The operational space of ASDEX Upgrade identified by separatrix conditions

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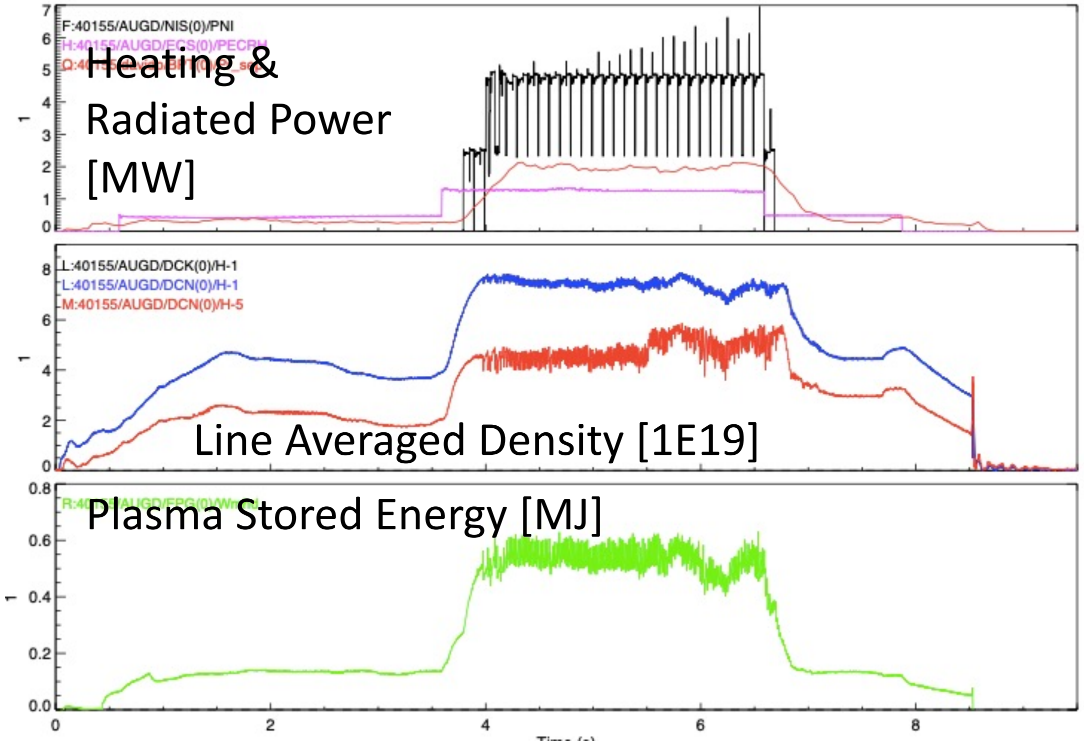
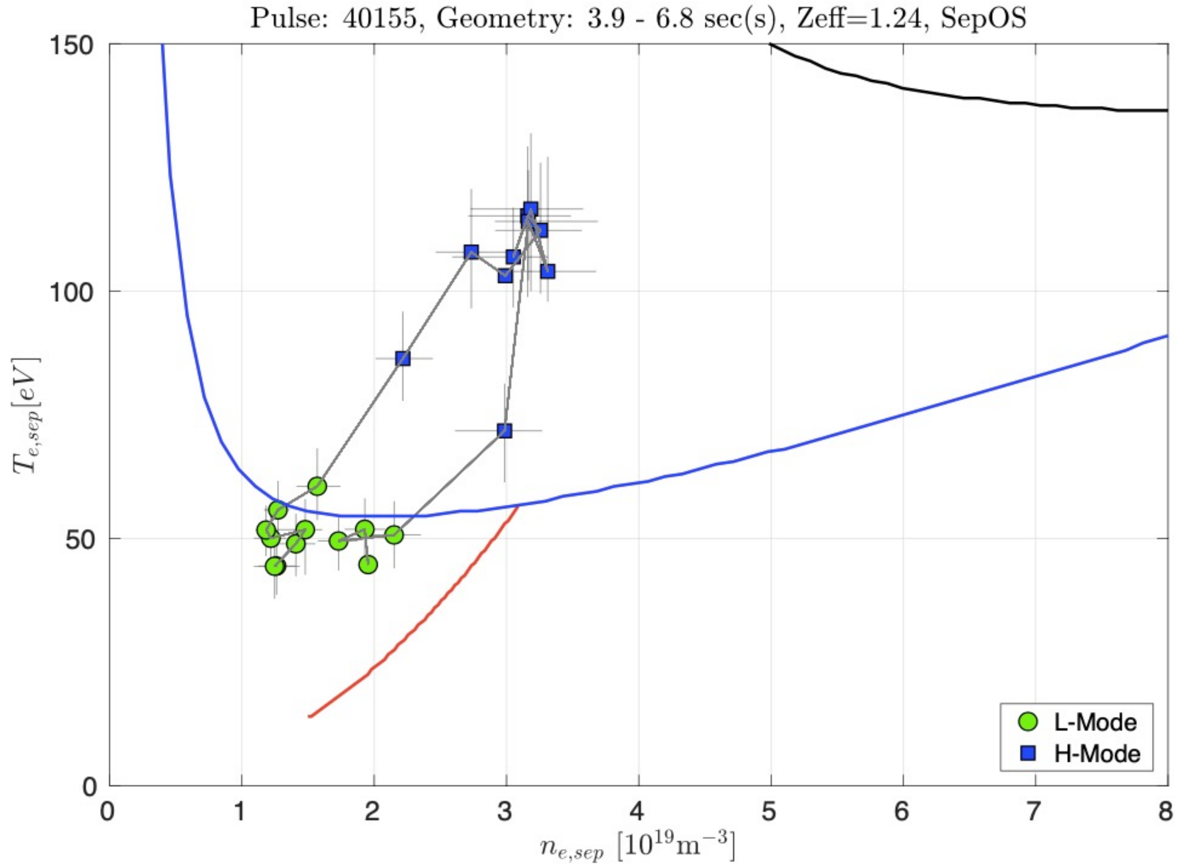
Separatrix $n_{e,sep}$ / $T_{e,sep}$ diagram, (#40155) L-H-L

