



Update EP-WF and ATEP status Validation, VNS

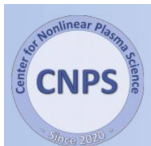
Philipp Lauber

thanks: **Matteo Falessi, Thomas Hayward-Schneider, Guo Meng, V.-Alin Popa, Tristan Sterkl, Leon Eppinger, Fulvio Zonca, Ch. Schmitz (TU Wien)**

acknowledgements to PSD DEMO central team, ASDEX Upgrade team



MAX-PLANCK-INSTITUT
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TECHNISCHE
UNIVERSITÄT
WIEN



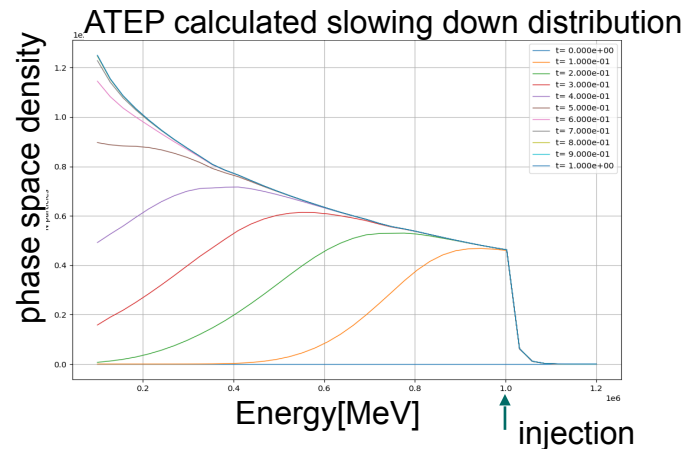
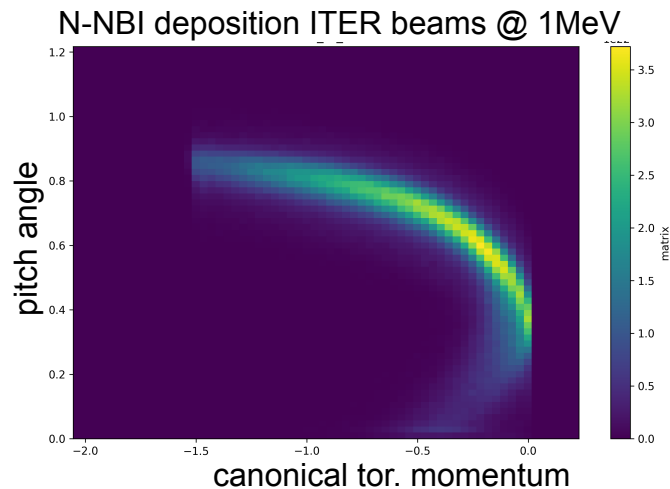
- ATEP-3D: muscle3 version and integration into HPFS/JINTRAC/ETS [V.-A. Popa]
- ATEP-3D: new python framework [T. Sterkl], update on calculation of transport coefficients
- EP- stability workflow: validation on AUG for isotope discharges [Master thesis L. Eppinger]
- EP physics in VNS: status and challenges [DEMO PSD]

Phase space resolved transport code for EPs: ATEP 3D

[T. Sterkl ,
PhD thesis started]

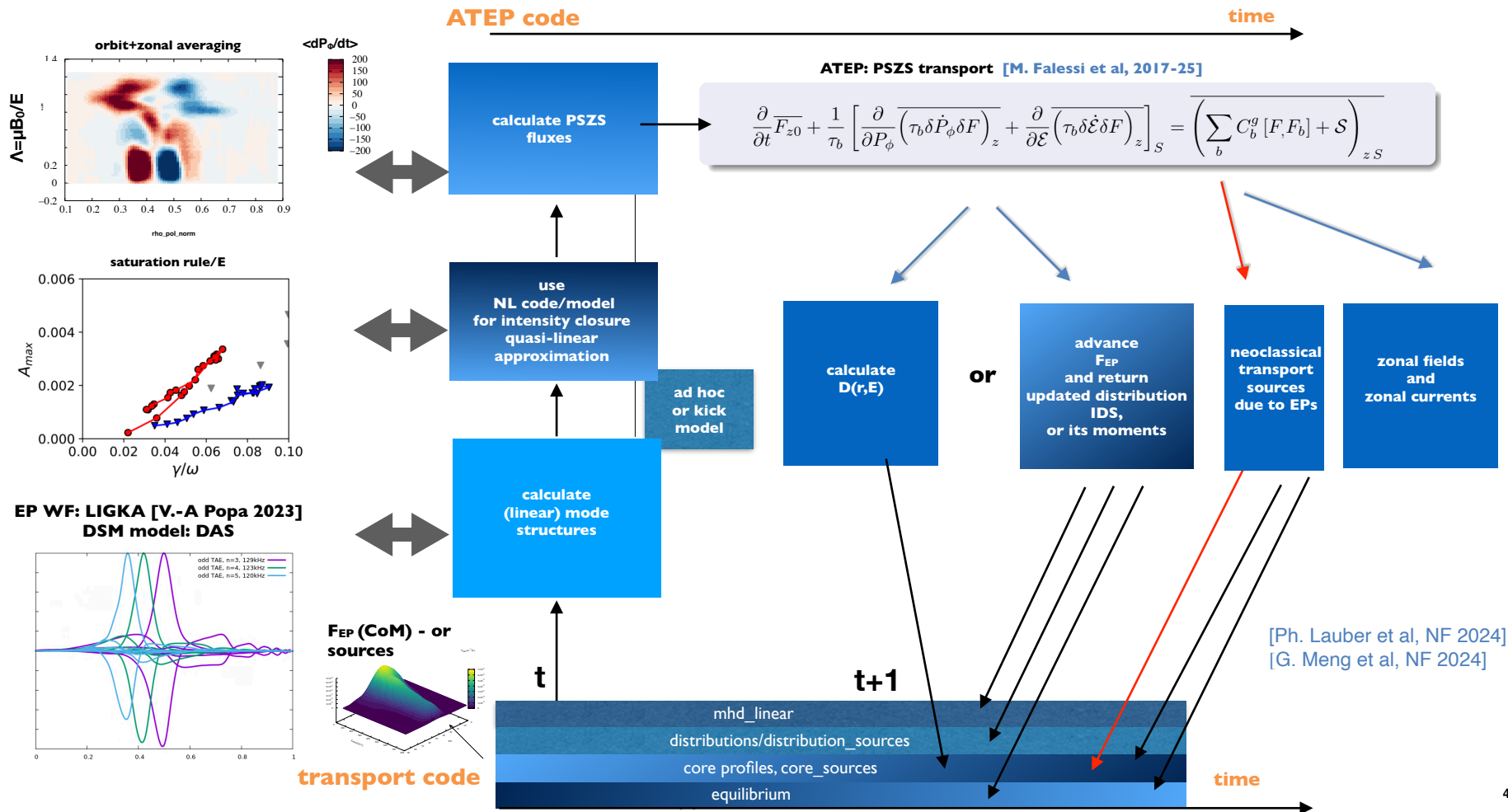


- ATEP has been transformed into a module (MUSCLE actor) and coupled to ETS – presently testing different coupling models
- EP-Stability workflow has been integrated into ATEP [see Alin's presentation]
- ATEP is completely moved to PYTHON, including new 3D python solver
- as transport codes cannot deal with EP-transport coefficients directly (a bit of a surprise to me) we need to provide particle, momentum and heat source profiles
- need to monitor electron and ion collisional losses
- implemented realistic sources for EPs as given by deposition code (here BBNBI) – see figure for new ITER baseline scenario case: NBI beams
- presently debugging/benchmarking with ASCOT [thx C De Piccoli for providing ITPEA 53299 benchmark data]





outline: ATEP code structure embedded in IMAS

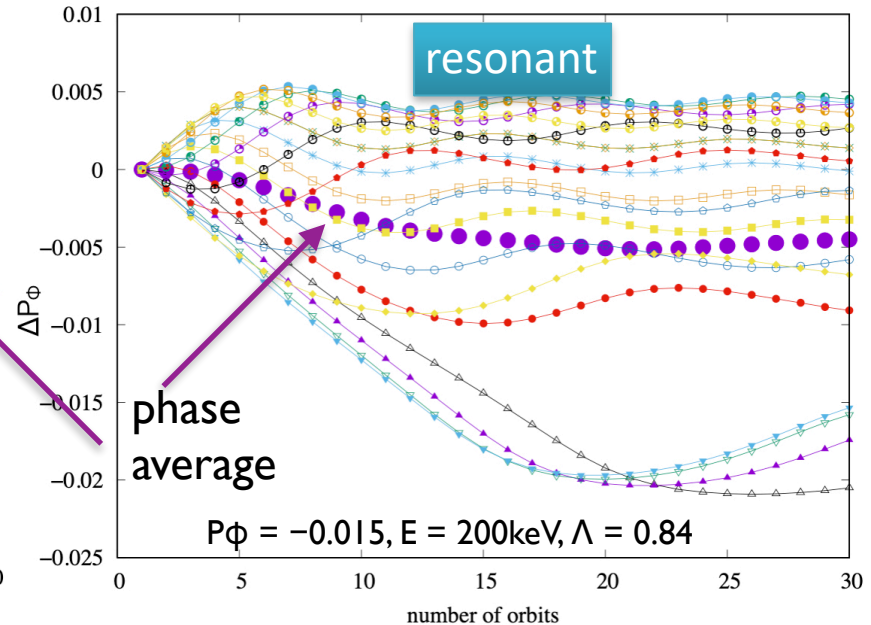
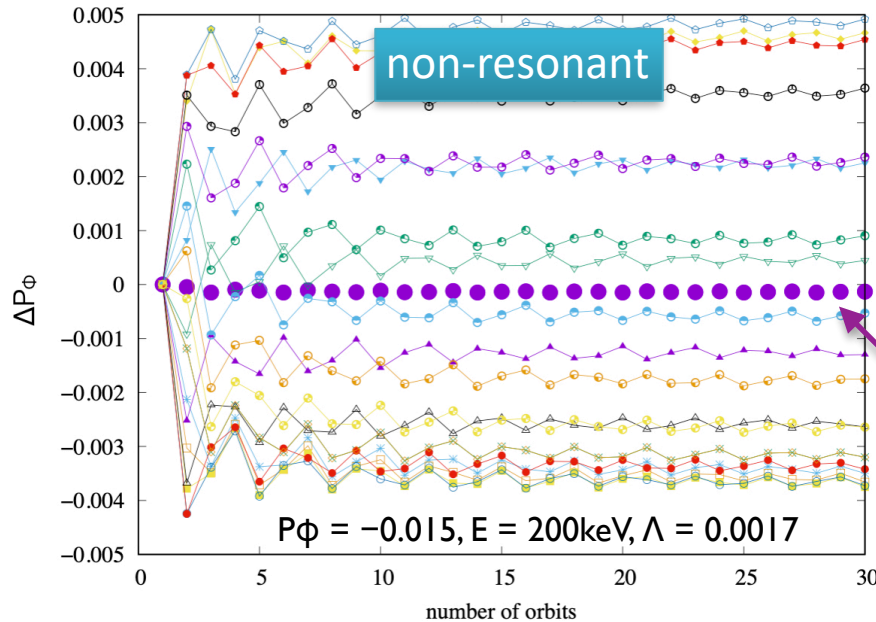




