Identification of scenario requirements for high performance DEMO operation

E. Fable

Acknowledgments: M. Siccinio, C. Angioni, F. Palermo, H. Zohm, and the ASDEX Upgrade Team, MPG-IPP Garching
JETpeak database group at CCFE

KDI#8 final meeting, 1 July 2020

DEMO scenario gross parameters

- DEMO parameters (scenario 2019):

  $R = 8.94$ m
  $a = 2.88$ m
  $B_T = 5.74$ T
  $Ip = 18.21$ MA
  $n_{avg} \sim 8 * 10^{19}$ m^{-3}
  $k = 1.7$
  triang = 0.33

- $H_{98} = 1$ (based on the ITER98(y,2) scaling for type-I ELMy H-modes)

- $P_{aux} \sim 50$ MW

- $P_{fus} \sim 2$ GW (400 MW alpha power) → 450 MW core heating power

- P_{rad},core ~ 250 - 300 MW → 150 - 200 MW power through separatrix

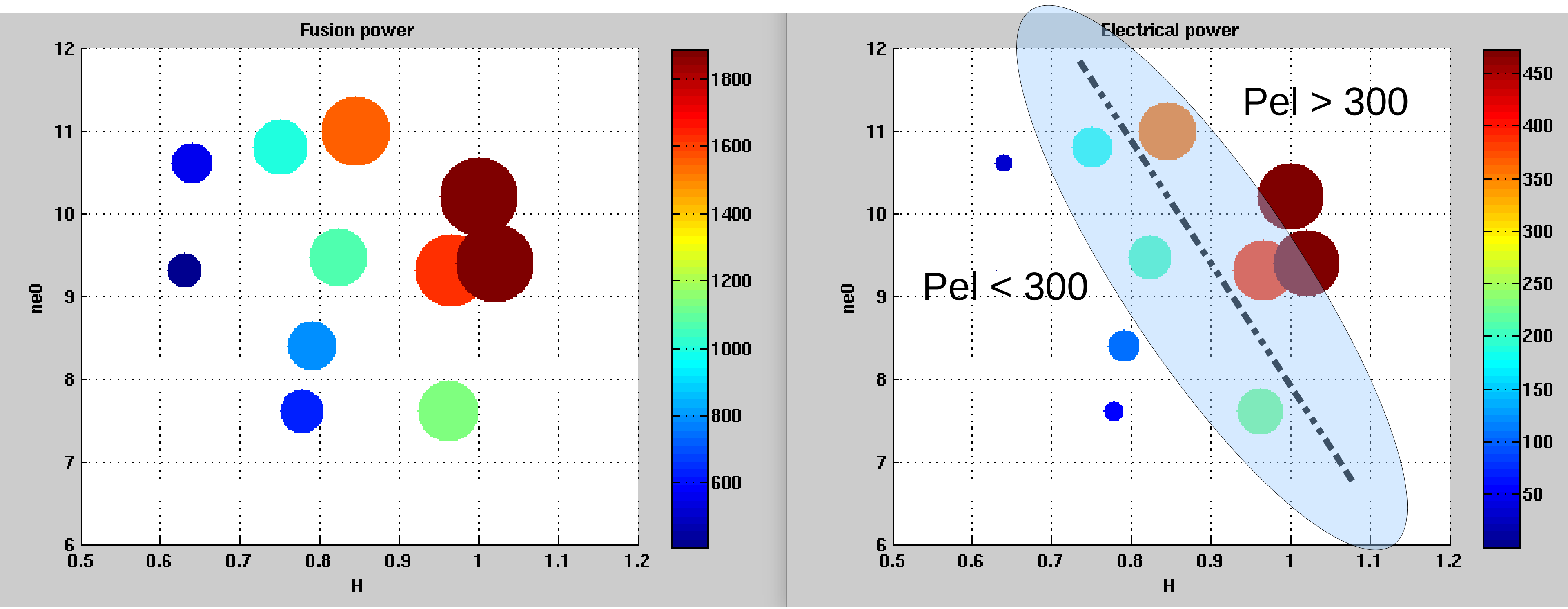
- $P_{sep}/P_{LH} \sim 1.2 – 1.5$ → $P_{LH} \sim 100 – 150$ MW

Relevance plane for a commercial reactor

- Let us target a > 300 MW electric, 9 meter machine with ~ 5.7 T and 19 MA of current.

$$P_{fus} \sim n^2 T^{1 \div 2}$$

- No pedestals (n_{sep} ~ 0.5 n_G = 3.3 10^{19} m^{-3}), T_{ped} < 1 keV



- The operational space in density peaking/H factor is rather sharply defined
- Target at least H > 0.7 to have a chance (but density peaking relevant at low H)

Typical scenarios behavior

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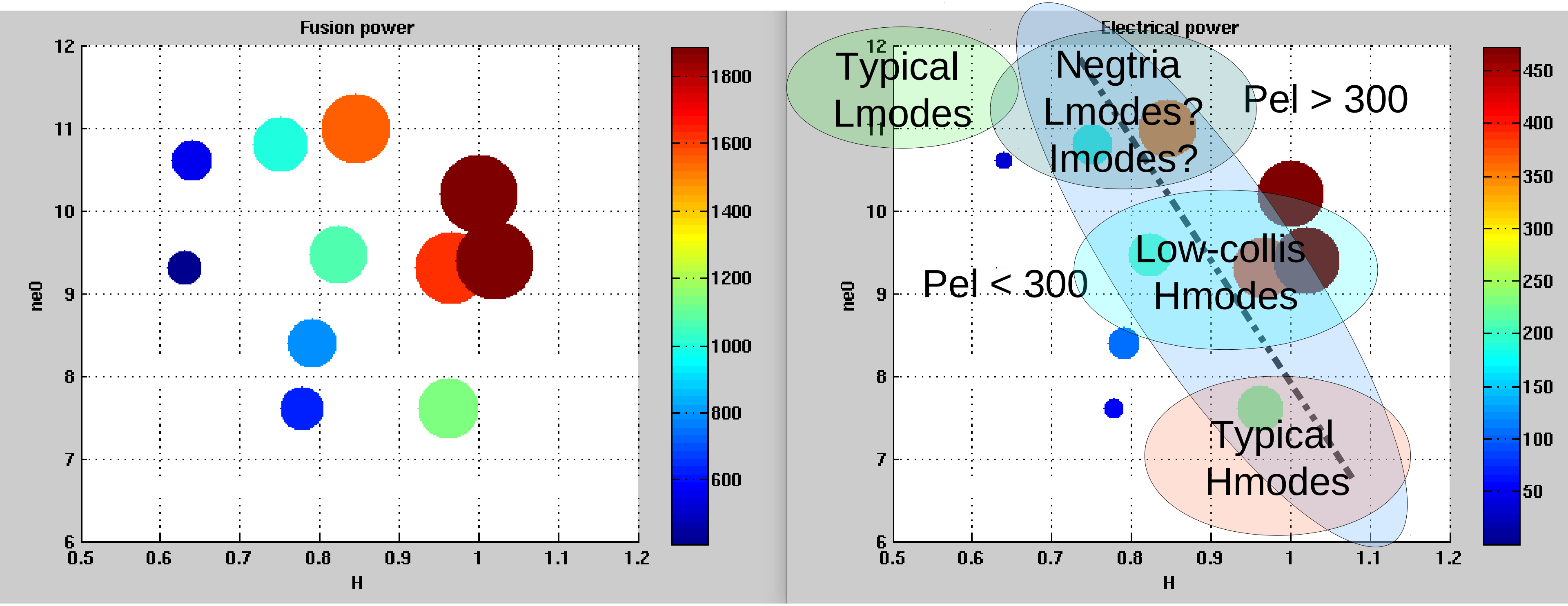

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Approaches to extrapolation towards DEMO

• Given profiles and an H factor, how does one extrapolate to DEMO?

• Does one extrapolate at constant H factor ? **NO**

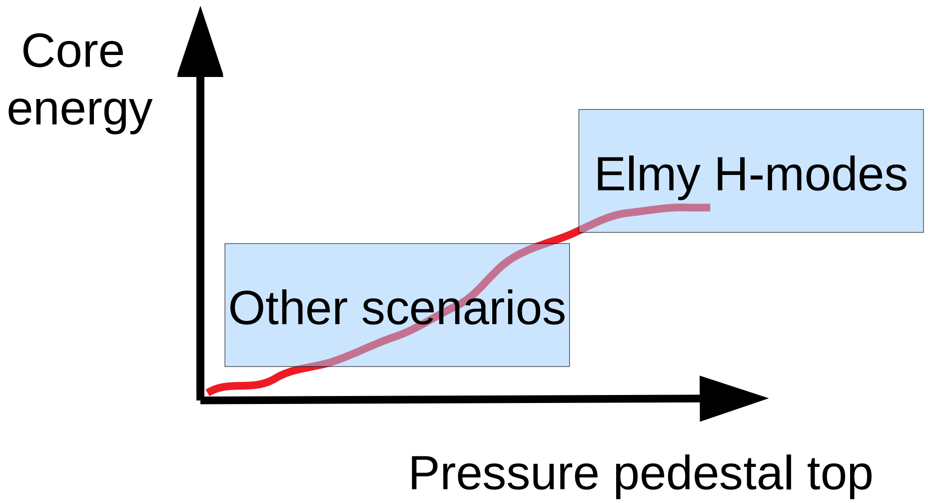
→ experiments claiming H ~ 1 (or larger) on scenarios which are NOT part of the standard H-modes (most standard and boring H-modes) database **cannot** be used for extrapolation

• Does one extrapolate separating *core* and *edge* confinement ? **YES**

→ this approach is the most meaningful albeit the hardest (edge confinement still very much unexplored in its details)

Common knowledge about scenarios

• Years of experimental results show that performance improves monotonically with pedestal top pressure, where the type-I ELMy H-modes tops all:



• This is a gross picture, key details are: ion vs electron pedestal top temperature, pedestal top density, quality of ion energy vs power scaling in the core, effect of line radiation sink and impurities.

• However, it will be assumed that, no matter what, a lower pedestal top ION pressure will lead to a lower fusion output at fixed auxiliary power.