- Separatrix position is numerically estimated solving Spitzer-Härm power balance (2PM) with Edge Thomson data

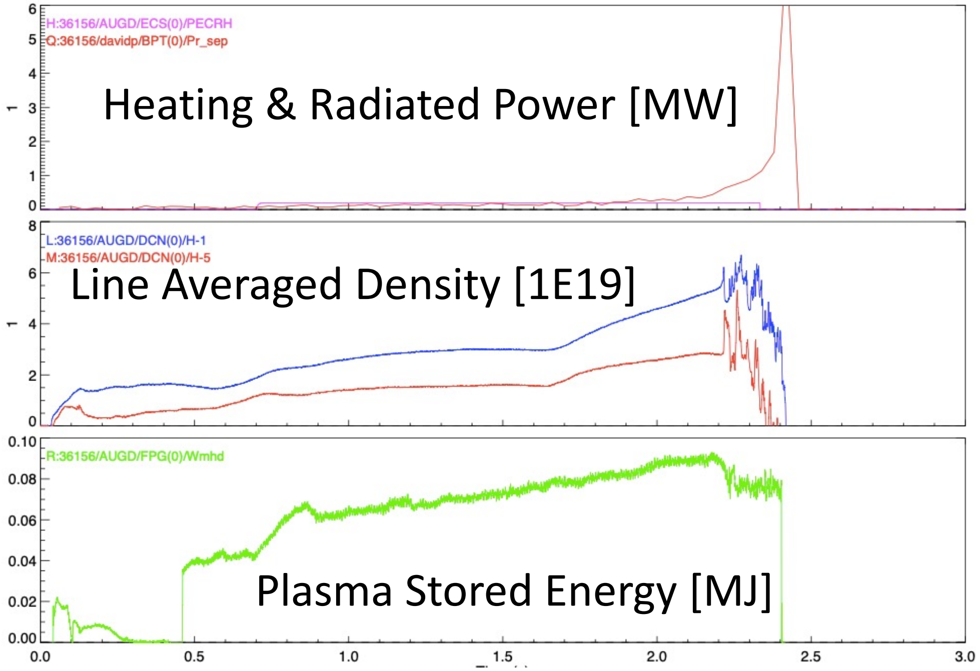
$$T_{e,sep} \approx \left(\frac{7\, P_{sep}\, \hat{q}_{cyl}^2 A}{16\, \kappa_0^e\, \hat{\kappa}\, \lambda_q} \right)^{\frac{2}{7}} \qquad \text{with} \qquad \lambda_q = \frac{2}{7} \lambda_T$$