update phase space transport coefficients: zonal and orbit averaging



start particles with different phase shifts with respect to wave: ($2\pi/n$, or random), follow several orbits to account for higher resonances, then average ($n=10TAE$; $\delta B/B = 1 \cdot 10^{-4}$)



calculate average dP_Φ

using power balance leads to QL model in ATEP paper



EP transport - different regimes



- wave-particle resonance leads to (inverse) Landau damping
- when described as Markov process (finite interact. time, small Kubo number) convection/diffusion equation arises from single wave resonance:

$$\frac{\partial F(v, t)}{\partial t} = -\frac{\partial}{\partial v} \cdot \left[\langle \Delta v \rangle F \right] + \frac{1}{2} \frac{\partial}{\partial v} \cdot \frac{\partial}{\partial v} \cdot \left[\langle \Delta v \Delta v \rangle F \right]$$

$$\partial_t n(x, t) = -\partial_x (V(x)n) + \partial_x^2 (D(x)n)$$

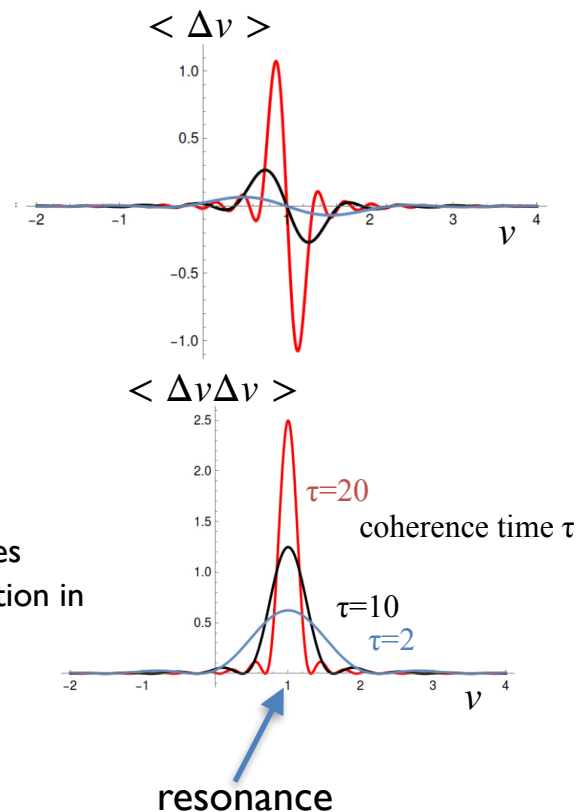
- convection terms requires perturbed orbit evaluation
- in case of small interaction times in 1d one can show that:

$$\langle \Delta v \rangle = \frac{1}{2} \frac{\partial}{\partial v} \langle \Delta v \Delta v \rangle$$

$$\frac{\partial F}{\partial t} = \frac{1}{2} \frac{\partial}{\partial v} \left[\langle \Delta v \Delta v \rangle \frac{\partial F}{\partial v} \right] = \frac{\partial}{\partial v} \left[D \frac{\partial F}{\partial v} \right]$$

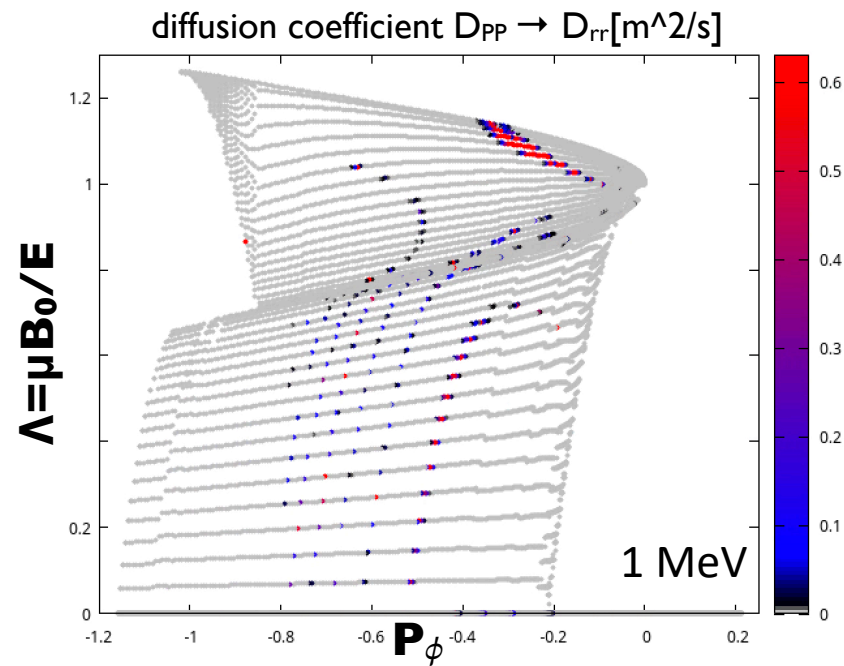
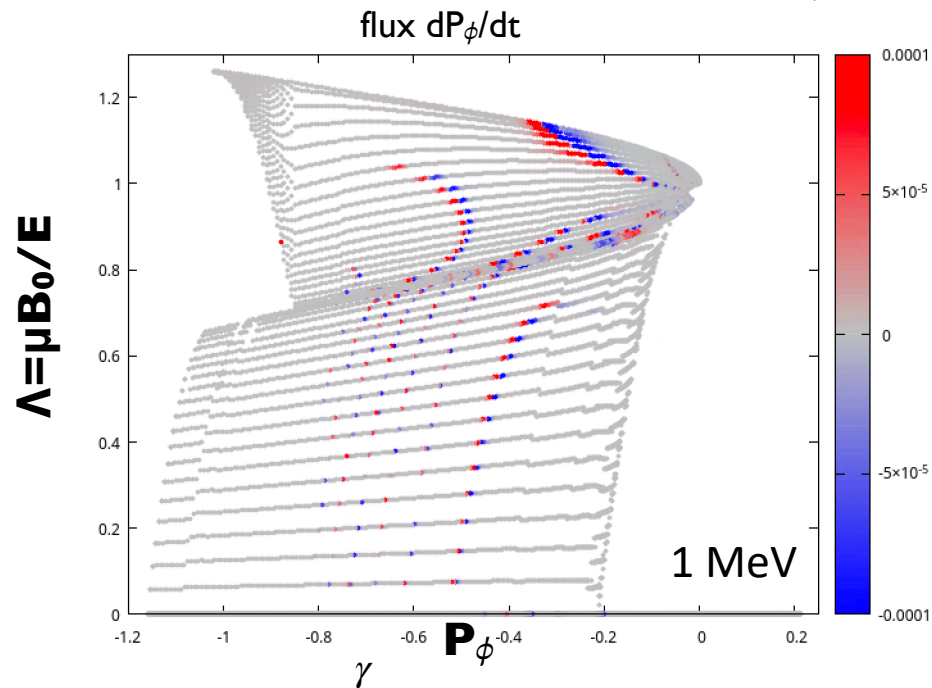
- same equation emerges from quasi-linear theory - requirement of overlapping resonances
- non-linear picture: transport emerges from stochastic orbits, stochastic Hamiltonian motion in velocity may be described by a Fokker-Planck equation (stochastic version of Liouville's theorem)
- Fokker-Planck equation can be written also as diffusion equation
- stochastic orbits are reason for irreversibility of system

[see also Escande & Sattin 2007; A Peeters, Ann Phys 2008]





$$D_{P,P} = \langle dP_\phi/dt \rangle^2 \cdot \tau_{ac}$$



$$\tau_{ac} = \frac{\gamma}{[\omega_{TAE} - \omega_{prec} - p\omega_{t,b}]^2 + \gamma^2}$$

τ_{ac} calculated numerically: include natural line broadening, finite island width; turbulent broadening can be added

[Berk, 1995/96, Gorelenkov 2018]

similarly for: $D_{E,E} = \langle dE/dt \rangle^2 \cdot \tau_{ac}$

$$D_{P,E} = \langle dP_\phi/dt \rangle \langle dE/dt \rangle \cdot \tau_{ac}$$

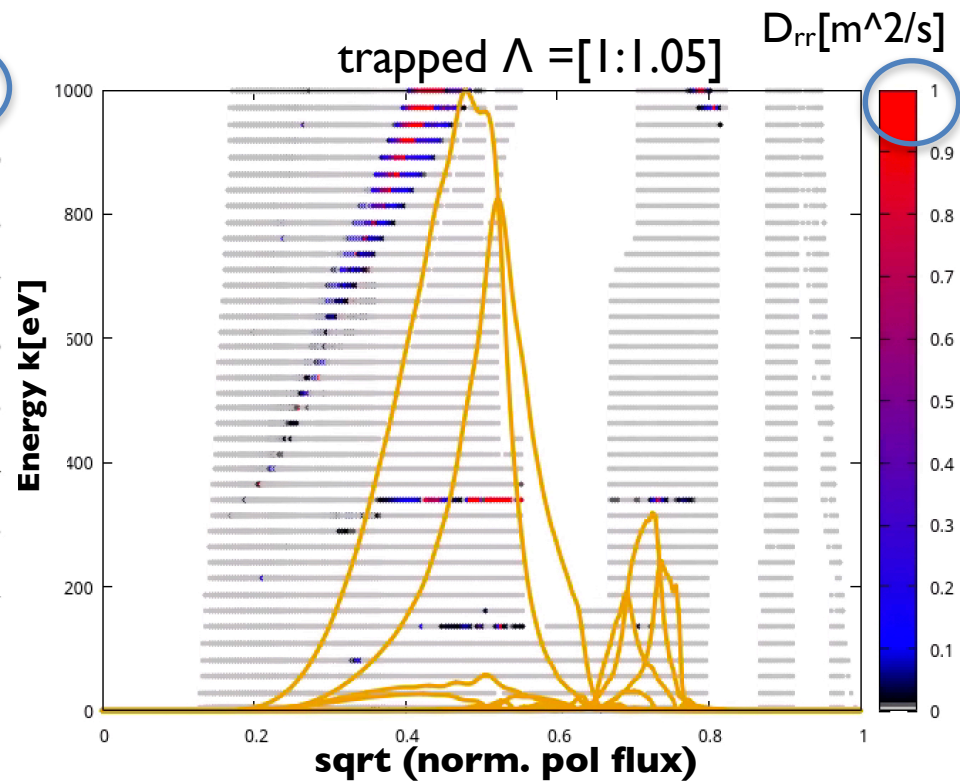
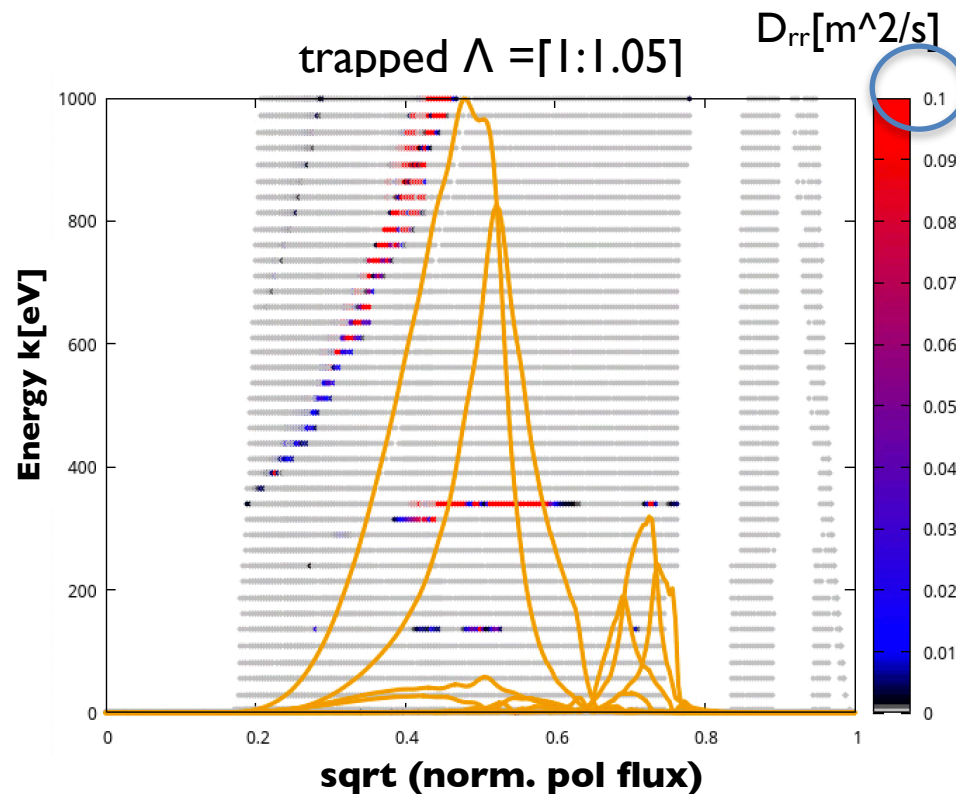