Main scenarios investigated

- Std H-mode:

  > pedestal as b.c. gives a robust basis for core performance, **leads to typical H ~ 1, at least > 0.8**

  > in typical conditions (high power, low radiation, medium density) → **ELMs, not tolerable in a reactor**

  > narrow SOL (in present machines), exhaust could be problematic

  > high core β → MHD

- Std L-mode:

  > no “pedestal”, **no ELMs**

  > larger SOL width, better exhaust, but more prone to radiative instabilities (colder SOL)

  > more difficult to extrapolate since no clear profile characteristics

- Other alternatives: ELM-free H-modes, high confinement L-modes/I-modes, advanced high-β scenarios (but ELMs still a problem?)

This is not a review of scenarios, but rather a scenario-independent guideline on how to extrapolate and then discriminate between scenarios

Reactor relevance and scenarios

- Is the scenario, in terms of physical parameters that are meaningful for extrapolation to a non-existent machine, leading to commercially viable fusion power?

- We define "commercially relevant" fusion power, e.g.
  - * P_{fus} > 1 GW at whatever size
  - * P_{fus} > 1.5 GW for R > ITER

- We characterize a scenario plasma by these parameters:

  > "pedestal" height (value of pressure at r/a=0.9)
  > core gradients (average R/L_T in 0.7 – 0.9)
  > quality of heating (heating normalized to gB factor at 0.9)

$$\hat{Q} = C \frac{Q B^2}{n T^{5/2}}$$

- where C is a constant factor, Q the heating in MW, B the reference toroidal field, n the local density, T the local temperature at 0.9
> T_e/T_i at pedestal and in the core → key to achieve fusion

Physical interpretation of this approach

> “pedestal” height (value of pressure at r/a=0.9): T_{ped}
> core gradients (average R/LT in 0.7 – 0.9): λ
> quality of heating (heating normalized to gB factor at 0.9)

$$\hat{Q} = C \frac{Q B^2}{n T^{5/2}}$$

- Of two scenarios, the one with lower $\hat{Q}$ at the same heating Q displays better confinement properties

- For extrapolation, the correlation λ vs $\hat{Q}$ can be used as metric for the calculation of the fusion power

- H and L modes are characterized based on these parameters independent of the physics mechanism that lead to either regime (that has a whole another level of extrapolation problem behind).

- Compatibility with detachment and “cold edge” not yet demonstrated for not-ELMy H-modes. But promising results in progress...

Relation to identity principles

> The establised paradigm to devise identity matches of plasmas is based on the quantities:

$$\nu, \beta, q, \rho_*, \lambda = f(n, R, B, T, P, I)$$

> perfect match leads to e.g.

$$P \sim R^{-3/4} \quad ; \quad n \sim R^{-2}$$

… which cannot be achieved!

- One has to choose which quantity to sacrifice to have an inverse scaling with size (so that present machines end up with lower power request than DEMO)

- For this we make the following assumptions:
  > if collisionality ν is sufficiently low, it goes into ~ saturation effect, ignore it
  > if ρ_* is sufficiently low, same as for collisionality
  > q is easier to match if the above two are ignored
  > in standard scenarios we ignore electromagnetic effects (ignore β)
  > the remaining parameters which are then chosen to be matched are:
  normalized temperature gradient λ and normalized heat flux $\hat{Q}$

Derivation of identity principles (1)

•

> Exact derivation:

$$\left.\begin{aligned} \nu &\sim nR/T^2 \\ \beta &\sim nT/B^2 \\ q &\sim RB/I \\ \rho_* &\sim \sqrt{(T)}/(RB) \end{aligned}\right\} \quad T(R), n(R), B(R), I(R)$$

$$\left.\begin{aligned} \lambda &= P/(RnT\chi) \\ \chi &\sim \rho_*^2 \sqrt{(T)} R \hat{\chi} \\ \hat{\chi} &= \hat{\chi}(\nu, \beta, q, \lambda) \end{aligned}\right\} \quad \begin{aligned} &P(R, \hat{\chi}\lambda) \rightarrow P(R) \sim R^{-3/4} \\ &\hat{\chi}(\lambda)\lambda = const \rightarrow \lambda = const \end{aligned}$$

- Leads to an inverse dependence which cannot be fulfilled as the power would be larger for smaller sizes.

- n, T defined at pedestal top, λ is normalized T gradient at ped top for core profile

- alternatively: n, T are averages but λ is an average core gradient (excluding pedestal)

New size scaling for “electrostatic collisionless” regimes

> Defined as the following relation:

$$\hat{Q},\lambda=f\left(R,n,B,T,P\right)$$

> perfect match leads to e.g.

$$P\sim\frac{nT^{5/2}}{B^2}$$

> But now we have couples (P,T) which define the same parameter, how to select one?

> to close the problem, we also match the ratio between surface and confinement time, giving

$$\tau=\frac{W}{P}\sim R^2 \quad ; \quad P\sim RnT \longrightarrow \boxed{P\sim nB^{4/3}R^{5/3}}$$

so from DEMO (P = 450 MW, n = 8, B = 5.7, R = 9) one gets for AUG (n=5, B = 2.5, R = 1.65) → **P ~ 5.5 MW**

Derivation of identity principles (2)

•> Exact derivation:

$$\hat{\chi}=\hat{\chi}(\lambda)$$
$$\chi \sim \rho_*^2 \sqrt{(T)} R \hat{\chi}$$
$$\hat{\chi}=const, \lambda=const, \chi=const$$
$$\lambda=P/(R n T \chi)$$

$$\Bigg\} \quad T \sim R^{2/3} B^{4/3}$$

$$\Big\} \quad P(R,n,B) \sim n B^{4/3} R^{5/3}$$

- Leads to a proportional dependence which is of practical implementation

- No physical justification for constancy of χ in m^2/s is actually invoked, since in reality this should be substituted by the criterion:

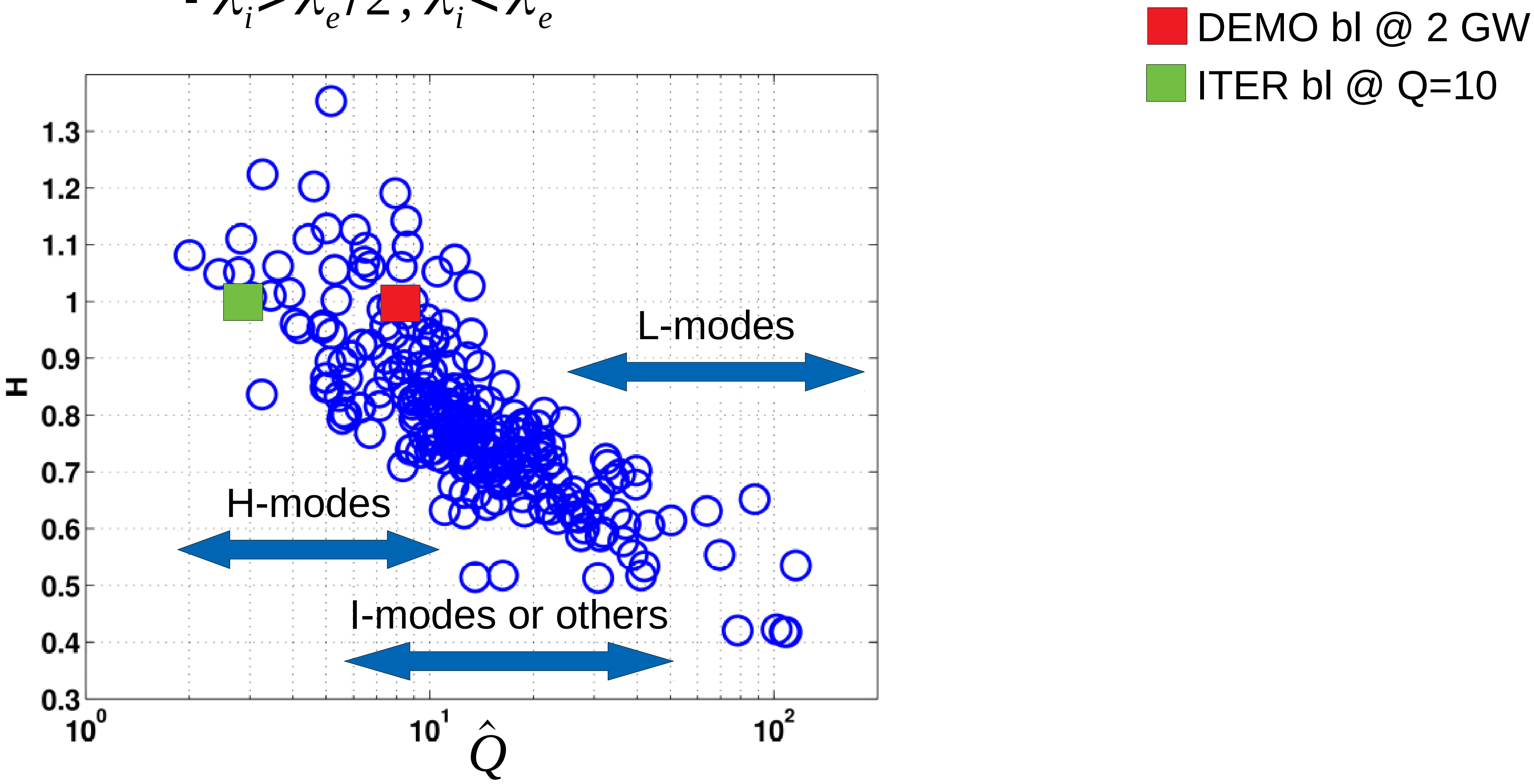
  > Pedestal top pressure consistent with type-I ELMy H-mode scaling

  → P_{ped} ~ scaling to be substituted instead of constant χ

- Since this criterion requires local parameters and precise profiles and pedestal scalings, in the following we use the constant-χ approach

Combining AUG and JET databases

- Putting together a database of std H-modes and L-modes from AUG and JET, and downsampling based on some criterion:
  - $T_e/T_i < 1.1$ at pedestal top
  - $\lambda_i > \lambda_e/2 \,;\, \lambda_i < \lambda_e$