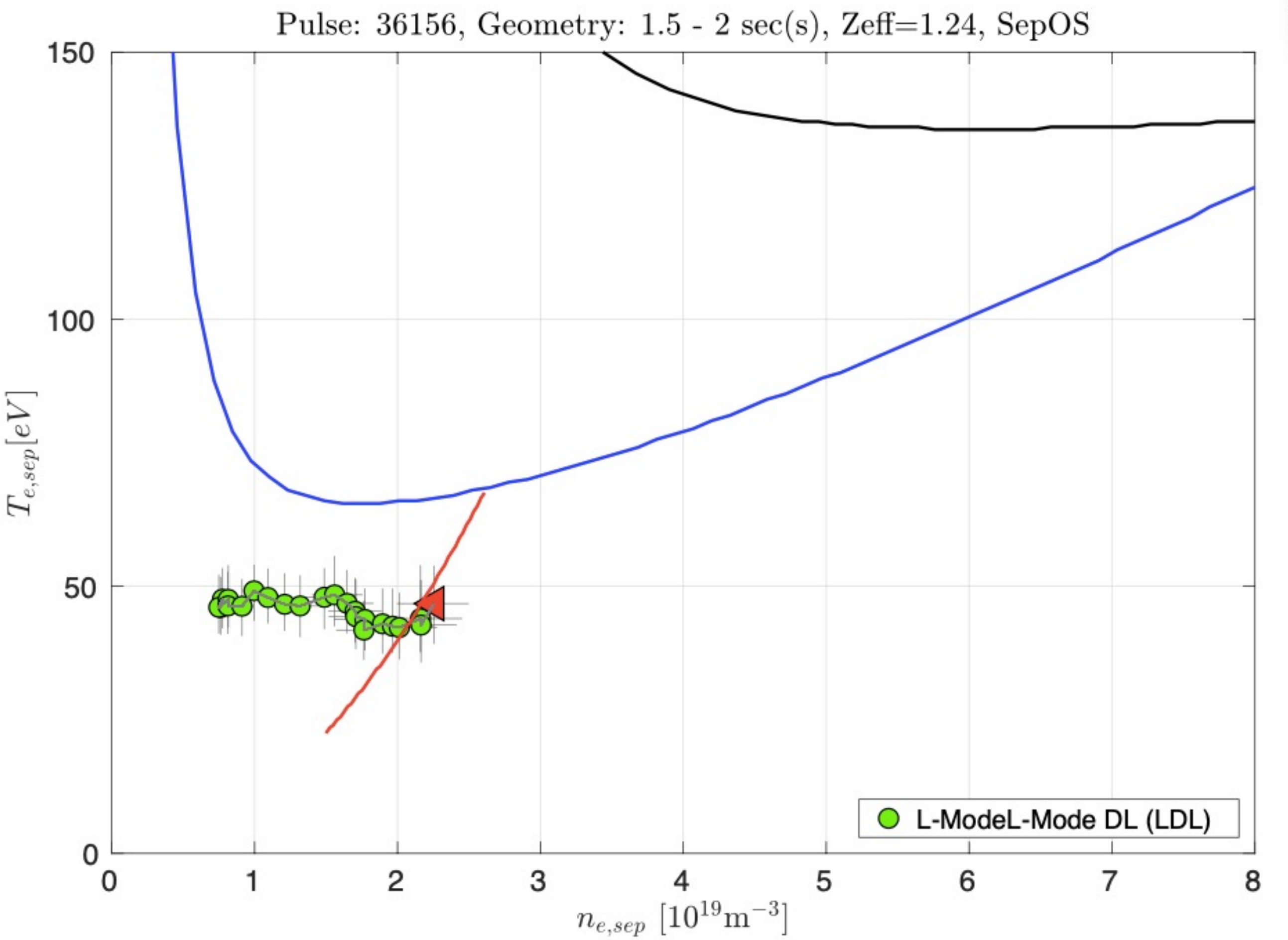




Separatrix $n_{e,sep}$ / $T_{e,sep}$ diagram, (#36156) L-Mode DL

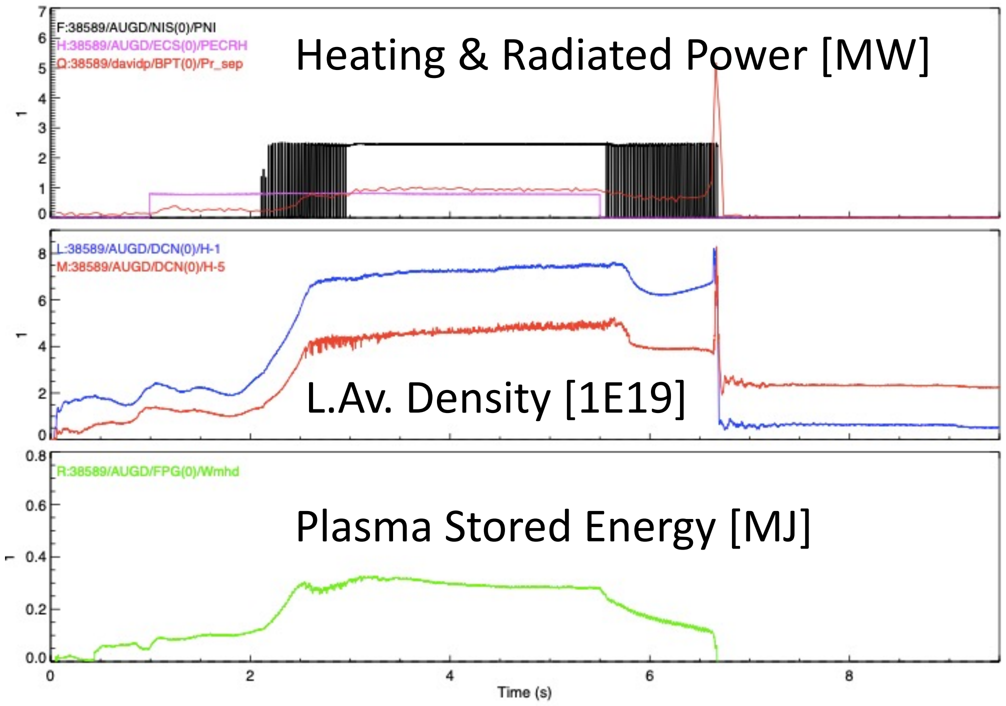
- L-Mode DL observed when ‚red' line is trespassed (not necessarily hit)

