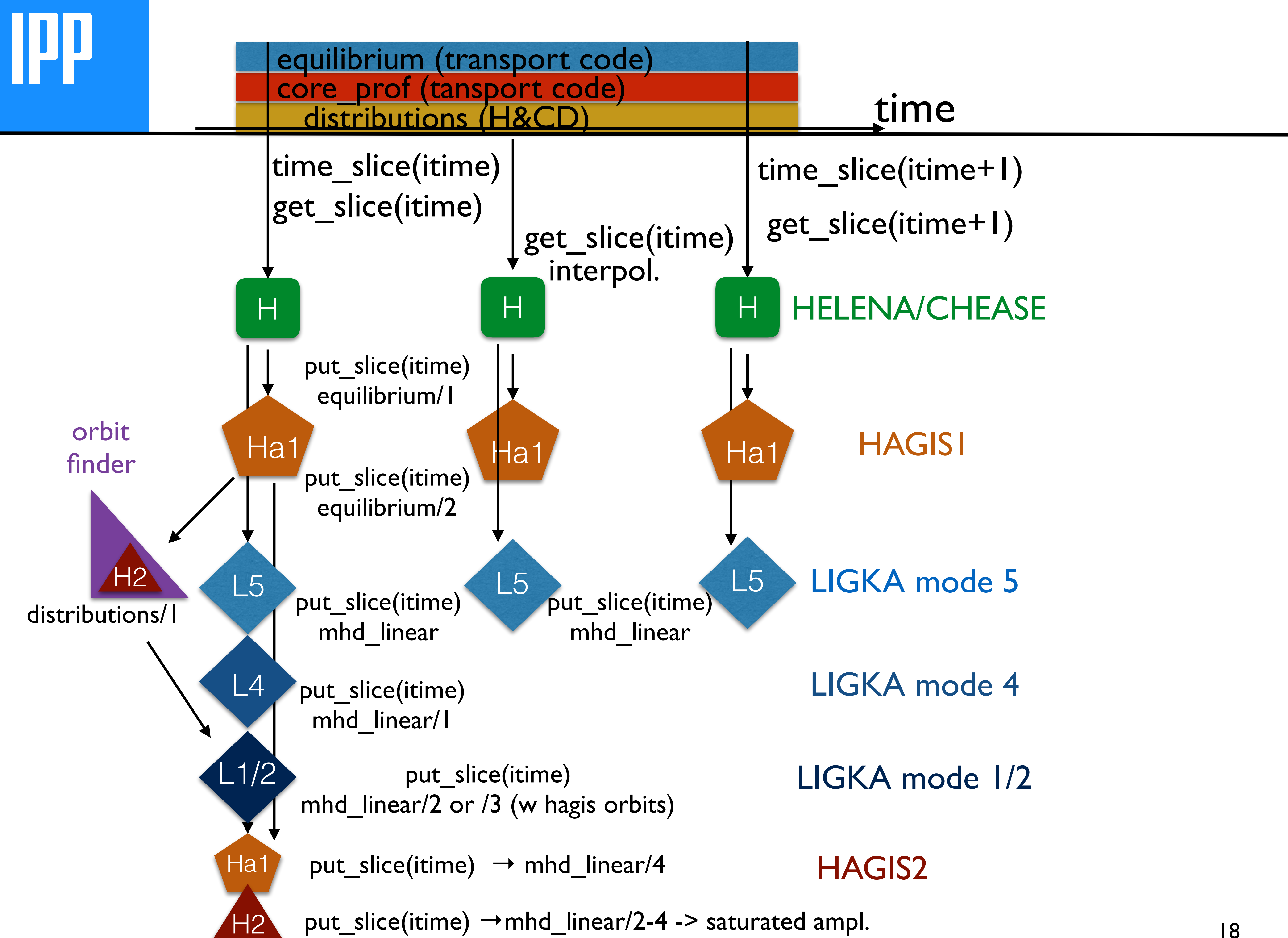
MHD and resonant instabilities in JT-60SA during current ramp-up with off-axis N-NB injection [Bierwage, PPCF 2017,2019]