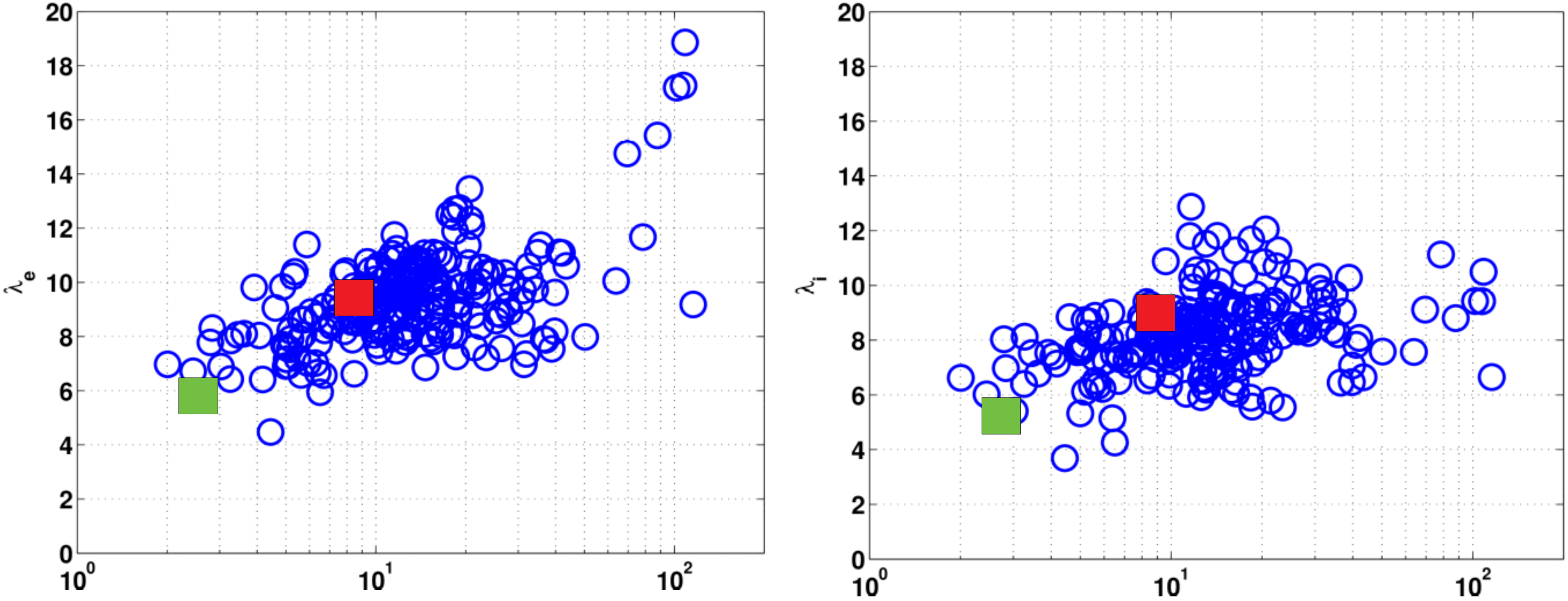


Profile behavior

• Let us look at the local gradients close to the pedestal top

• While in L-mode one could reach quite high electron temperature gradients, that is not the case for T_i

- Reason for ITER being systematically more conservative: similar pedestal as DEMO but at much lower heating and lower expectations (Q = 10 instead of 40)



General observations: electrons

- Higher normalized heating at the edge → higher logarithmic gradients, electrons look like are not very stiff in the region 0.7 – 0.9 and beyond [O. Sauter et al., PoP 2014]

- This is very much scenario independent

- Scatter at similar normalized heating due to variations in collisionality, density profiles, T_e/T_i, impurity content, heating mix, etc etc.

- Scenarios with dominant electron heating but strong equipartition end up in $T_e>T_i$ in the center anyway, but $T_i \sim T_e$ or slightly larger at the edge, but very hard to predict

- Electron pedestal strongly sensitive on local power sinks (radiation) and on the incoming electron heat flux, seems to be easily built up with power in certain conditions (low density, weak radiation)

General observations: ions

- Look more stiff in the near-edge region, harder to increase logarithmic gradient, especially when $T_i < T_e$

- Improvements come from higher Z_{eff} (dilution), rotational shear, magnetic shear / q ratio, $T_i/T_e > 1$

- Ion pedestal very much less characterized than electron pedestal in regimes different from ELMy H-mode

- Not yet clear how this scales with incoming power, T_i/T_e, and other local parameters.

How is extrapolation done then?

• Apart from looking directly at profile behavior, one could ask how to build up the fusion power

• The idea is to assume that the same normalized heating will lead to self-similar profiles. This idea actually is an old one and is used for identity experiments when matching nu, beta, rho*, q. However, the size scaling is negative if all of them are matched. As such, we neglect those and concentrate only on normalized heating

• Assuming that the normalized heating is then due to the choice of pedestal temperature, one can recast it as:

$$T_{ped} \sim \left(\hat{Q}\right)^{-2/5}$$

• And rescale present profiles to match this calculated quantity. Then the fusion power can be computed from the rescaled profiles

• For the density profile, this is rescaled to a pedestal value of DEMO of 0.9 Greenwald fraction

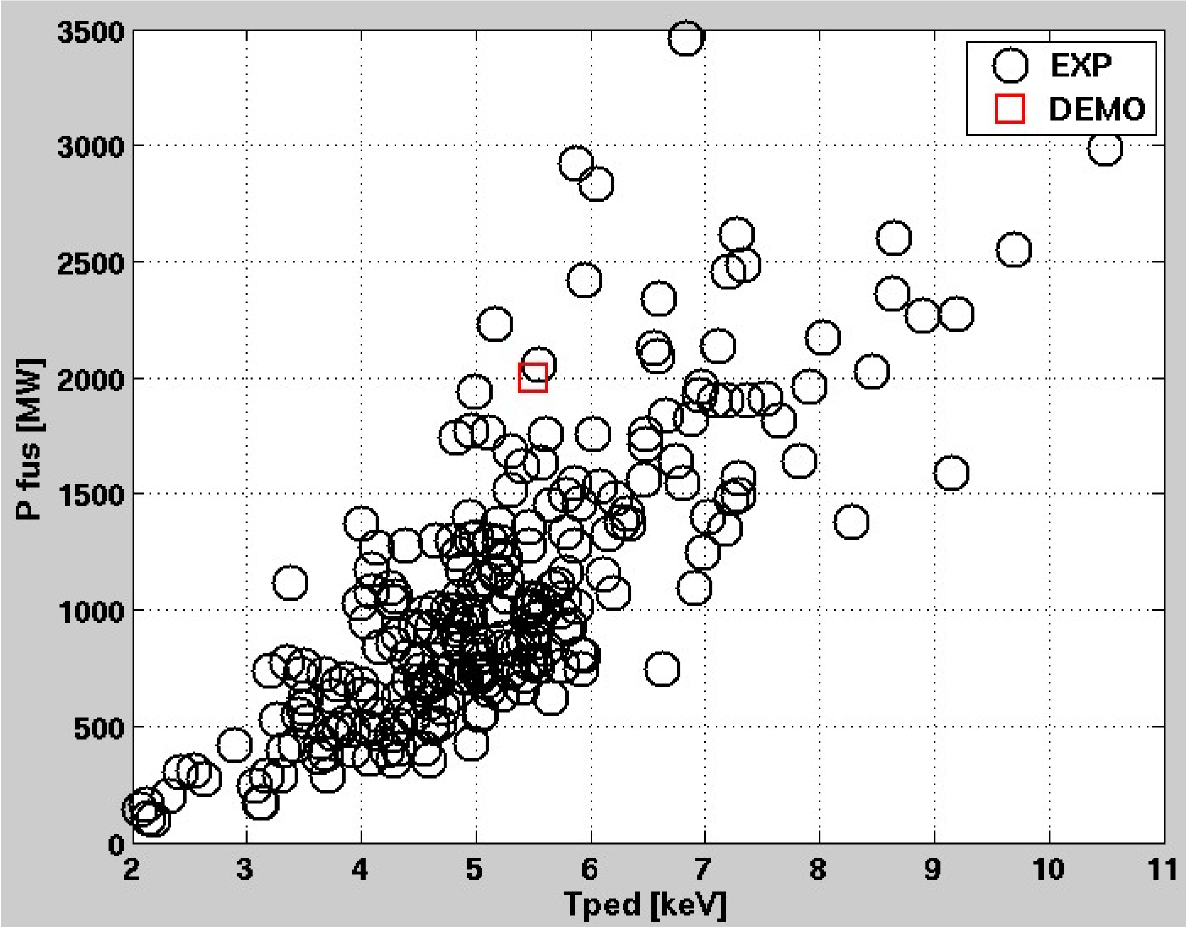
• The absorbed power is assumed to be 150 MW at 0.9 for DEMO and is fixed for all cases

Result of extrapolation

- As expected, present experiments lead to a scaling of fusion power versus pedestal top temperature which makes sense

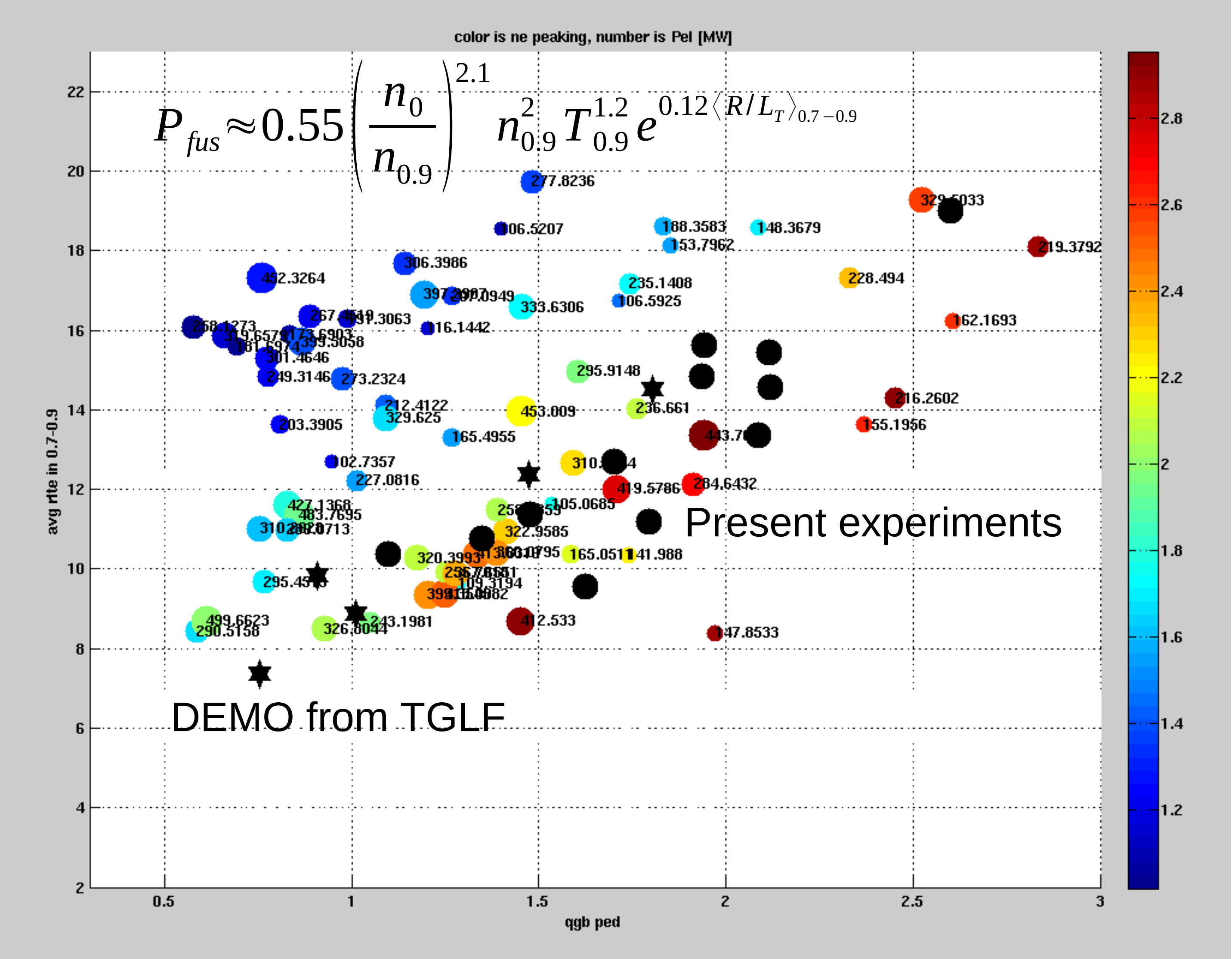
- DEMO lies a bit on the optimistic side