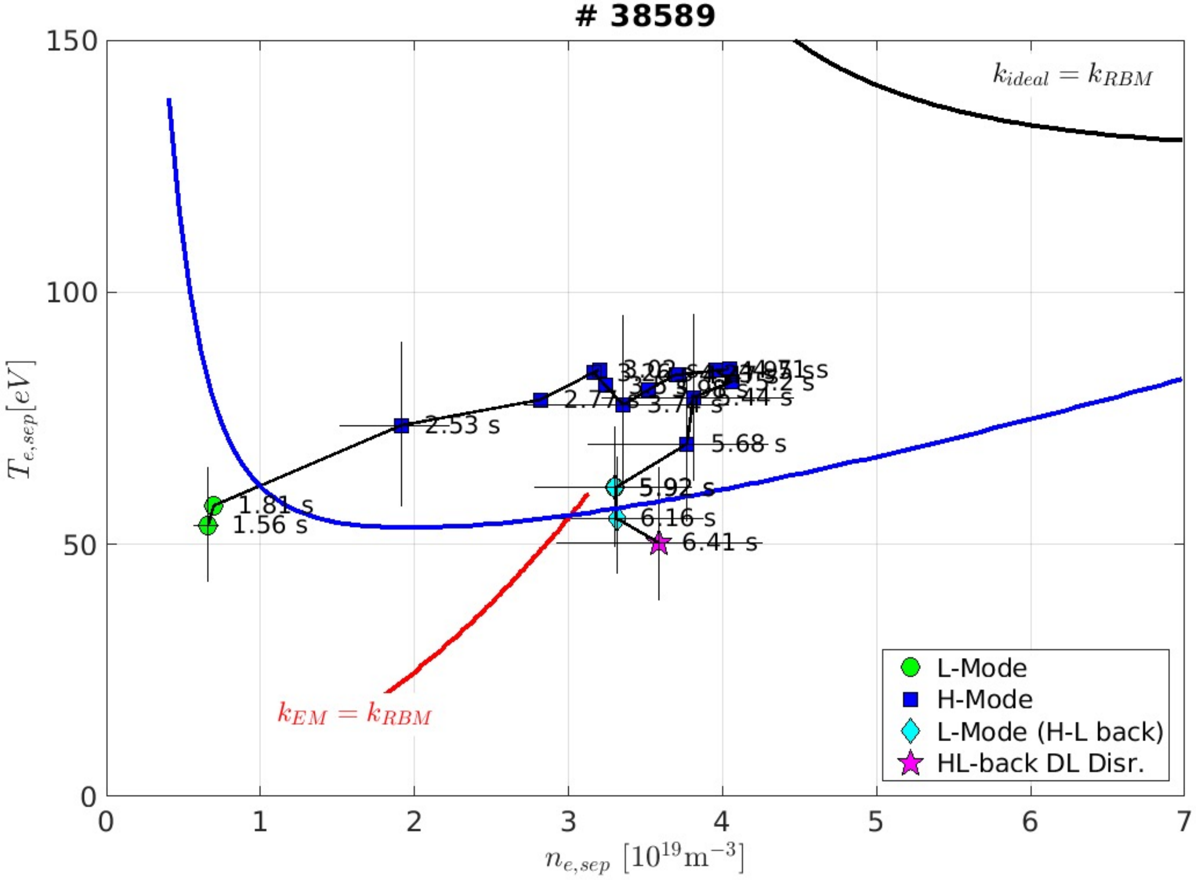




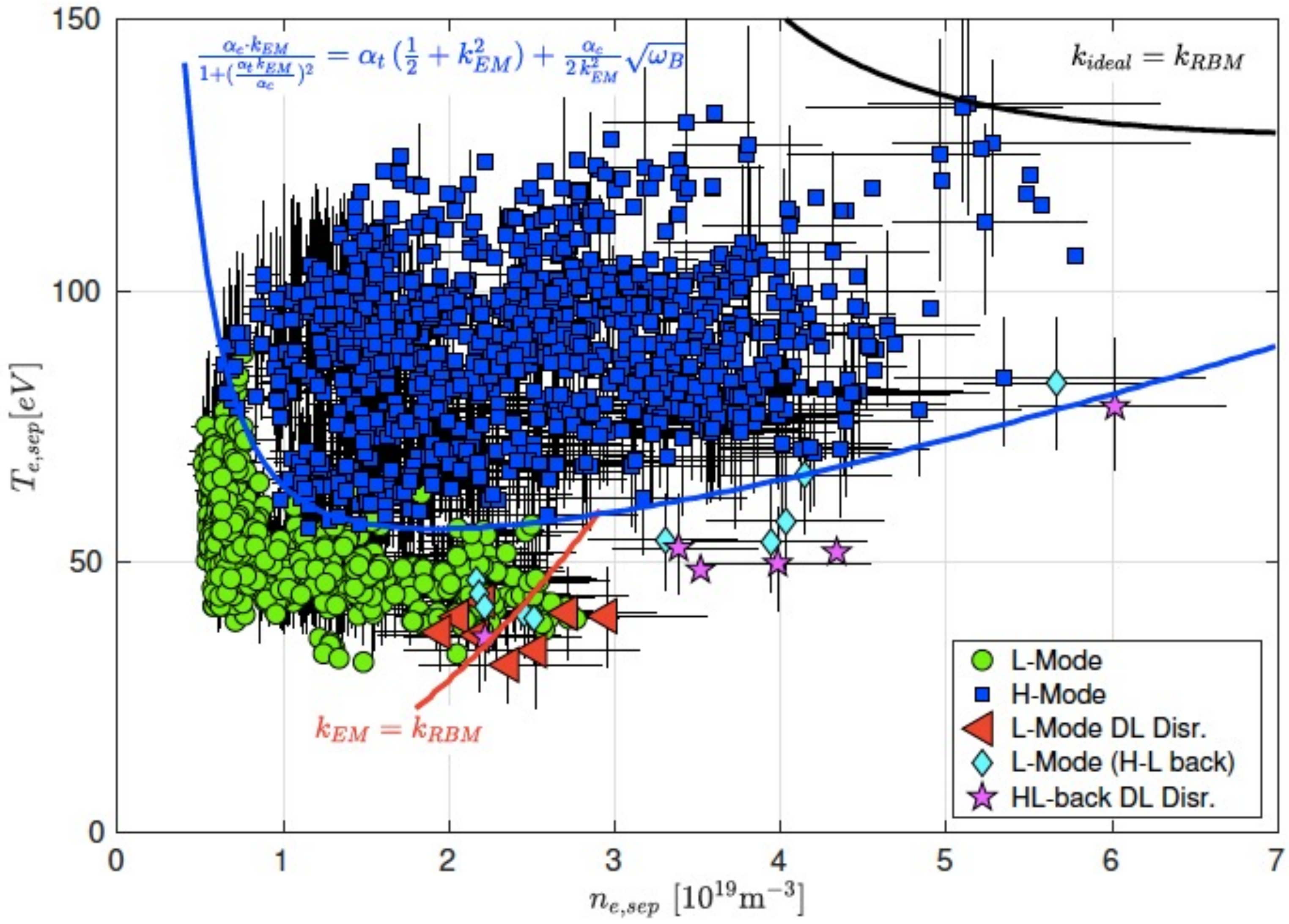
Separatrix $n_{e,sep}$ / $T_{e,sep}$ diagram, (#38589) L-H-L disruptive