scaling with mode amplitude



$\text{dB}/B = 1 \cdot 10^{-4}$

$\text{dB}/B = 4 \cdot 10^{-4}$





fastest approach: use quasi-linear expression



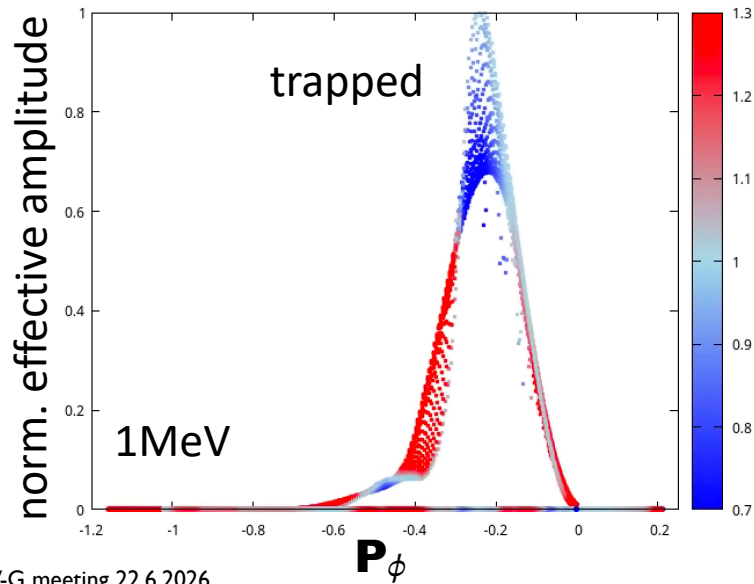
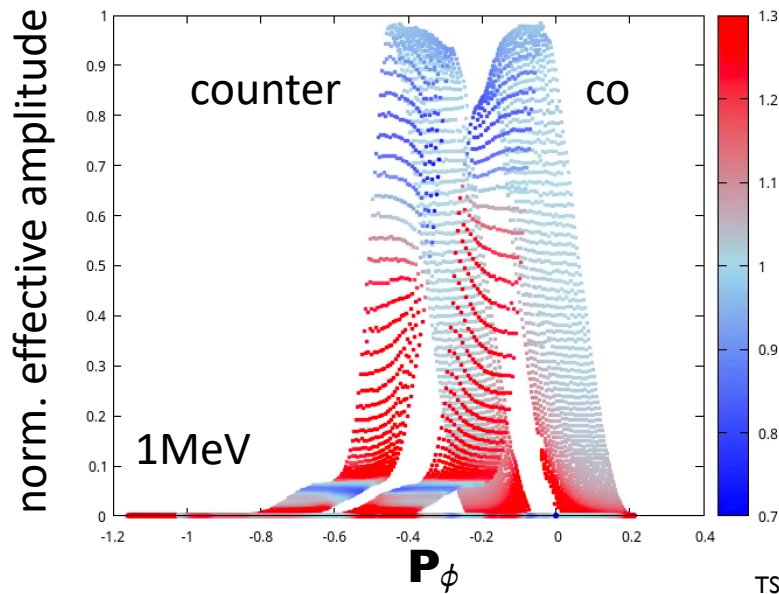
$$D = \text{const} \sum_m \phi_{m,TAE,eff}^2 \cdot \frac{\gamma}{[\omega_{TAE} - \omega_{prec} - p\omega_{t,b}]^2 + \gamma^2}$$

effective mode amplitude seen by particle on their orbits

as before: correlation time

only integration over one **unperturbed** orbit is necessary!

finite orbit width factor:
 $\langle A(r) \rangle_{\text{orbit}} / A(\langle r_{\text{orbit}} \rangle)$

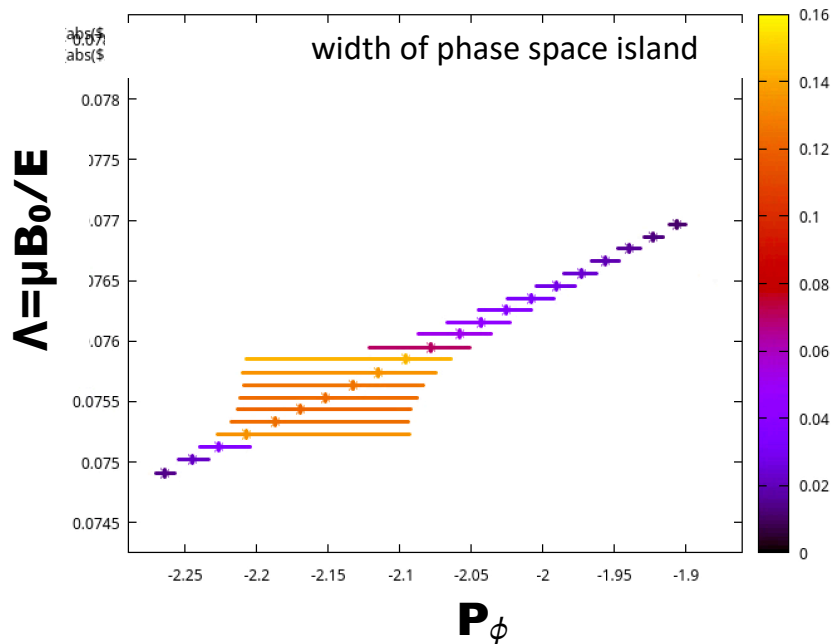


details: T. Sterkl
Master Thesis
[TU Wien, 2025]

consistent with PSZS formulation

- determine phase-space island width w by following particles $O(10)$ orbits
- determine time dt for an orbit to cross island (width/average step-size time transit time)

$$D = \frac{\langle w \rangle^2}{2dt}$$



details: T. Sterkl
Master Thesis
[TU Wien, 2025]

convenient framework to compare and reconcile the different ways of determining D and V
3 different approaches give us similar, but not exactly the same results ($\sim 10\%$)



- 3 different approaches give us similar, but not exactly the same results (~ 10) - to be examined in depth comparing to refined theoretical models [M. Falessi] and HAGIS/ORB5
- continue benchmarking and integration with DAS/PEANUT/FALCON code suite [M. Falessi]
- work on ZF reduced models [R. Stucchi, N. Chen, X. Wang, M Falessi, F Zonca]
- validation of ATEP within scenario transport codes with the help of C. De Piccoli



- ATEP-3D: muscle3 version and integration into HPFS/JINTRAC/ETS [Alin]
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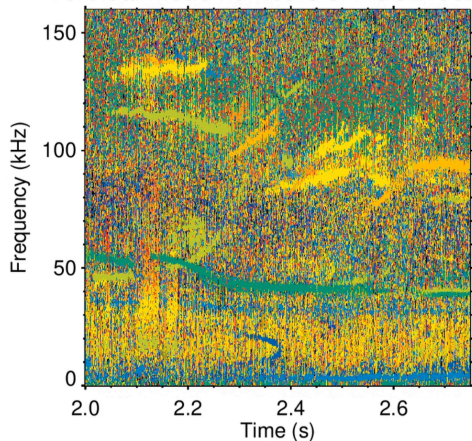
[L. Eppinger,
ongoing master thesis]

identified set of representative discharges with strong EP-driven activity:

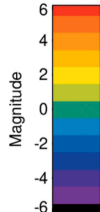
	time interval [s]	plasma isotope	NBI isotope	B_t [T]	I_p [kA]	mode
#36760	2.55–2.65	H	H	-2.53	792	L [81]
#39681	3.6–4.1	H	D	-2.20	713	L $\rightarrow$ H [82]
#36267	2.1–2.65	D	D	-2.53	794	H [81]
#41437	2.6–3.2	He	D	-2.01	619	H

Table 5.1 Overview of the discharges chosen for analysis. The colors correspond to those used in Fig. 5.1.