- Pedestals < 4 keV seem to be “unusable”



Where are we with present experiments?

- In the $Q_{gB,ped}$, R/L_{Te}, $n_{peaking}$ space (with fixed $n_{e,ped}$ = 6)



Equipartition in DEMO

• A key parameter to determine quality of confinement is ratio of ion to total heating $\boldsymbol{Q_i/Q}$

• Typical behavior (linked to ITG physics): better ion confinement at larger Q_i/Q ratio (due to ITG becoming less strong as $T_i \rightarrow T_e$ from below)

• An exercise using Fenix (flight simulator @ IPP) for DEMO:

> fixed central electron heating (auxiliary) at 50 MW, scan pedestal top temperature value (from 1 to 6 keV), using TGLF

• The result of this exercise should show how the alpha power builds up from a pre-heated plasma (in the electrons), where the pedestal is an unknown quantity

• It also shows how strong are the temperatures coupled in such conditions

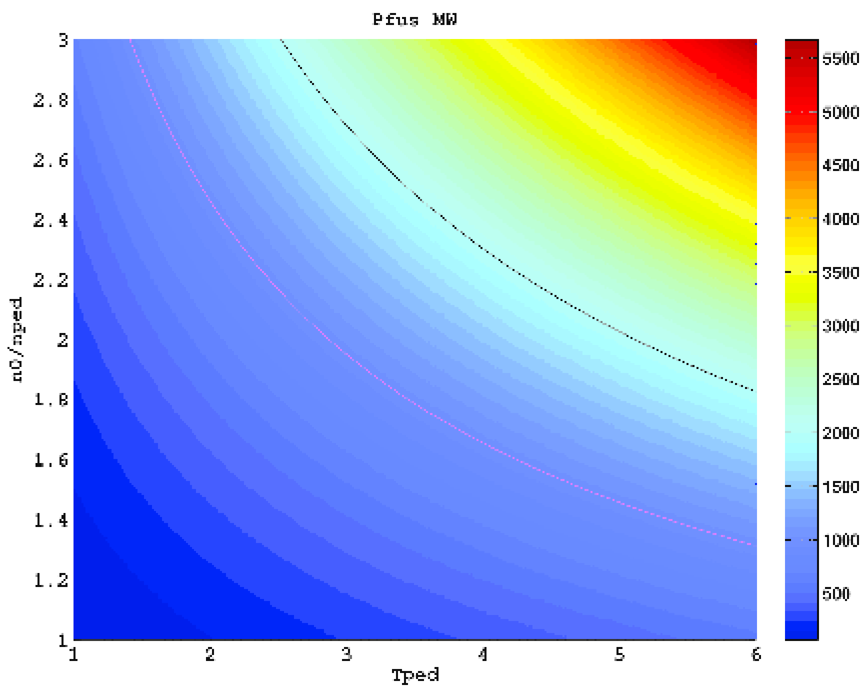
> Result: Q_i/Q at 0.9 is robustly between 0.6 and 0.65 but decreases below 0.5 inwards

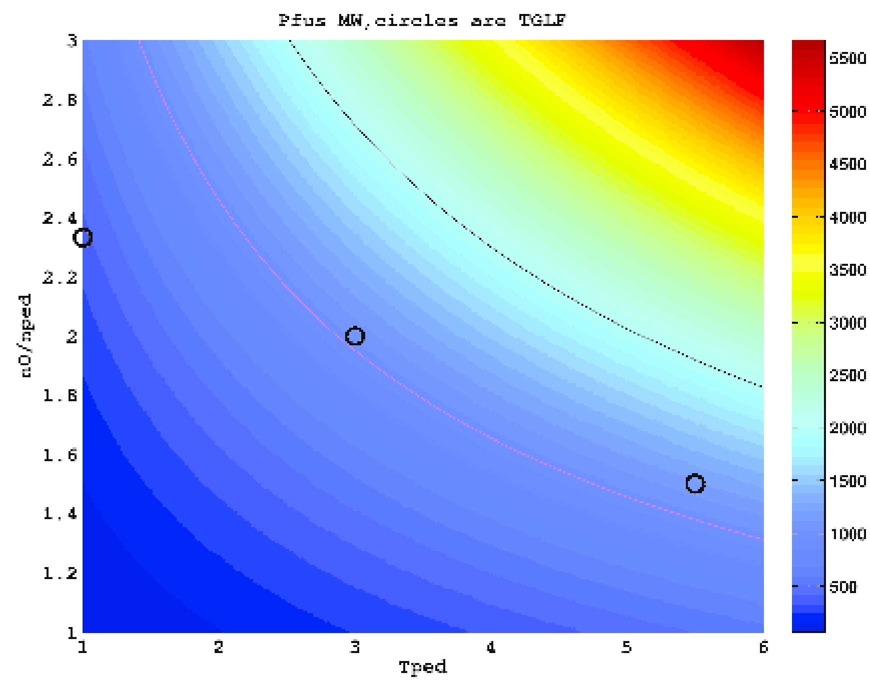
Results of pedestal scan for DEMO

- Use the scaling:

$$P_{fus} \approx 0.55 \left(\frac{n_0}{n_{0.9}} \right)^{2.1} n_{0.9}^2 T_{0.9}^{1.2} e^{0.12 \langle R/L_T \rangle_{0.7-0.9}}$$

- Assume constant ion normalized gradient = 10 and pedestal top density and scan pedestal top and density peaking

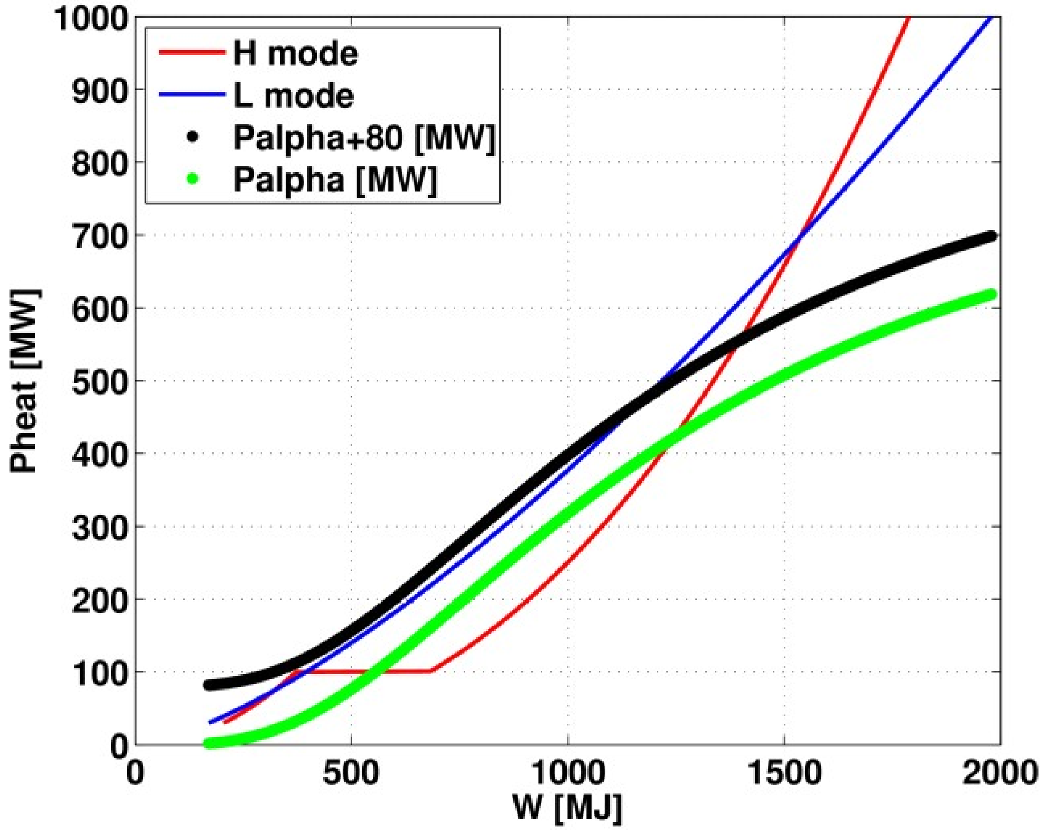




Interlude: alpha power dynamo

- What exactly is the path of alpha power generation in a tokamak plasma?