3. ITER

ITER pre-fusion plasmas

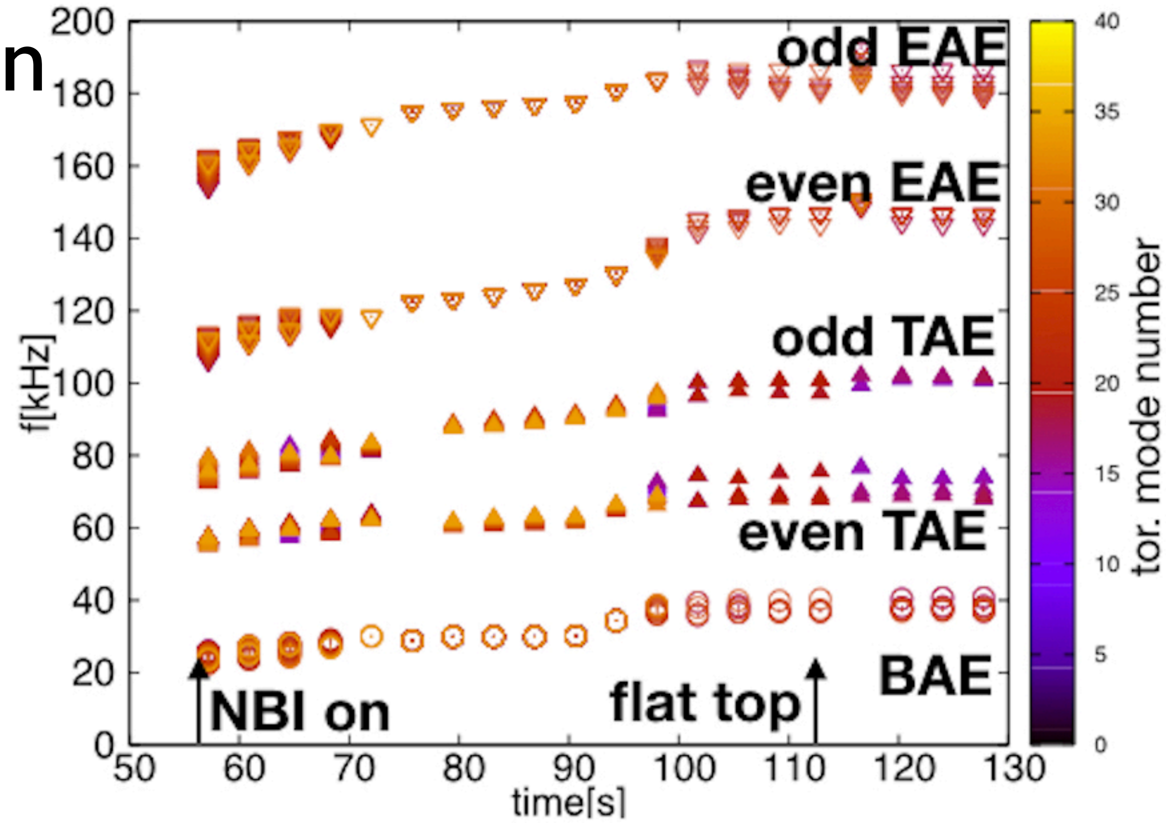
- overview studies for most relevant scenarios (SA, ITER) started with LIGKA-IMAS (python workflows)
- time-dependent workflows: HELENA (CHEASE) -LIGKA (local/global)
- studies based on METIS runs performed by M. Schneider
- NEMO/SPOT-IMAS data available for this pre-fusion case [M. Schneider]- particle IDS has the same structure as MEGA output; straightforward adoption of already developed routine for MEGA