Toroidal mode numbers of AUGD 36267



Color scale

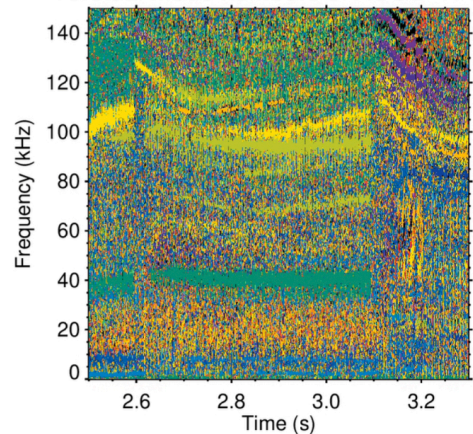


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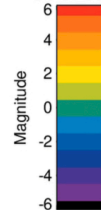
Time stamp: 1770040373467
version: 2
shot: AUG0 36267
data history: Loaded with MTR
coord: 3D Geometrical_Loaded with
window: Gauss
width: 160
height: 160
freq: 640
step: 200
averages: 0
filter: Res_pos.
mode: steps / margins: 1,000
ChiSquare: 0.00000 %
Power limit: 0.00000 %
Q limit: 0.00000 %
channel pairs: 28
MH1-B31-40-MH8-B31-14
MH1-B31-40-MH8-B31-03
MH1-B31-40-MH8-B31-01
MH1-B31-40-MH8-B31-02
MH1-B31-40-MH8-B31-02
MH1-B31-40-MH8-B31-02
MH1-B31-40-MH8-B31-25

```

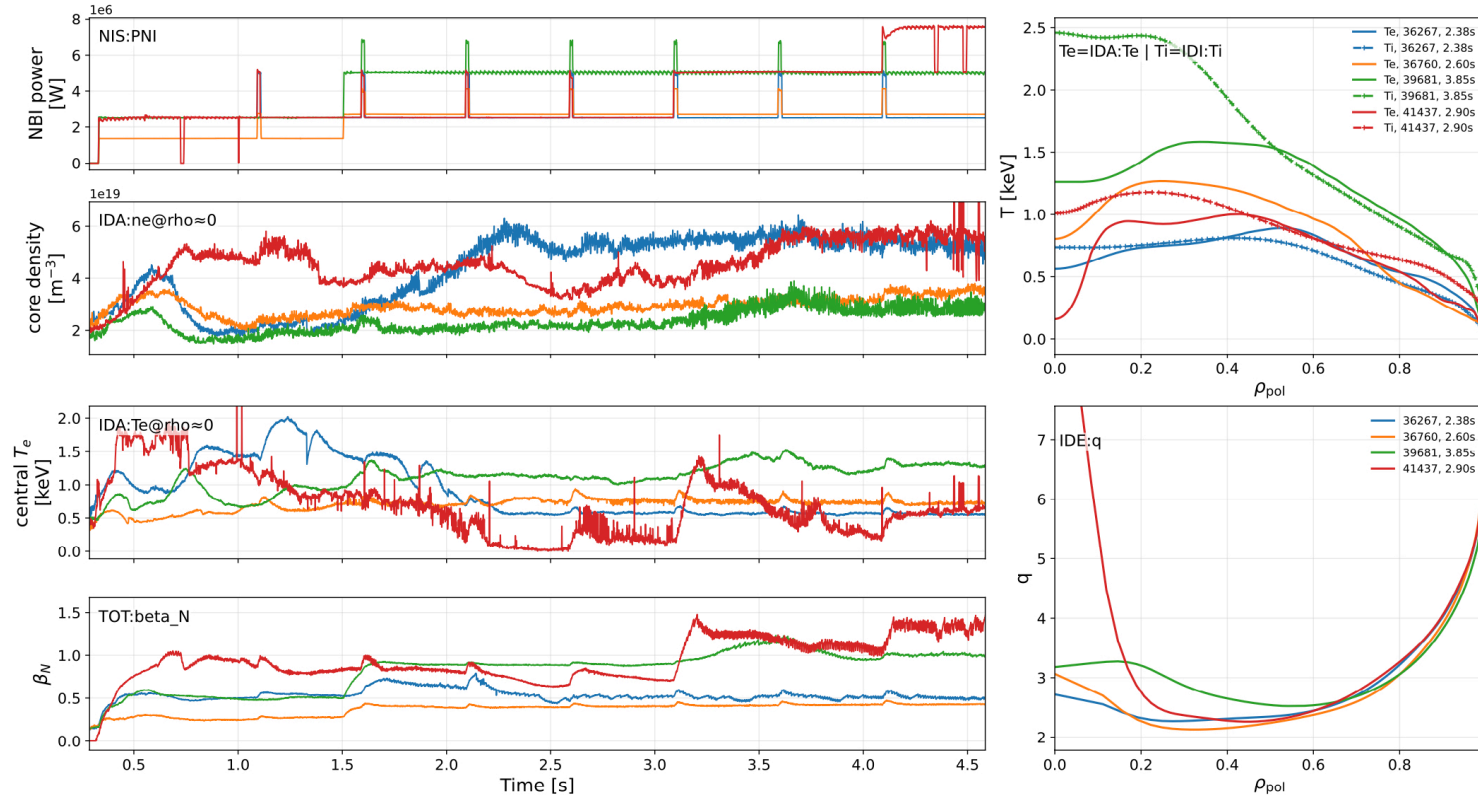
Toroidal mode numbers of AUGD 41437



Color scale



Time stamp: 1769979374631
version: 1.5.2
shot: AU00 41437
data header: Loaded with MTR
coord. history: Geometrical_Loaded with
window: Gauss
weight: 1
0.000000000000000000
lim: step: 200
averages: 0
filter: flat_pos.
mode steps / margin: 1,000
coord. limit: 0.000000 %
Power limit: 0.000000 %
Q limit: 100 %
MTR: 1769979374631-36
MHS: 1769979374631-40
MHS: 1769979374631-14
MHS: 1769979374631-03
MHS: 1769979374631-01
MHS: 1769979374631-02
MHS: 1769979374631-15
MHS: 1769979374631-09
MHS: 1769979374631-15
MHS: 1769979374631-15

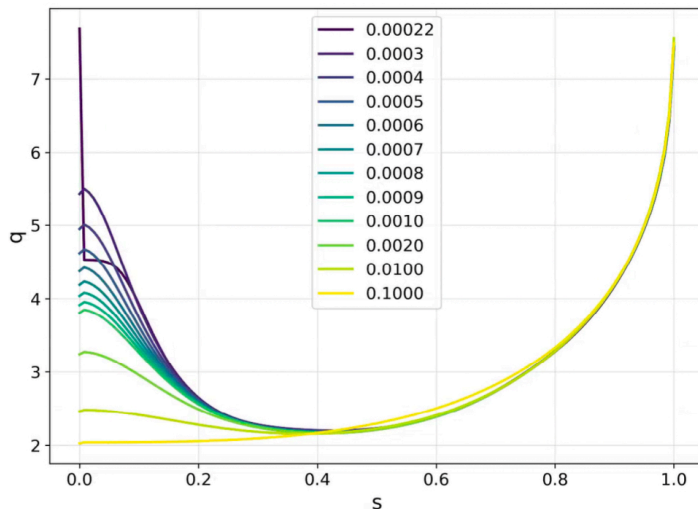




aim:

I. push automated analysis of experimental data; challenges:

- equilibria; q profiles; example: current hole equilibria sensitivity
- profile availability and consistency using IDA: quasi-neutrality; MHD/kinetic pressures; various fixes and developments for 'TRVIEW' tool [G.Tardini]
- behaviour of EP-WF: exception handling, robustness to numerical parameters
- handle correctly positive and negative mode numbers and Doppler shifts



q in core $r < 0.3$ cannot be measured reliably;
IDA suggests $q_0 = 6$!
determine sensitivity: control q -profiles with
'tensprof' parameter in CHEASE

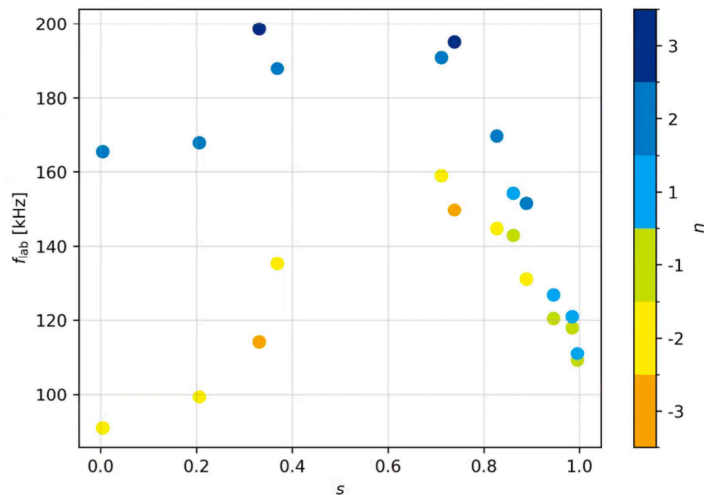
compare to q_0 -scan to experiment for
selected time point to use it as constraint



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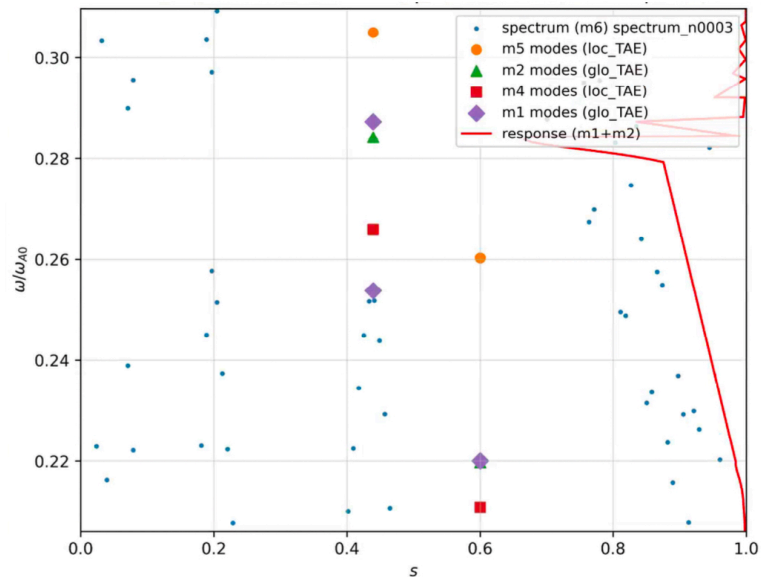
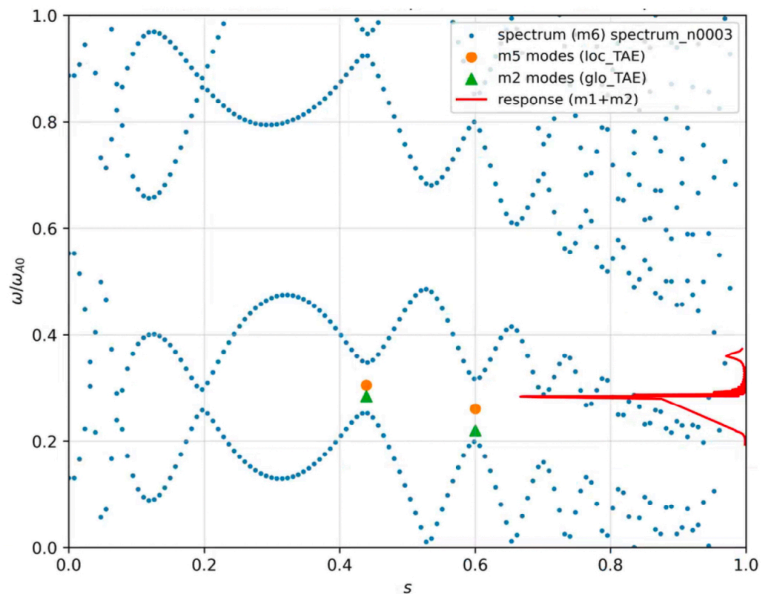




validation isotope-mixed discharges ASDEX Upgrade



example EP-WF results: #36267 at $t = 2.1$ s





aim:

1. push automated analysis of experimental data; challenges:
2. in-depth investigation of damping rate scaling with isotopes [old PENN results on JET, JET antenna results; Lauber AAPPs-DPP 2021]