- Suppose W ~ $P^{0.7}$ in L-mode, W ~ $P^{0.42}$ in H-mode, but with an off-set



Energy scaling in AUG, as well as average temperature

- Rather scenario independent scaling from AUG:

$$W \sim n_{ped}^{0.6 \div 0.7} T_{ped}^{0.2 \div 0.3} P_{heat}^{0.2 \div 0.3}$$

- Similar scaling for ions and electrons (but critically depend on equipartition of P_{heat} between the species)

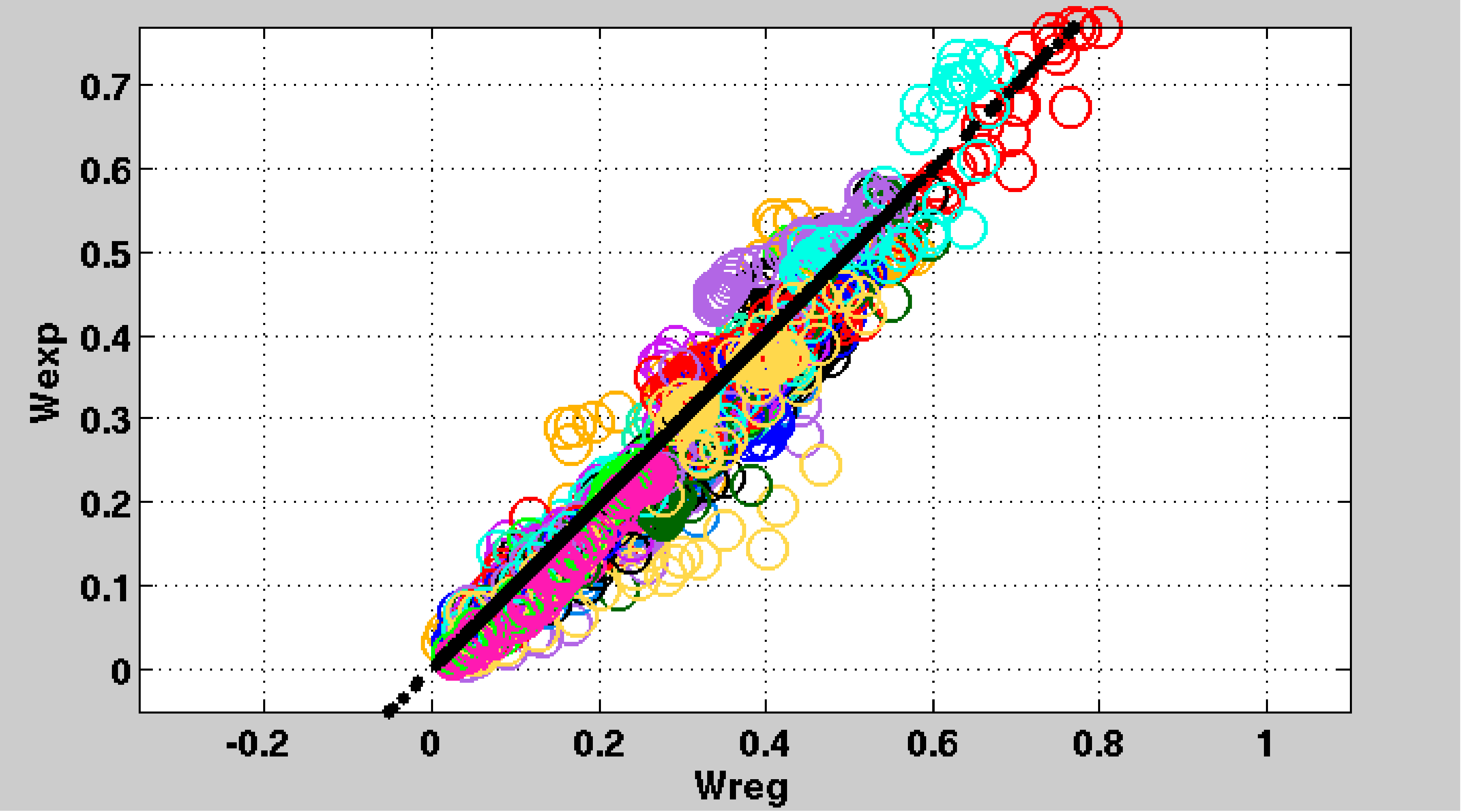
- Core average temperatures (assuming $n_{avg} \sim n_{ped}$):

$$T_{avg} \sim \frac{T_{ped}^{0.2 \div 0.3} P_{heat}^{0.2 \div 0.3}}{n_{ped}^{0.3 \div 0.4}}$$

- Displays a general improvement with density and a weak power dependence, as well as pedestal top temperature.

Energy scaling in AUG, plot

$$W \sim n_{ped}^{0.6\div0.7}\,T_{ped}^{0.2\div0.3}\,P_{heat}^{0.2\div0.3}$$



Alpha power dynamo from AUG exps

- Put experimental data in an "alpha power" formula using as reference the 5.5 MW found before:

$$T_{avg}=\frac{1}{3}\frac{W}{N}$$

$$P_{\alpha}=P_{\alpha,0}\left(\frac{n}{n_{ref}}\right)^2\frac{\sigma_{DT}(T)}{\sigma_{DT}(T_0)} \quad ; \quad T=\frac{T_{avg}}{T_{ref}}T_0$$

$$T_0=22\,;n_{ref}=5\,;P_{\alpha,0}=5.5\,;T_{ref}=1.55$$

> (if T_i was available, replace T_{avg} with $T_{i,avg}$)

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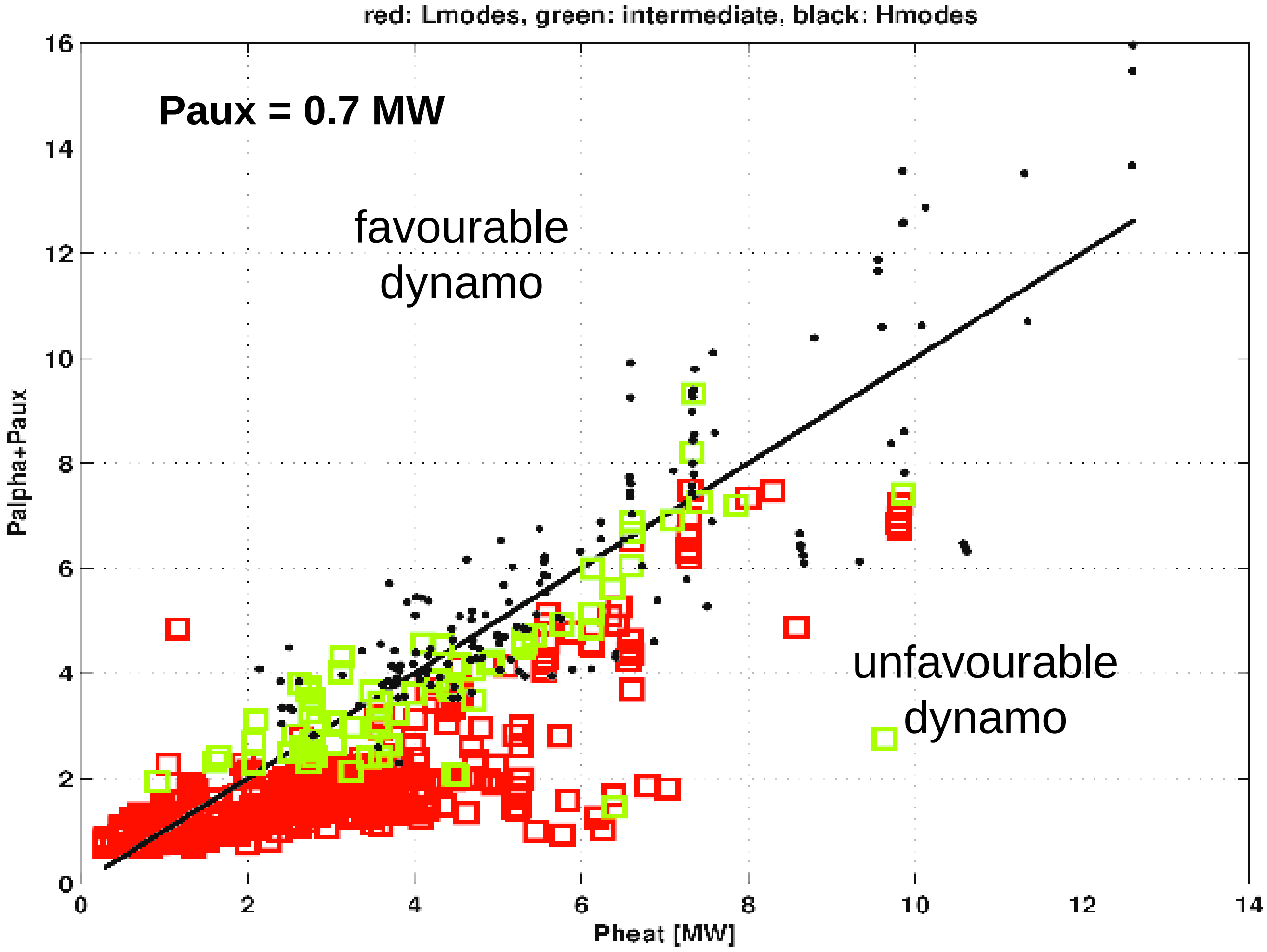
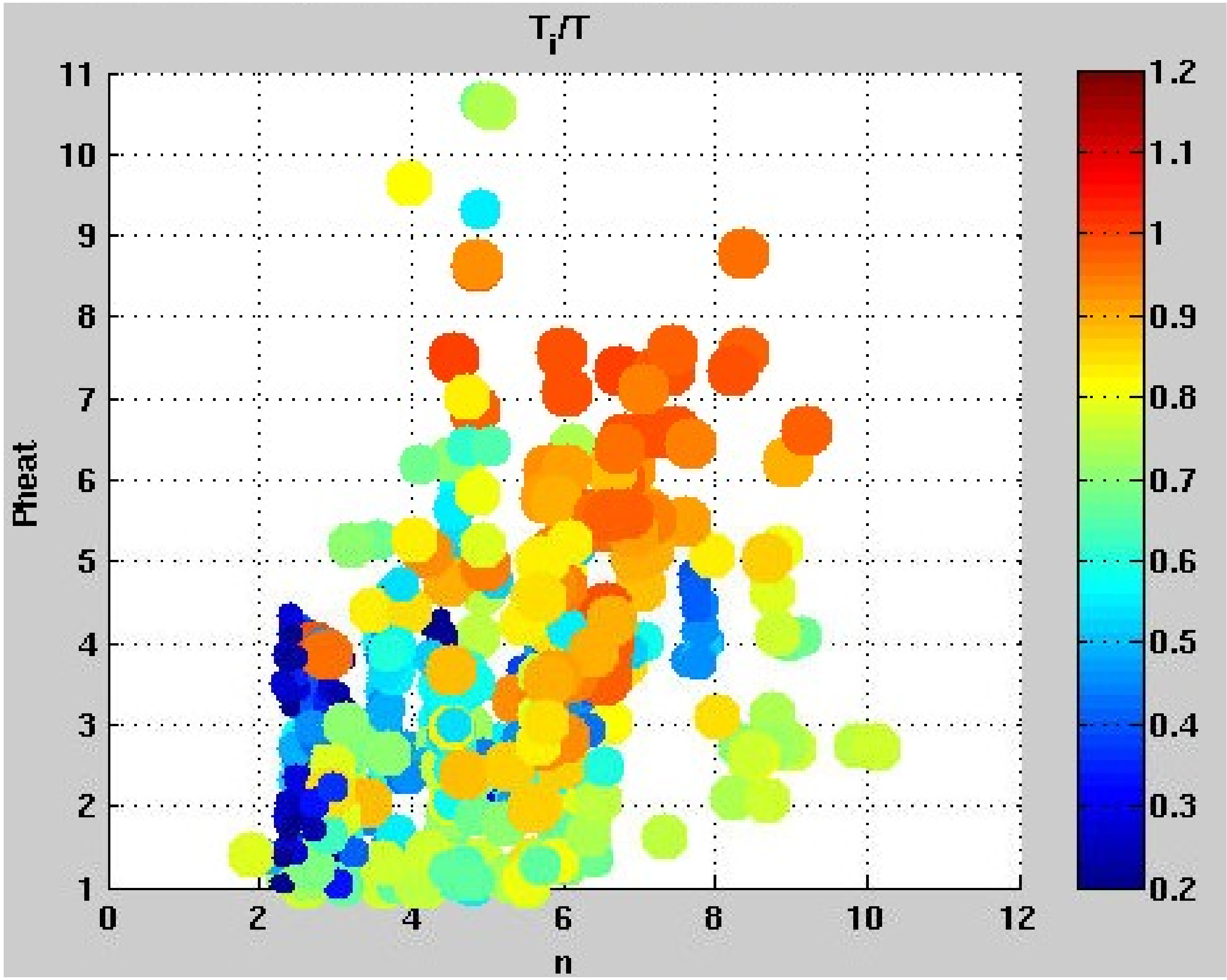