- Disruptive L-H-L transition observed when back transition is ‚right' of red line





The separatrix operational space for 0.8MA, -2.5T, LSN



- Black Line: Ideal-Ballooning
- Red Line: L-Mode DL
- Blue Line: L-H / H-L Transition

- Disruptive discharges are ‚right' of the red line and ‚below' the blue line

- T_i=T_e is assumed

- Data: #123, 1881 data points

Definitions of characteristic wavenumbers

- Wavenumbers are derived from DALF system (B.Scott). Work highly motivated by B.LaBombard (NF05) & RDZ PRL'98

$$\alpha_t = 3.13 \cdot 10^{-18} R_{geo}\, \hat{q}_{cyl}^2 \frac{n_e}{T_e^2} Z_{\mathrm{eff}} = \frac{2\lambda_p}{R}$$

- **Electromagnetic wavenumber**: Transition between electromagnetic ($k<k_{EM}$) and electrostatic regime ($k>k_{EM}$)

$$\frac{\beta_e}{\mu} \equiv (k_{\mathrm{EM}})^2$$

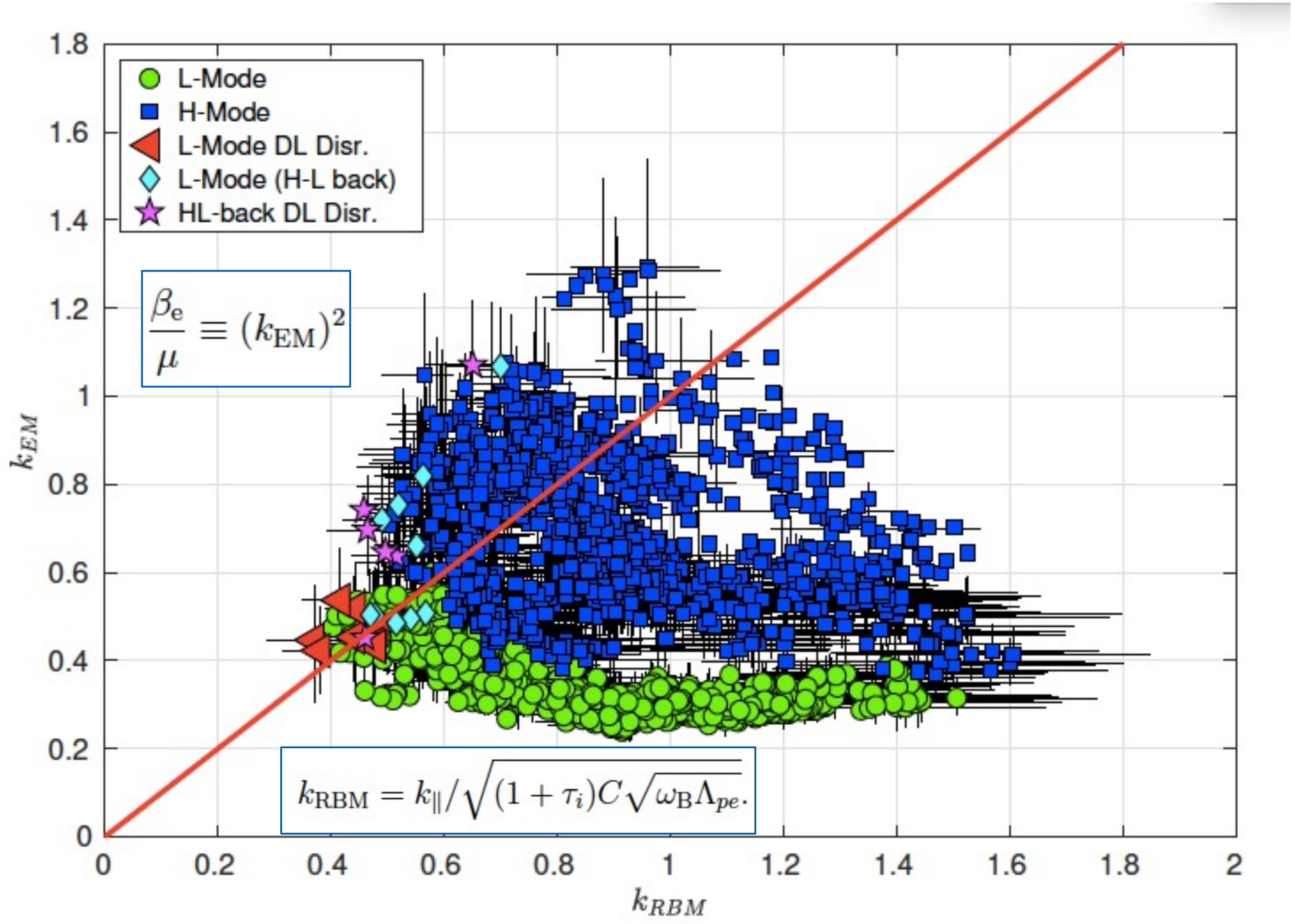
- **Resistive Ballooning Mode wavenumber:** Typical scale of the RBM