3. Assess drive and related transport - in particular impact of AEs on NBI-CD

present status [to be reported by Leon in fall 2026]:

- implemented control of isotope mixes within experimental uncertainty: profiles of ion-mix are difficult to measure - but extremely important to understand for burning/beam-target plasmas - dilution/fusion rate!
- mix of ion Landau damping (expected to decrease for heavier isotopes), radiative damping and non-local continuum damping - no simple trend visible on first glance
- ion LD scales with $\sim (v_{A0}/v_{th,i})^{3/2} \exp[-v_A/(3 v_{th,i})]^2$, ion mass cancels for ion LD
- increase in damping due to KAWs /electron LD



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NBI physics and EP Stability/Transport

Plasma System Division

DEMO Central Team

PSD: Philipp Lauber ,Clarisse Bourdelle, Francesco Maviglia, Andrea Quartararo, Sven Wiesen, Pasquale Zumbolo and WPDES contributors: A. Snicker, K. Särkimäki, C. De Piccoli;
and Mattia Siccinio, M. Weiland





VNS current design point

[M. Siccino, ESM Jan 2026]

Parameters (METIS): (0.5D modeling)

Major Radius = 2.67 m

Toroidal Field = 5.6 T

Aspect Ratio = 4.25

Sep. Elongation = 1.6

Triangularity = 0.23

NBI Power = 42.5 MW

Beam Energy = 120 keV

EC Power = 8 MW

Safety Factor $q_{95} = 3.1602$

Line average density = $11 \times 10^{19} \text{ m}^{-3}$

Plasma Surface = 95.3809 m²

Peak NWL = 0.5114 MW/m²

Av. NWL = 0.32058 MW/m²

BetaN = 2.7209 %Tm/MA

Fusion Power = 38.2219 MW

Centr. El. Temperature = 12.9134 keV

Pl. Current = 2.5401 MA

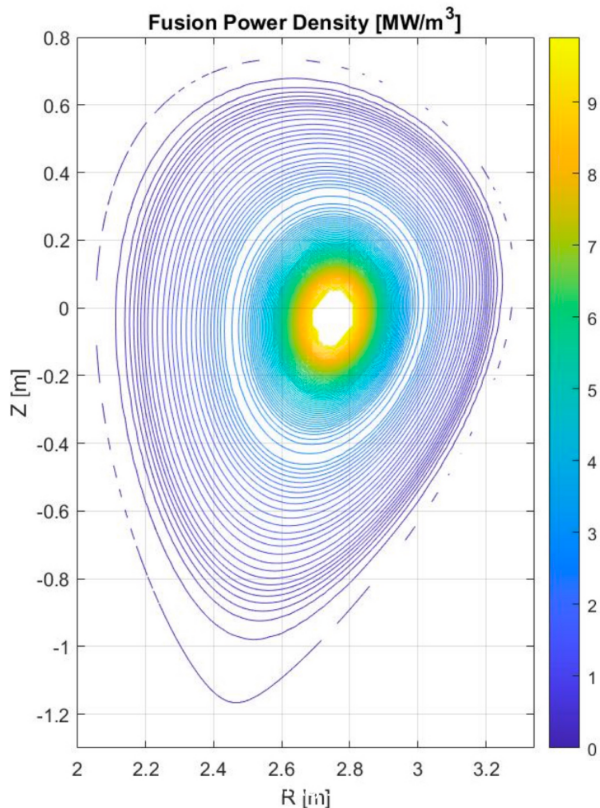
Tot. Beta Poloidal = 1.8749

D Fraction in Bulk Plasma = 0.17006

Power to Divertor = 55.6196 MW

Fully non-inductive plasma!

~ 50dpa [displacements per atom] in few years



4 beam lines (deuterium):

~15MW per beam line

3 operational/1 recycling

NBI needs to be optimised to facilitate: D-T, current drive, profile shaping (MHD), rotation, neocl. W transport, heating mix

~7.5 MW alpha particle heating,

8MW EC power

started 12/2025:

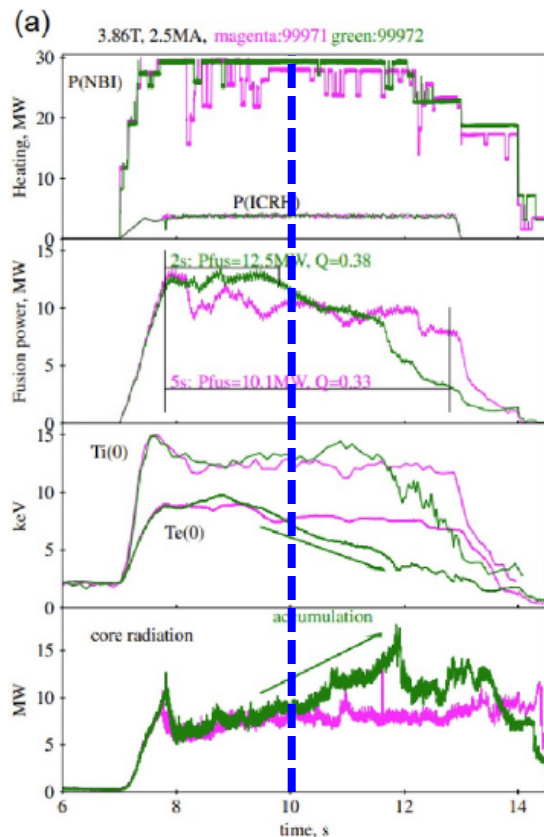
PSD to investigate the current design point with higher fidelity models (ASTRA/TGLF/RABBIT; ASCOT, EP-Stability WF, ATEP,...)

first: JET validation



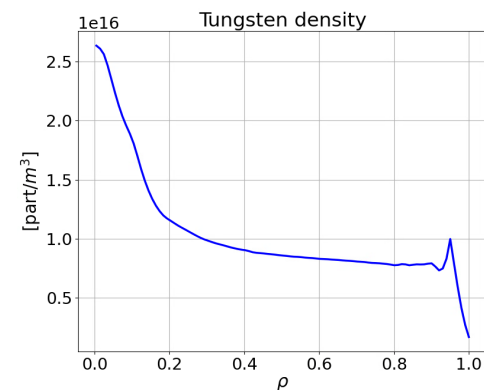
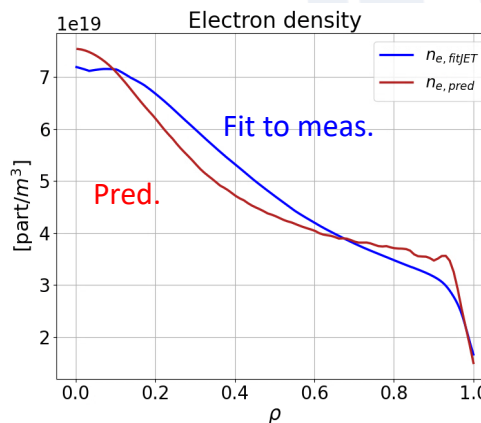
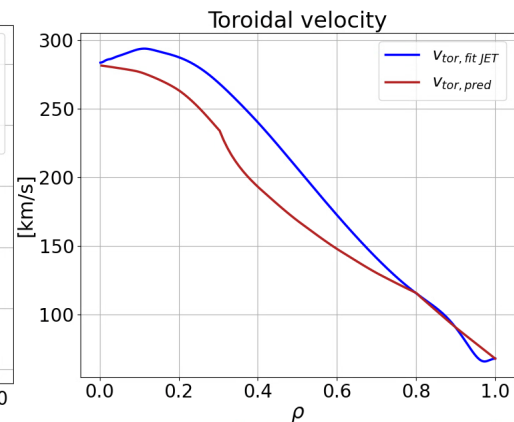
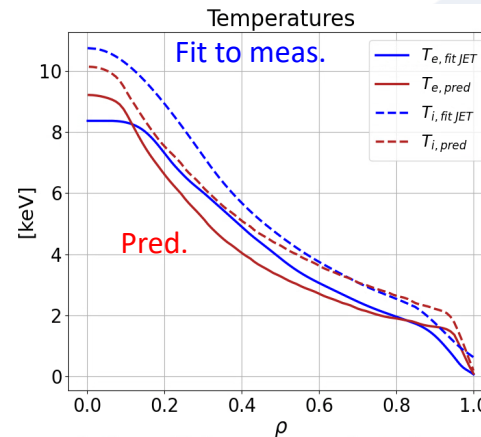
Integrated Modelling settings, validated on JET DTE2 record beam-target

[E. Bray, March 2026]