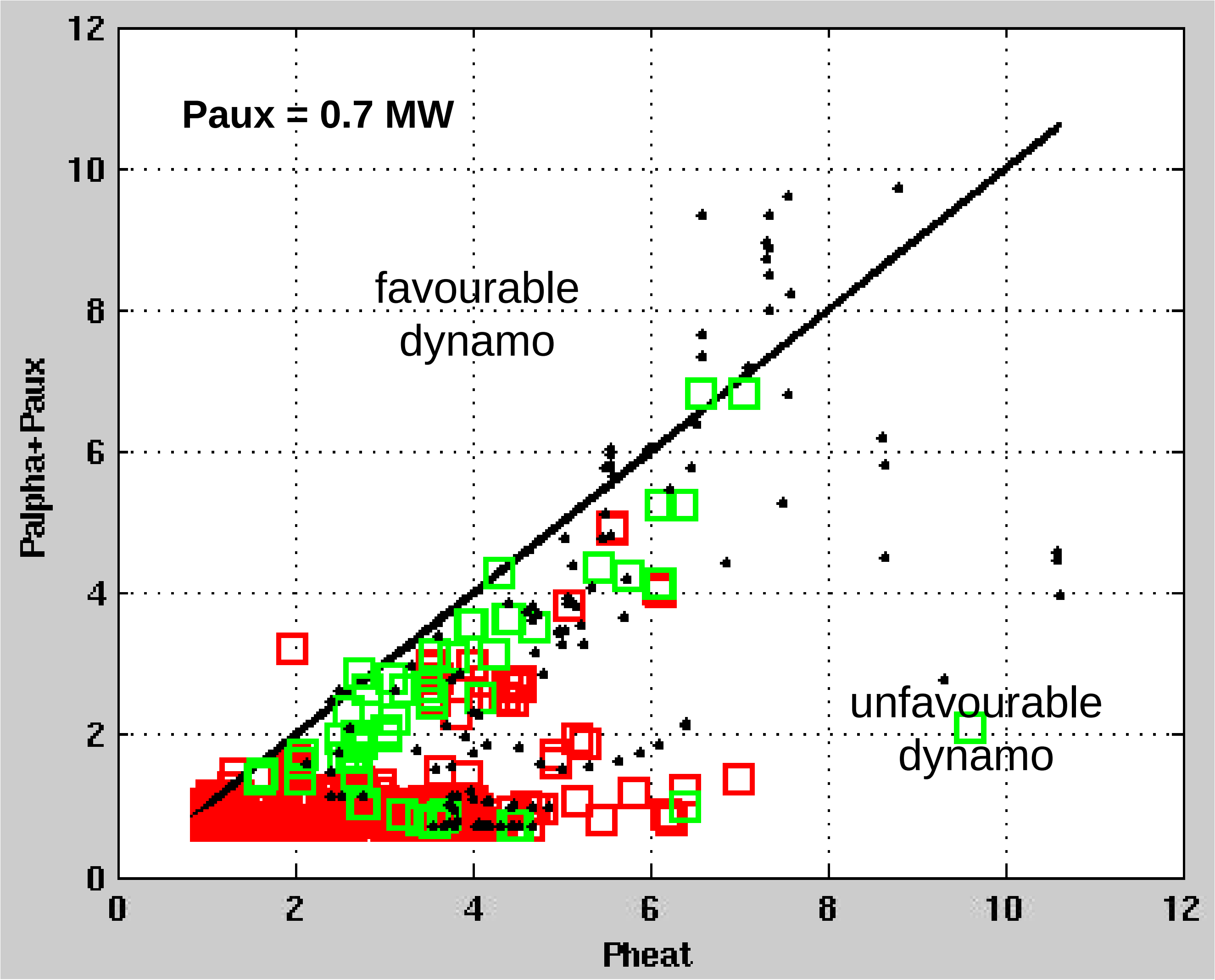
Behavior of T_i w.r.t. T

- Notice that for P > 4 MW its NBI for most cases

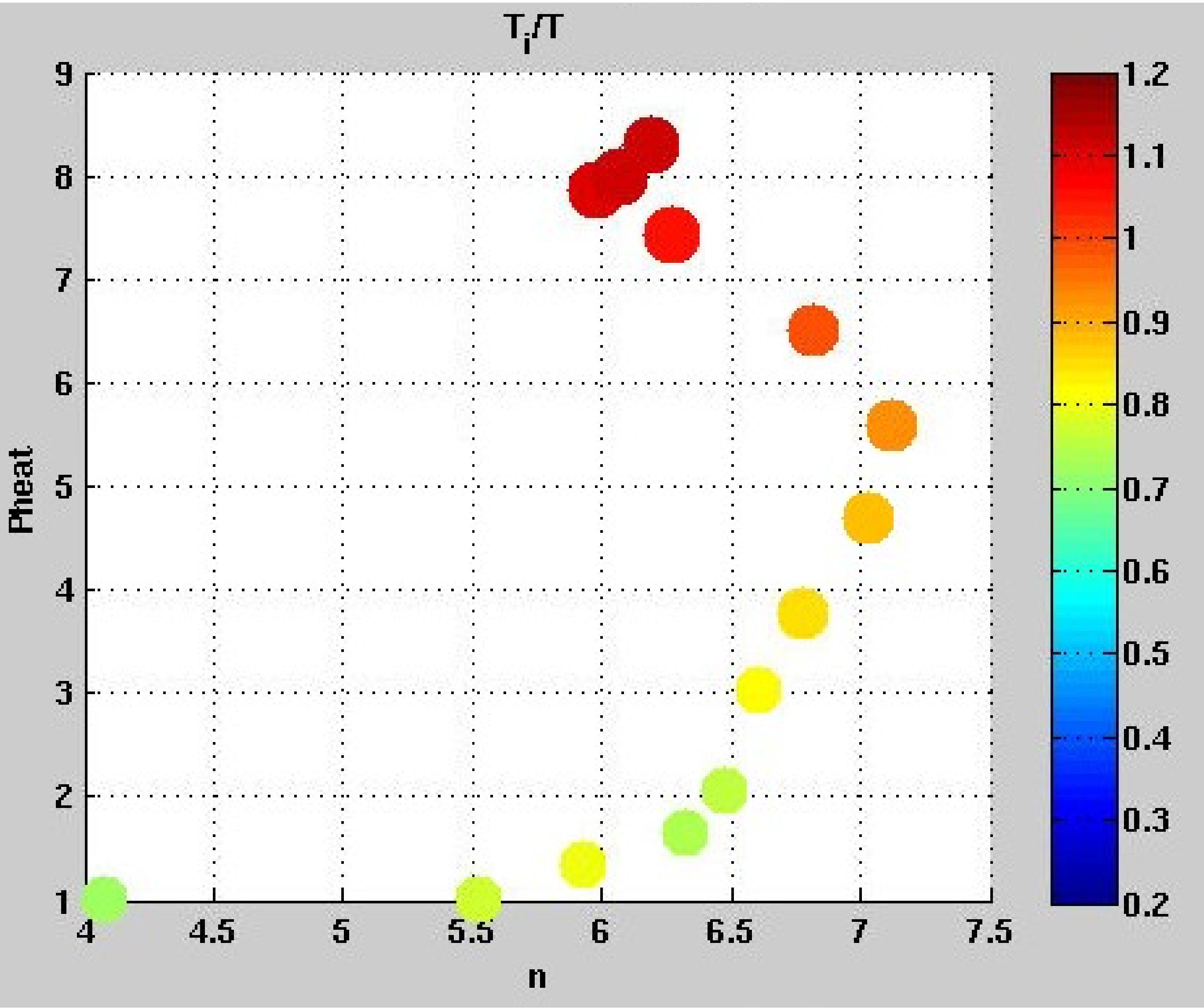


Downselect to $T_i/T_e < 1$.