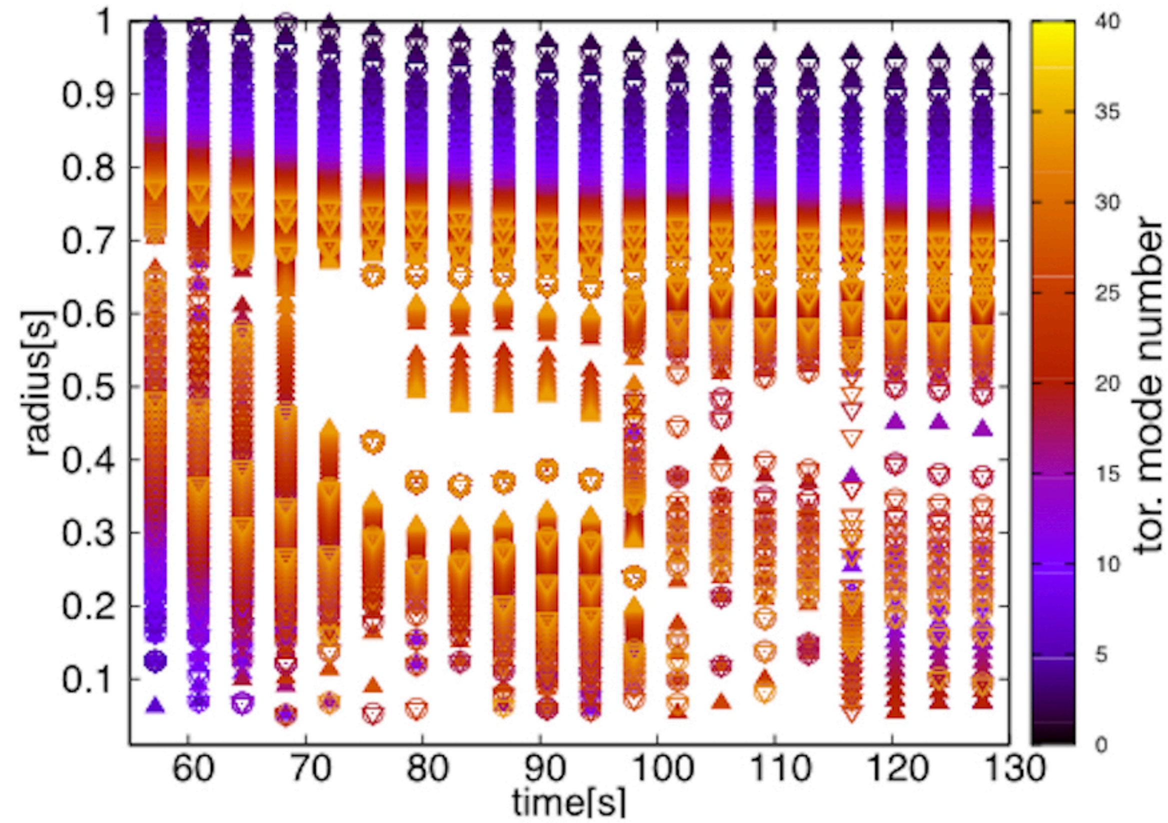


equilibrium (transport code)
core_prof (tansport code)
distributions (H&CD)
time
time_slice(itime)
get_slice(itime)
get_slice(itime)
interpol.
time_slice(itime+1)
get_slice(itime+1)
H
H
H
HELENA/CHEASE
put_slice(itime)
equilibrium/1
Ha1
Ha1
Ha1
HAGIS1
orbit
finder
put_slice(itime)
equilibrium/2
H2
distributions/1
L5
L5
L5
put_slice(itime)
mhd_linear
put_slice(itime)
mhd_linear
LIGKA mode 5
L4
put_slice(itime)
mhd_linear/1
LIGKA mode 4
L1/2
put_slice(itime)
mhd_linear/2 or /3 (w hagis orbits)
LIGKA mode 1/2
Ha1
put_slice(itime) → mhd_linear/4
HAGIS2
H2
put_slice(itime) →mhd_linear/2-4 -> saturated ampl.