Predicted
 $P_{fus} \sim 10\text{ MW}$
NB: ICRH not self-consistent, w/o RF beam-target

Predicted:
 $P_{rad} \sim 6/7\text{ MW}$



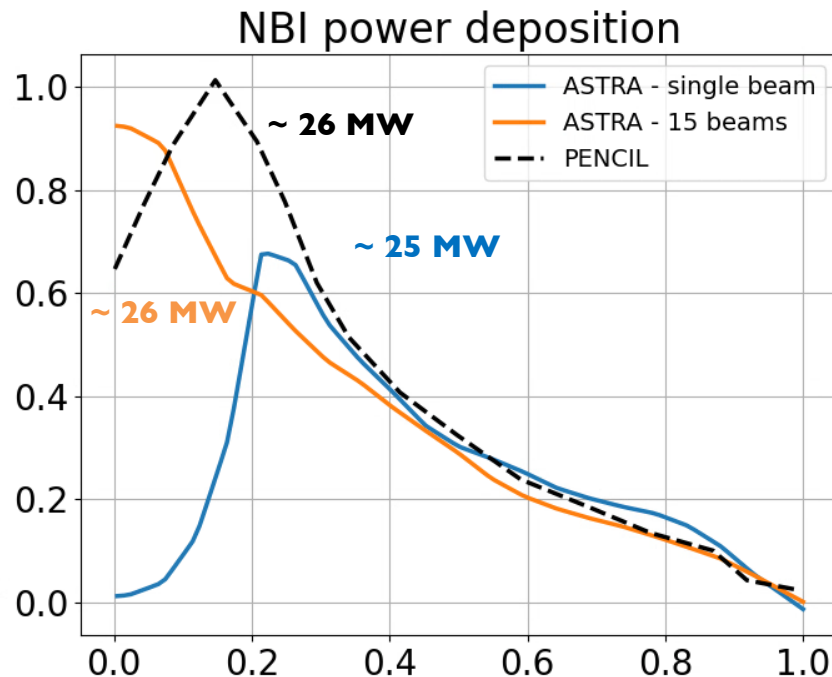
NB: ICRH not self-consistent, w/o RF beam-target

[Maslov M. et al., Nucl. Fusion **63** (2023) 112002]



JET validation - NBI geometry and deposition (PENCIL vs RABBIT)

[E. Bray , March 2026]



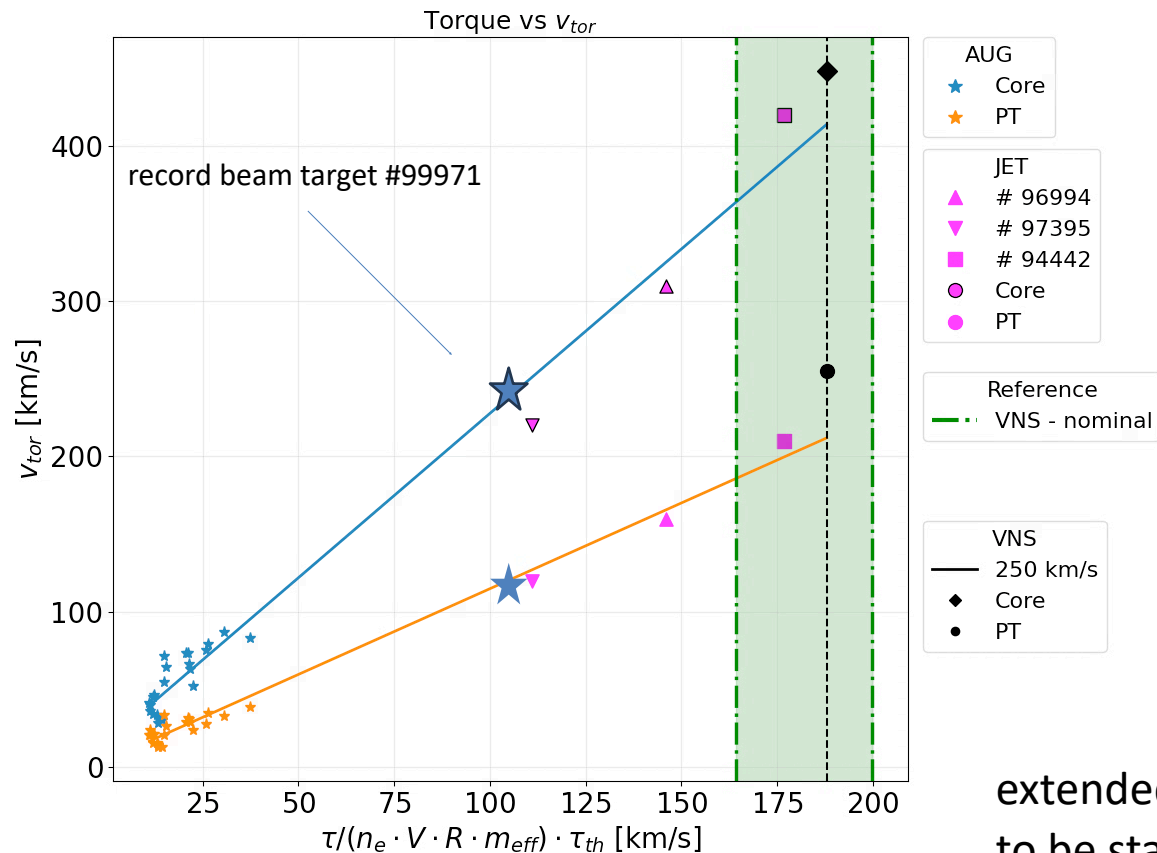
many other succesful benchmarks of RABBIT with TRANSP/Nubeam for AUG, JET, DIII-D etc [Weiland et al 2018-2026]

reasonable agreement; remaining differences: FOW effects (PENCIL: no FOW)



High- rotation cases at JET – close to expected VNS values

[E. Bray , March 2026]



significant beam power is 'lost' to rotation:
lower effective energy of injected ions in the
reference frame of the rotating plasma
good agreement of RABBIT-TRANSP for AUG
[M. Weiland]

however: some differences reported on highly
rotating plasmas in JET [Siren EPS 2019]
between ASCOT/TRANSP-NUBEAM

Is rotation correctly predicted for higher
rotation cases #94442?

rotation effects on AE stability/transport!

Fishbones observed in JET 99971 - modelling
to be done!

extended validation on JET needed
to be started - help of TSVV appreciated



Results of the current design point

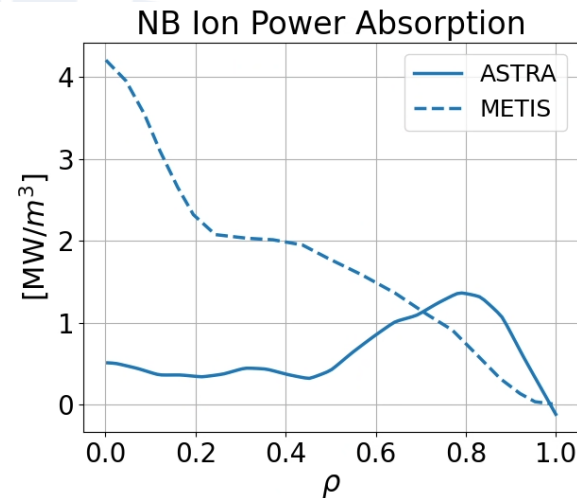
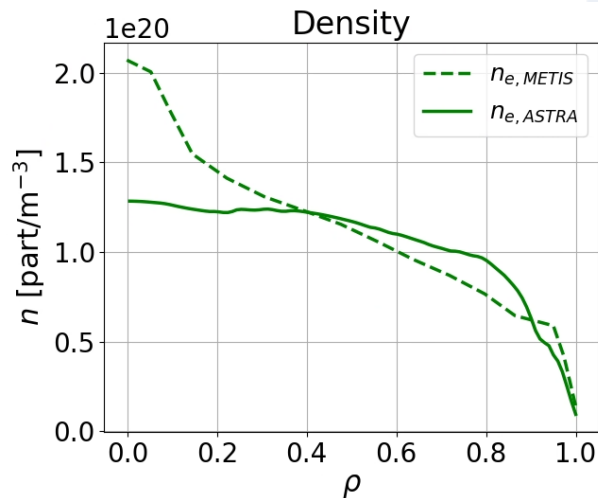
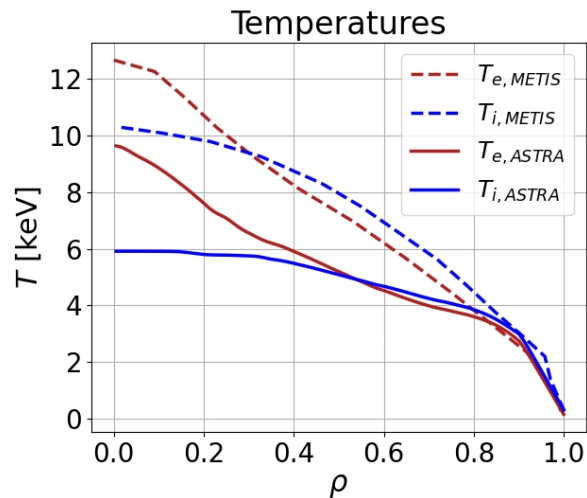
Param.	Value	Units
P_{NBI}	42.5	MW
E_{beam}	120	keV
P_{ECRH}	8	MW
$n_{e,avg}$	11	10^{19} m^{-3}
I_{pl}	2.5	MA
B_T	5.6	T
$1/\epsilon$	4.25	-
R_{tor}	2.67	m

- Current driven by ECRH self-consistently modeled
- Flux particle fractions for 120 keV
- TGLF-SAT2 with EM settings

Flux fractions	E_0	$E_0/2$	$E_0/3$
120 keV	0.452	0.417	0.131

[Computed by C.Hopf]

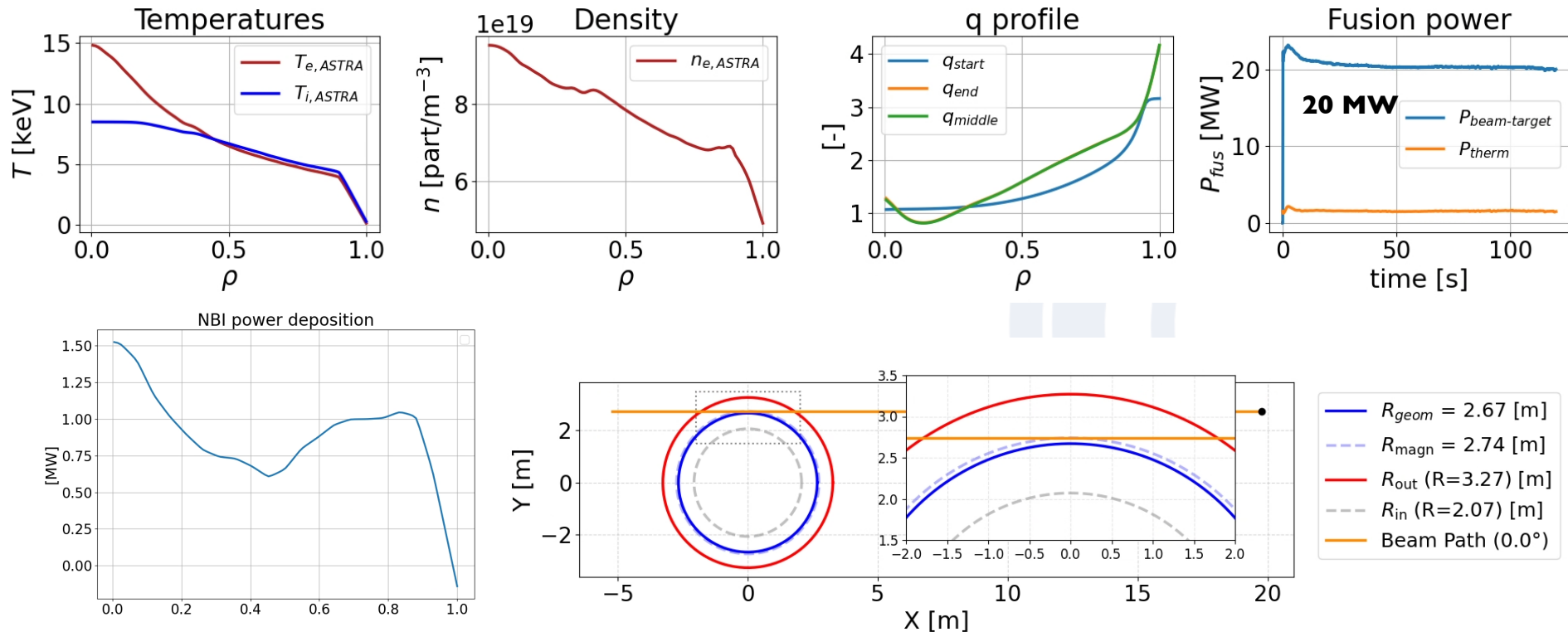
- Inefficient penetration of the beam
- P_{fus} produced around **15 MW**





Updated results with tangential beam injection ~150keV

[E. Bray, March 2026]



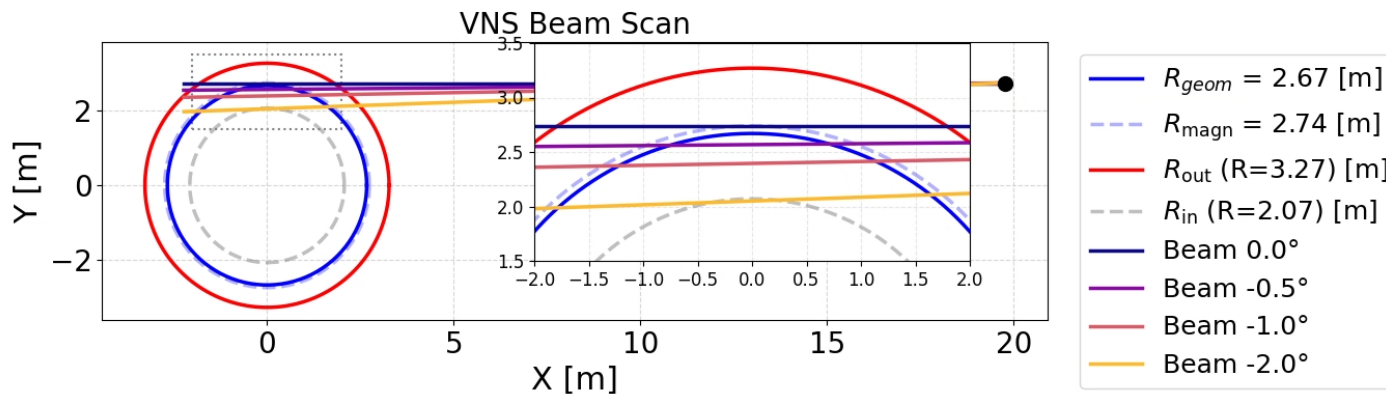
- Slightly better beam penetration, but the fusion power produced is quite low



Scan of the injection angle

[E. Bray , March 2026]

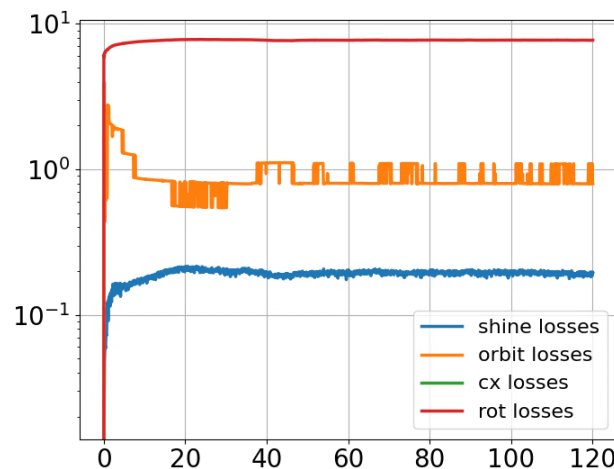
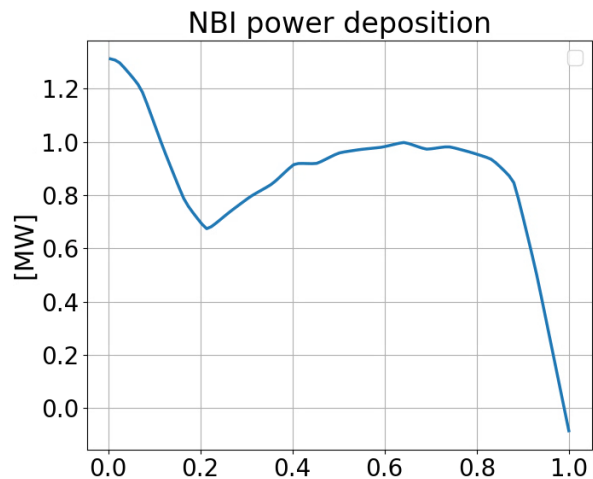
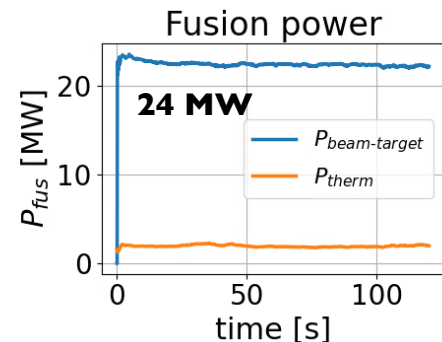
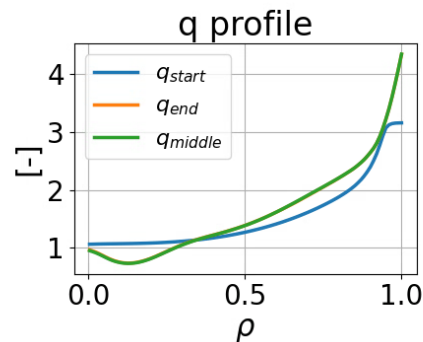
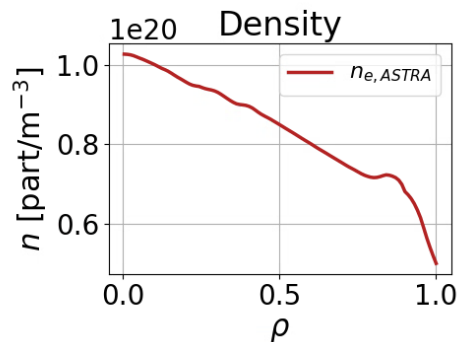
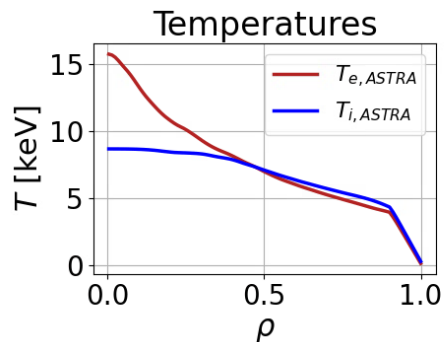
	Injection angle	NBI power	NBI beam energy	ECRH power	Pfus [MW]	Vloop	Rot losses [MW]	Vtor,0 [km/s]