- Using T_i

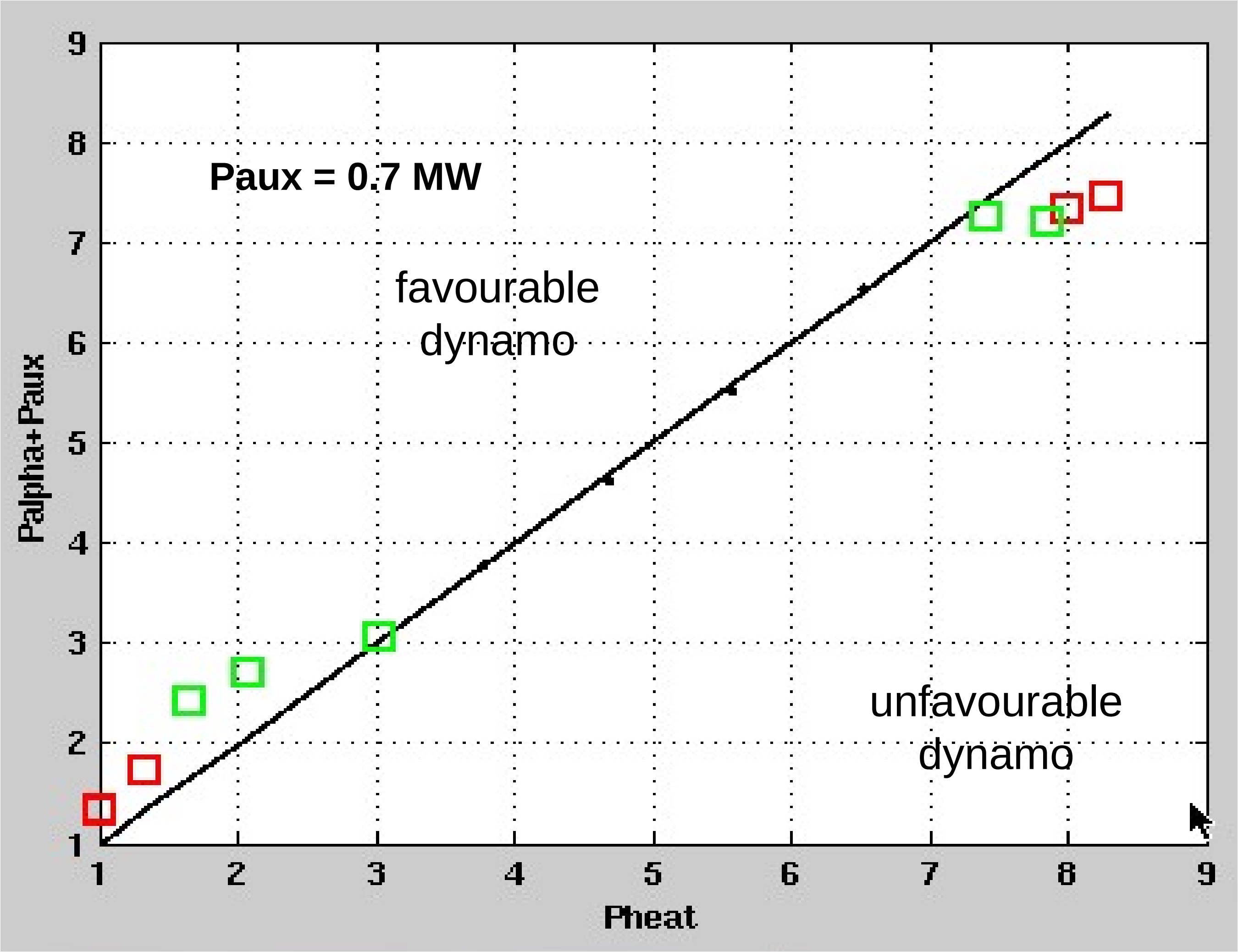


Evidence radiative scan in H-L mode



Evidence radiative scan in H-L mode

- Using T



Evidence radiative scan in H-L mode

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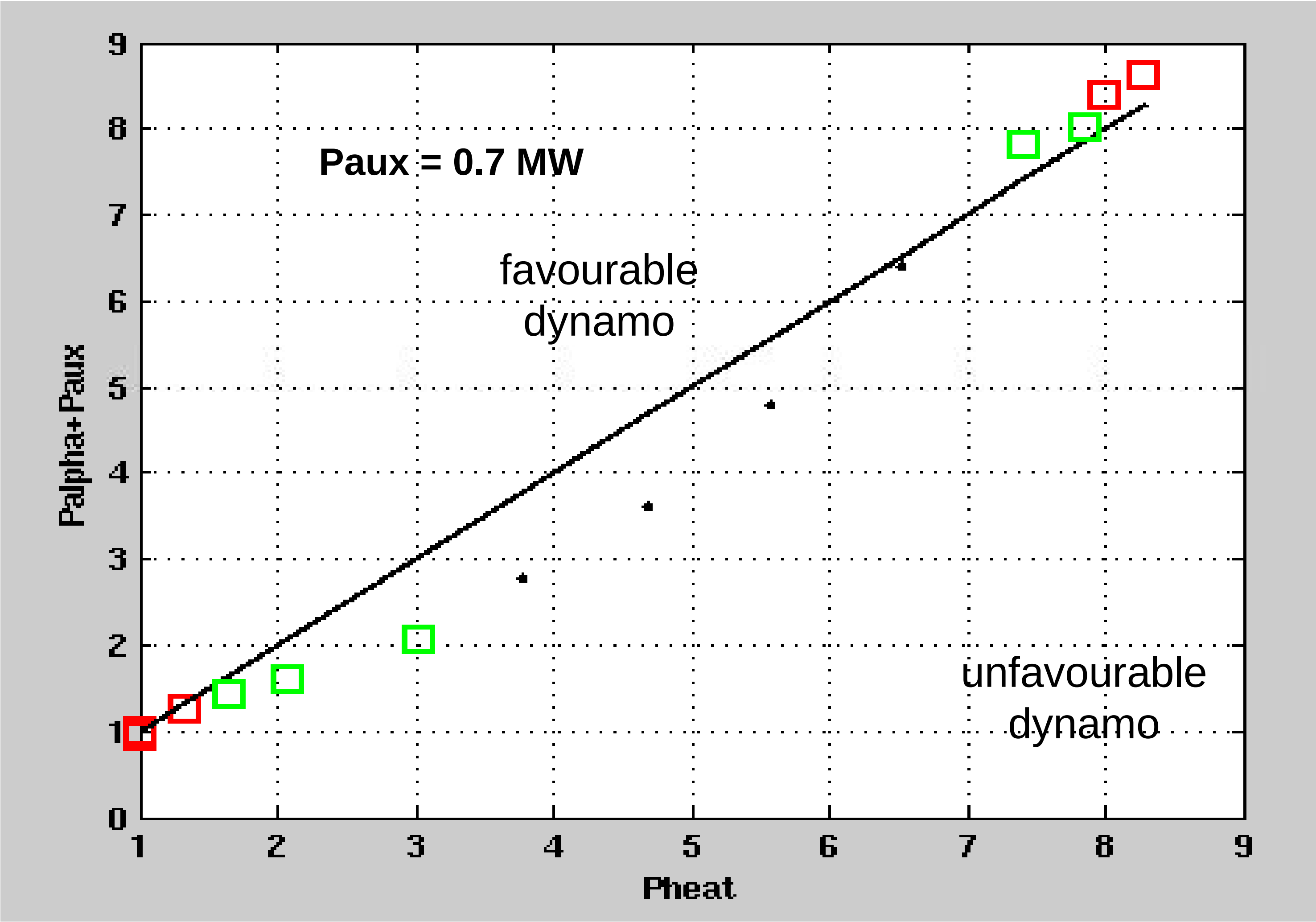

Conclusions and outlook

• Alternative no-ELM scenarios (where the pedestal is maintained at a lower level w.r.t. the peeling-ballooning limit) are becoming more and more studied due to untolerable heat loads due to type-I ELMs in std H-modes

• In general, one can devise a way to extrapolate based on present observations even if the physics is not yet completely understood, assuming a basic constancy of the gyro-Bohm power ratio.

• The main problem remains how to extrapolate the pedestal height if the regime is not in the standard “EPED-applicable” type-I ELMy H-mode

• Not only, but the temperature ratio in a highly radiative regime, and its impact on edge turbulence are not yet fully studied

• From the pedestal inside instead, we can safely use established transport model like TGLF

Proper extrapolation

```
Tdemo=13; Tfusref=22; ndemo=8;
bdemo=5.7; rdemo=9;
Pdemo=450;pauxdemo=50;

baug=2.5;raug=1.65;

C1=Pdemo/(ndemo*Tdemo.^(5/2))*bdemo^2;  % constant gB flux
C2=Pdemo/(rdemo*ndemo*Tdemo);  % constant chi

Tref=(C2/C1)^(2/3)*raug.^(2/3)*baug.^(4/3);
Pref=C2*Nas*raug*Tref; paux=Pref/9.;

palf0=Pref-paux;
T=Tfusref*Tavg/Tref;
g=svdtt(T);
pafaz=palf0.*g/svdtt(Tfusref);
ptotpr=pafaz+paux;
PDEMO=ptotpr./Pref*Pdemo;
PTDEMO=ptotas./Pref*Pdemo;
PDEMOA=PDEMO-pauxdemo;
```

Investigation of edge velocity shear generation with NBI for QH-mode in DEMO

E. Fable

MPG-IPP Garching

Acknowledgments: P. Vincenzi (CNR, RFX Padova, IT) for NBI input data

KDI#8 final meeting, 1 July 2020

DEMO QH-mode scenario 2019

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  Ip = 18.21 MA

  n_{avg} ~ 8.5 * 10^{19} m^{-3}

  k = 1.7

  triang = 0.33

- P_{aux} ~ to be calculated MW

- P_{fus} ~ 2 GW

Physics to be investigated

- QH mode requires a certain velocity shear to be triggered
  [A. M. Garofalo et al., NF 2011]

- Basically, ExB shear > (value), linked to edge MHD (i.e. Alfvén speed)

- The dimensionless criterion chosen here is (0.16 is obtained from DIII-D formula applying DIII-D minor radius):

-

$$\frac{a}{V_A} a \frac{d\Omega}{dr} \approx 0.16 ;$$

$$V_A = \frac{B}{\sqrt{(\mu_0 n M)}} ; \qquad E_r = B_\phi (V_{dia} - V_\theta) + B_\theta V_\phi$$

$$\Omega = \frac{E_r}{R B_\theta} = \frac{B_\phi}{R B_\theta}(V_{dia} - V_\theta) + \frac{V_\phi}{R} = \frac{q}{r}(V_{dia} - V_\theta) + \frac{V_\phi}{R} ;$$

- where *a* is the plasma minor radius, *r* is the local minor radius

- Note that V_{dia} is large and negative, i.e. it is much more convenient to inject counter-current toroidal rotation rather than co-current

Value for DEMO

- Applying the criterion for DEMO we get (w_{ped} = 15 cm):

$$\frac{a}{V_A} a \frac{d\Omega}{dr} \approx 0.16; \qquad \frac{d\Omega}{dr} \approx \frac{\Omega}{w_{ped}}$$

$$\rightarrow \Omega \approx 2.55 \cdot 10^4 [rad/s] \rightarrow V_E \approx -19\, km/s$$

- First estimate of "natural" (i.e. without rotation) edge shear is
  V_E ~ - 8 km/s

- Missing ~ -10 km/s of perpendicular rotation, that is ~ - 120 km/s of toroidal rotation which have to come from NBI counter-current injection (or ~ + 360 km/s from co-current torque)

- So... how much torque is required to drive ~ -120 km/s of pedestal top rotation?