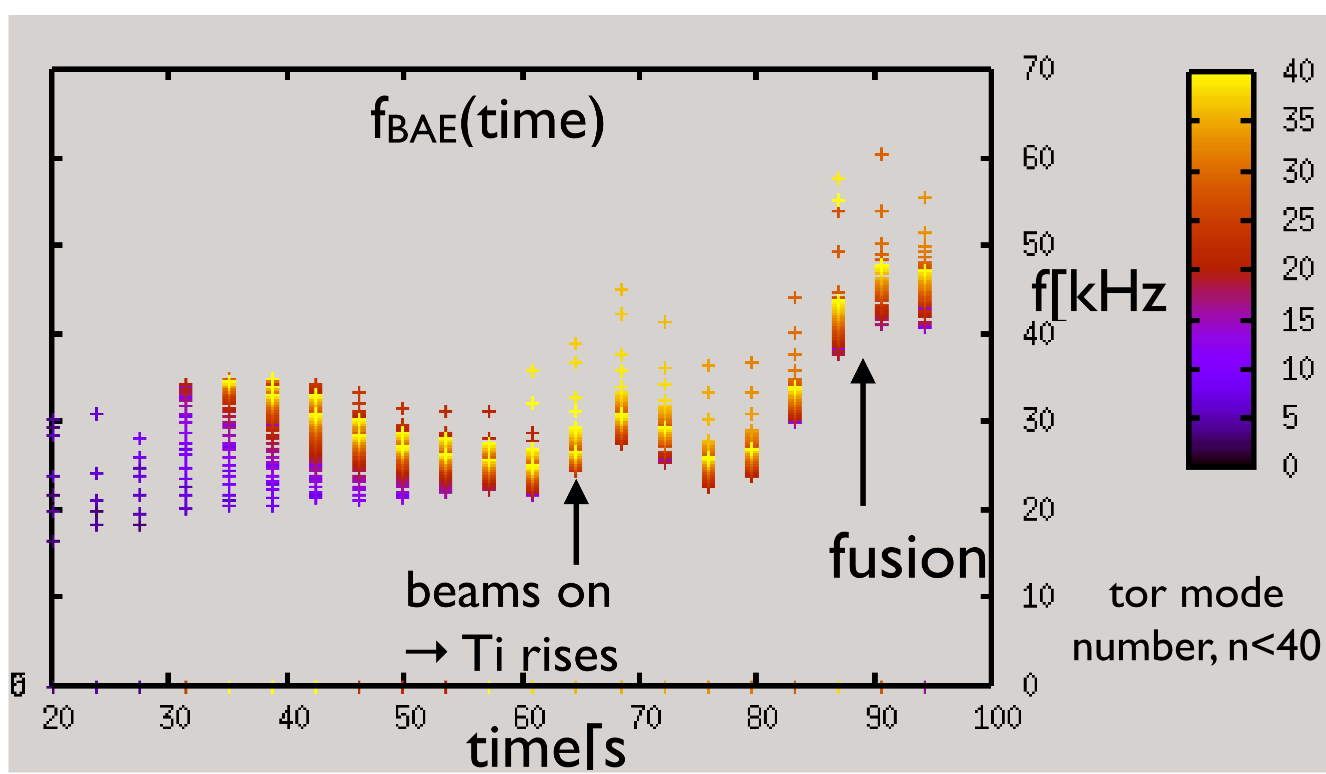
some results:

pre-fusion





ramp-up of 15MA scenario



outlook:

- try IMAS workflows on JT-60SA data (gateway - LIGKA libs to be installed)
- test workflows with MEGA/NEMO-SPOT distributions functions in LIGKA
- possible development of MEGA-netcdf interface to IMAS
- compare distribution to ASCOT, compare with ASPACK (IST)
- try other scenarios
- test various high-res equilibrium codes based on low-res transport codes
- strong push to do all this in IMAS

expected physics results:
understand & predict linear mode onset for global AEs/EGAMs
understand & predict their mutual non-linear interaction
understand & predict non-linear behaviour (chirping/bursting)
understand & predict non-linear EP transport & test transport models
understand & predict self-organisation