Design	180	42.5	120	8	16,80	14 mV	8.73	740
150 keV	180	42.5	150	10	21.54	-10 mV	8.10	665
0.5 degree	179.5	42.5	150	10	24.11	1-2 mV	7.72	646
1 degree	179	42.5	150	10	28.62	10 mV	7.07	620
2 degree	178	42.5	150	10	32.05	18 mV	5.7	550





Results of the reference case with inclination 0.5°

[E. Bray, March 2026]



7,7 MW

VNS: strongly driven system, large EP fraction



- dimensionless parameters (mode spectrum/turbulence spectrum) not relevant for burning plasma physics
- large EP fraction (consisting of D beam in T plasma, and alpha particles) - non-perturbative studies needed (on-axis $p_{EP} \sim 1-1.5 p_{thermal}$)
- mode number spectrum expected to leak at low toroidal mode numbers: 5-12; alpha particles may drive even lower n modes
- EP gradients similar to AUG EP super-shots expected [Lauber IAEA 2018, NLED AUG case, G Vlad RMPP 2025]

EP - driven mode stability can be roughly described by β_{EP}/β_{back} (caveat: complex nonlocal dependencies of kinetic drive and damping mechanisms and gradients)

1. beam ions: $\frac{\beta_{EP}}{\beta_{back}} \sim \frac{n^{-1} T_e^{3/2}}{n T_e} \sim T_e^{1/2} n^{-2}$ scaling (slowing down time/plasma beta)

2. beam target alphas: $\frac{\beta_{\alpha}}{\beta_{back}} \sim \frac{\dot{n}_D \cdot n_T \cdot T_e^{3/2}}{n \cdot n T_e} \sim \frac{T_e^{1/2}}{n}$

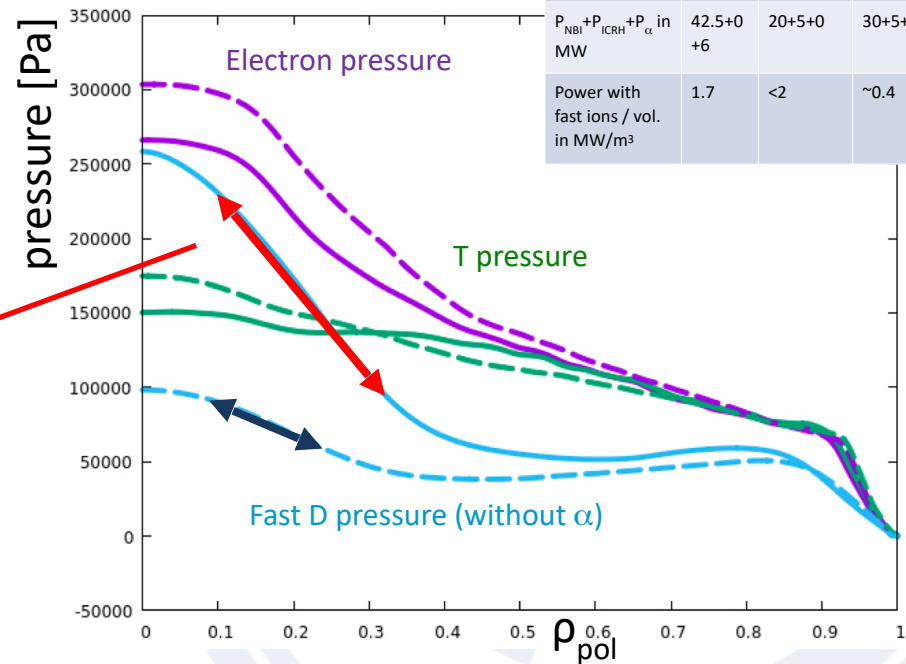
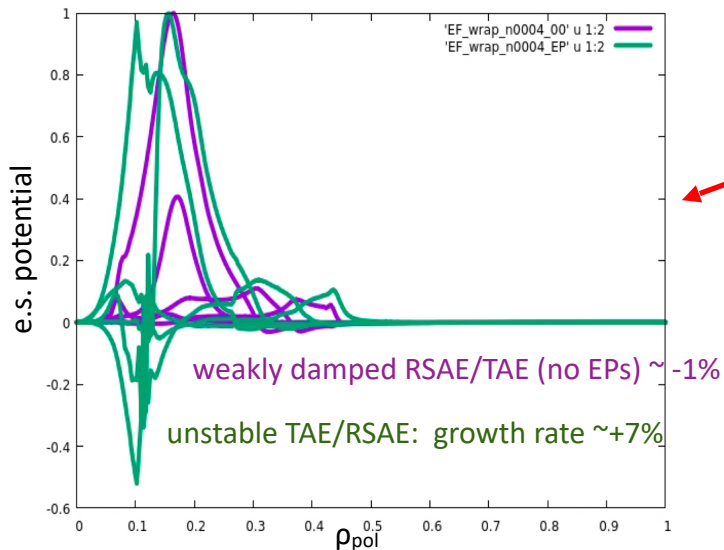
needs to be
included into
scenario optimisation

in VNS: both beam D (1.) and alpha particles (2.) pressure of beam D $\approx$ pressure of alphas



if NBI penetrates: steep gradients of energetic particle pressure

- assess the Energetic Particles (NBI ions and alphas) high pressure gradient stability and control
- **energetic particles (NBI+) driving instabilities /EPMs/ avalanches which impact NBI CD efficiency, penetration**



	VNS	AUG	JET
Vol in m ³	28	13	90
$P_{NBI} + P_{ICRH} + P_{\alpha}$ in MW	42.5+0+6	20+5+0	30+5+1
Power with fast ions / vol. in MW/m ³	1.7	<2	~0.4

previous VNS cases

-- : $P_{fus} = 20$ MW - dashed lines

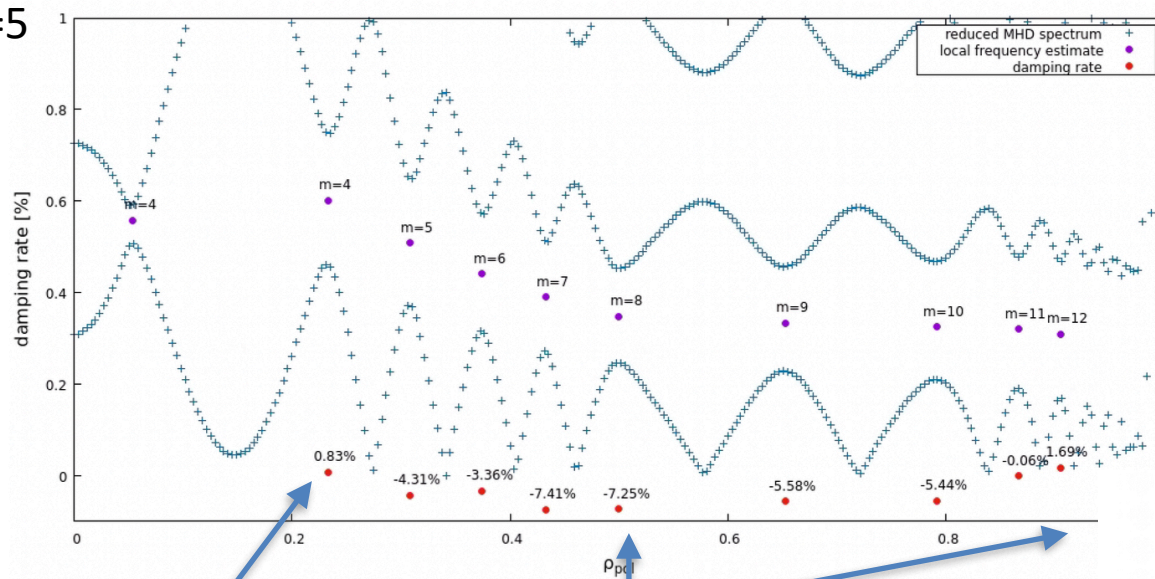
- : $P_{fus} = 28$ MW (~ref.) - solid lines

NB: such instability reported to reduce NBI CD on KSTAR [Kim NF2024]
validation on KSTAR foreseen

if NBI penetrates: steep gradients of energetic particle pressure



[C Schmitz, TU Wien June 2026]



unstable

damping increased by
NBI (as seen in JET)

using equivalent Maxwellian

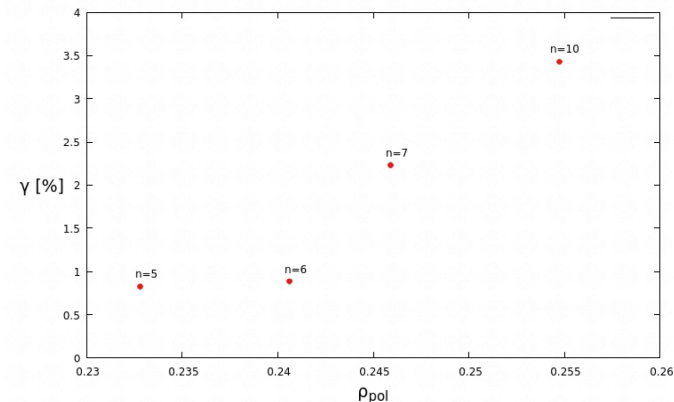
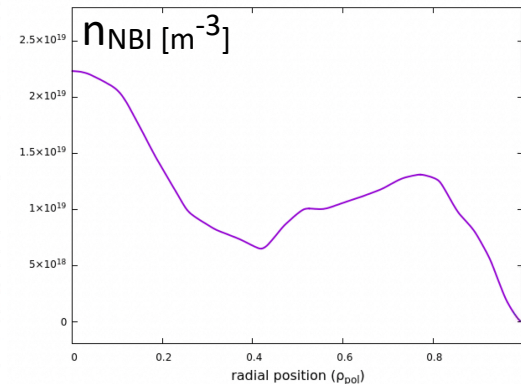