- Assuming that the angular momentum confinement time in the edge is the same as the energy confinement time, this would mean a torque of:

Torque for DEMO

- So... how much torque is required to drive ~ -100 km/s of pedestal top rotation?

- Assuming that the angular momentum confinement time in the edge is the same as the energy confinement time, this would mean a torque of:

- $$S \chi_\phi n R M \frac{V_\phi}{w_{ped}} = T_\phi$$

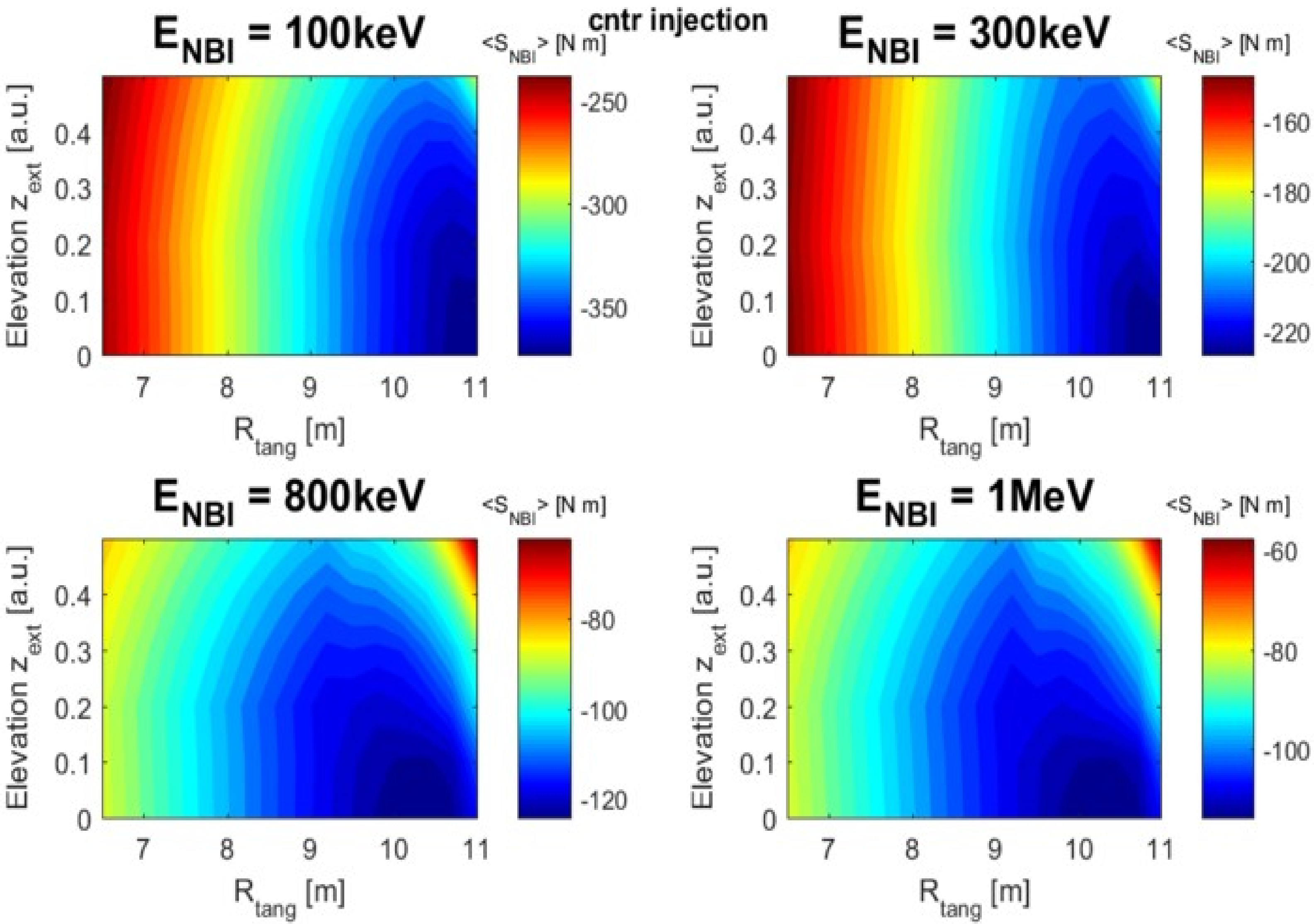
$$S = 1320[m^2]; \quad \chi_\phi \approx 0.25; \quad n = 4.2$$

$$T_\phi [Nm] \approx 400 [Nm]$$

- very rough calculation, to be done with ASTRA properly.

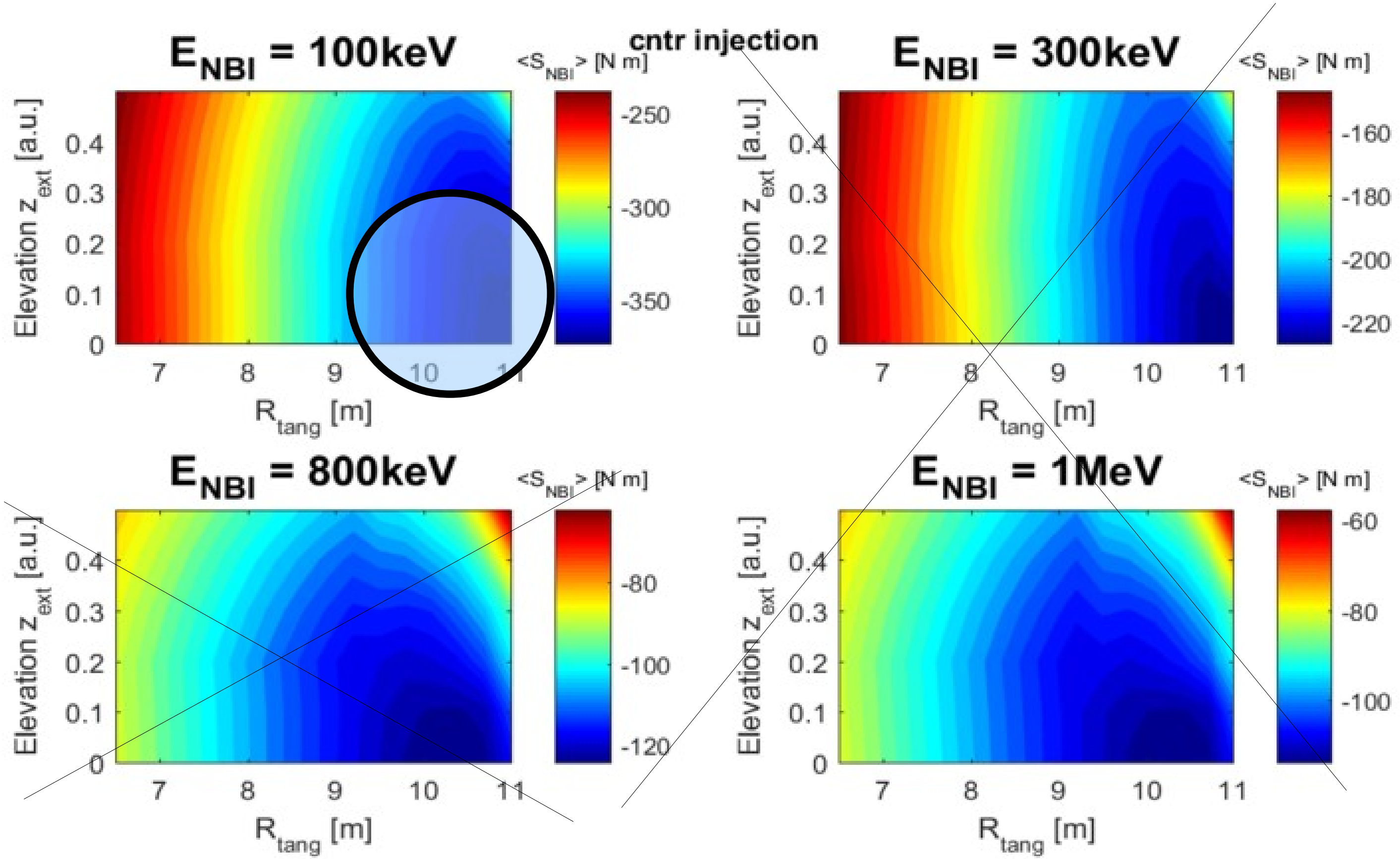
- Result: confirmed by ASTRA

Results from P. Vincenzi @ 76 MW



Operational space @ 76 MW

- very narrow operational space
- expect linearity in power, which would make e.g. 300 keV available @ 140 MW



Discussion

• If a dimensionless parameter for the QH mode entrance is assumed, for DEMO this leads to a certain requirements in edge radial electric field shearing

→ as already mentioned by Pietro, needs large torque

• Since DEMO naturally has already a rather large counter-current ExB rotation, to reach the desired value it is better to inject counter-current torque to add the remaining rotation on top of the natural rotation

• This remaining counter-current rotation/torque is estimated and is the ultimate result of the study. The relation by torque and power is provided by the work done by P. Vincenzi

• Regarding pedestal rotation vs torque, the model assumes a pedestal confinement time which is the same in angular momentum as well as in ion energy, and given by the local transport coefficients

→ to check against experimental evidence

Conclusions & outlook

- The chosen criterion is just the DIII-D one times a machine size to make it dimensionless → absolutely no first principles here

- It could be that the reality is more favourable (more unfavourable means no QH-mode)

- Present results show that with the assumptions used here the required torque is at the limit of the lowest energy, highest tangency radius cases done by Pietro.

- Main things to improve:
  - QH criterion
  - pedestal transport model for toroidal rotation