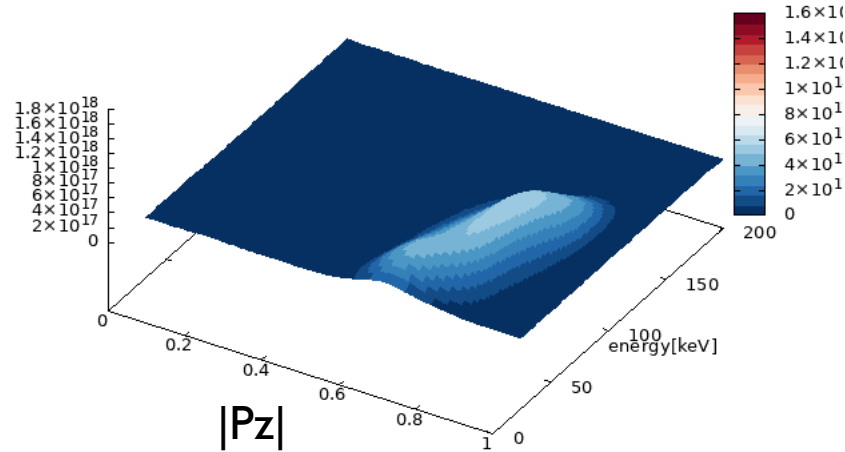


Figure 4.11: Damping rate for core-located TAE gap for increasing toroidal mode number

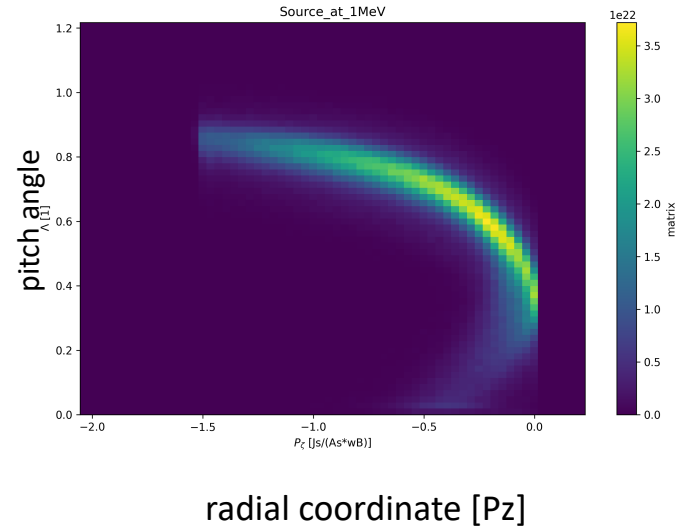
VNS CoM F_{NBI} as given by ASCOT

dPz (Pz,Lambda), Lam=0 [μ B/E]



recently: ATEP can use source deposition (BBNBI) directly [T. Sterkl]:

N-NBI deposition ITER beams @ 1MeV



- phase space transport analysis for most unstable AEs/energetic particle modes
- multi-modes + different AE types + fishbones + ripple
- comprehensive evolution of non-linear equilibria by evolving zonal state

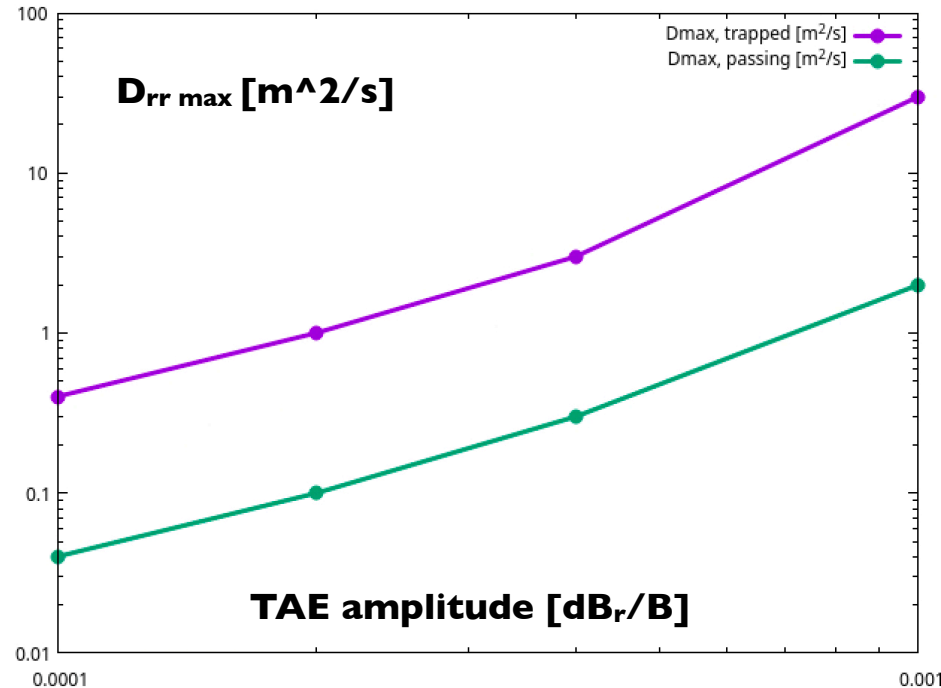


- **High Neutron Wall Load comes with exhaust challenge**
 - Cannot increase Z_{eff} too much - negative impact on V_{loop}
 - T rich plasmas, hence larger fueling means high T throughput
 - Large flux to wall: W erosion level to be done
- **Exhaust requirement and NBI penetration**
 - Target protection through large flux, means large n_{sep}
 - NBI penetration needs low density at sep/ped **VNS ref case in ASTRA ~25 MW w/o W (no margin) peak NWI ~0.34 MW/m² NOT compatible with exhaust $n_{\text{sep}}=5 \times 10^{-3}$ $Z_{\text{eff}}=1.4$ to allow for NBI penetration...**
- **NBI torque comes with NBI CD**
 - NBI torque vs W neoclassical transport compatibility [E. Bray TTF 2025] will be reassessed on refVNS case
 - NBI CD vs MHD stability to be modeled, not yet done
 - NBI power lost for fusion via mechanical energy transferred to the torque: **validation on high-rot. cases in JET**
- **NBI penetration vs loss of CD efficiency**
 - NBI less tangential, better penetration, but less CD **only 2 Wb available at flat top so NEED $V_{\text{loop}} < 2\text{mV}$! For > 20 min...**
 - Compensated by ECCD on axis, at cost of q profiles incompatible with MHD stability to be modeled, not yet done
- **NBI penetration vs drive for Energetic Particle modes** → **validation of fishbone/AE physics on JET DT record cases**
 - Larger pressure gradients of fast D from NBI : support from TSVs, EP-turbulence in presence of large p_{NBI}
 - Interplay with NBI CD efficiency see KSTAR long pulses with NBI [Kim NF 2024] - AUG NBI-CD drive

presently ongoing: change heating mix, coil design, identify required R&D,...
consistent action plan needs to be set up (after next GA?)



scaling with mode amplitude



typical range of
experimentally
measured TAE
amplitudes

can be integrated and weighted with distribution function to determine an effective $D_{rr}(r), D_{rr}(r, E)$ and fed back to transport code