$$k_{\mathrm{RBM}} = k_{\|} / \sqrt{(1+\tau_i) C \sqrt{\omega_{\mathrm{B}} \Lambda_{pe}}}.$$

- **Collisional (Ideal) wavenumber**: Transition between inductive ($k<k_{ideal}$) and collisional ($k>k_{ideal}$) dominated parallel dynamics

$$\frac{\hat{\beta}\sqrt{\omega_{\mathrm{B}}}}{C} \equiv k_{\mathrm{ideal}}^2$$

L-Mode Density Limit found when $k_{EM} = k_{RBM}$



- $k_{EM}=k_{RBM}$ describes L-Mode DL
- Does **not** apply to H-Modes
- In line with RDZ-PRL-1998 as $\alpha_{MHD} \sim R\, q^2\, \lambda_p^{-1} k_{EM}$ and $k_{RBM}=\alpha_d$
- In line with B.Scott as DLs fulfill $\alpha_t>1$ and thus transport is interchange-dominated
- H-Modes can have higher n_{sep} than L-Modes

Comparison to Greenwald density

We are interested to compare the separatrix density $n_{\mathrm{e,sep}}$ when Eq. 2 is fulfilled to the Greenwald density n_{GW}. Inserting the definitions for $k_{\mathrm{EM}}$and k_{RBM}we have

$$\frac{\beta_{\mathrm{e}}}{\mu_{\mathrm{e}}} = \frac{\alpha_{\mathrm{c}}}{\alpha_{\mathrm{t}}}\sqrt{\omega_{\mathrm{B}}} \tag{G.1}$$

which rewrites as (by assuming $B_{\mathrm{tor}}^2 \approx B_{total}^2$ and using $C_{\alpha_t} = 3.13 \cdot 10^{-18}$)

$$\frac{2\mu_0 n_{\mathrm{e,sep}} T_{\mathrm{e,sep}}}{\mu_{\mathrm{e}} B_{\mathrm{tor}}^2} = \frac{\alpha_{\mathrm{c}}}{C_{\alpha_t} R_{geo} \hat{q}_{cyl}^2 \frac{n_{\mathrm{e,sep}}}{T_{\mathrm{e,sep}}^2} Z_{\mathrm{eff}}} \sqrt{\frac{2\lambda_p}{R_{geo}}} \tag{G.2}$$

Using

$$\frac{B_{tor}}{\mu_0 R q_{cyl}} = \frac{I_p}{2\pi a^2 \hat{\kappa}^2} = \frac{1}{2 \cdot 10^{20}} \frac{n_{\mathrm{GW}}}{\hat{\kappa}^2} \tag{G.3}$$

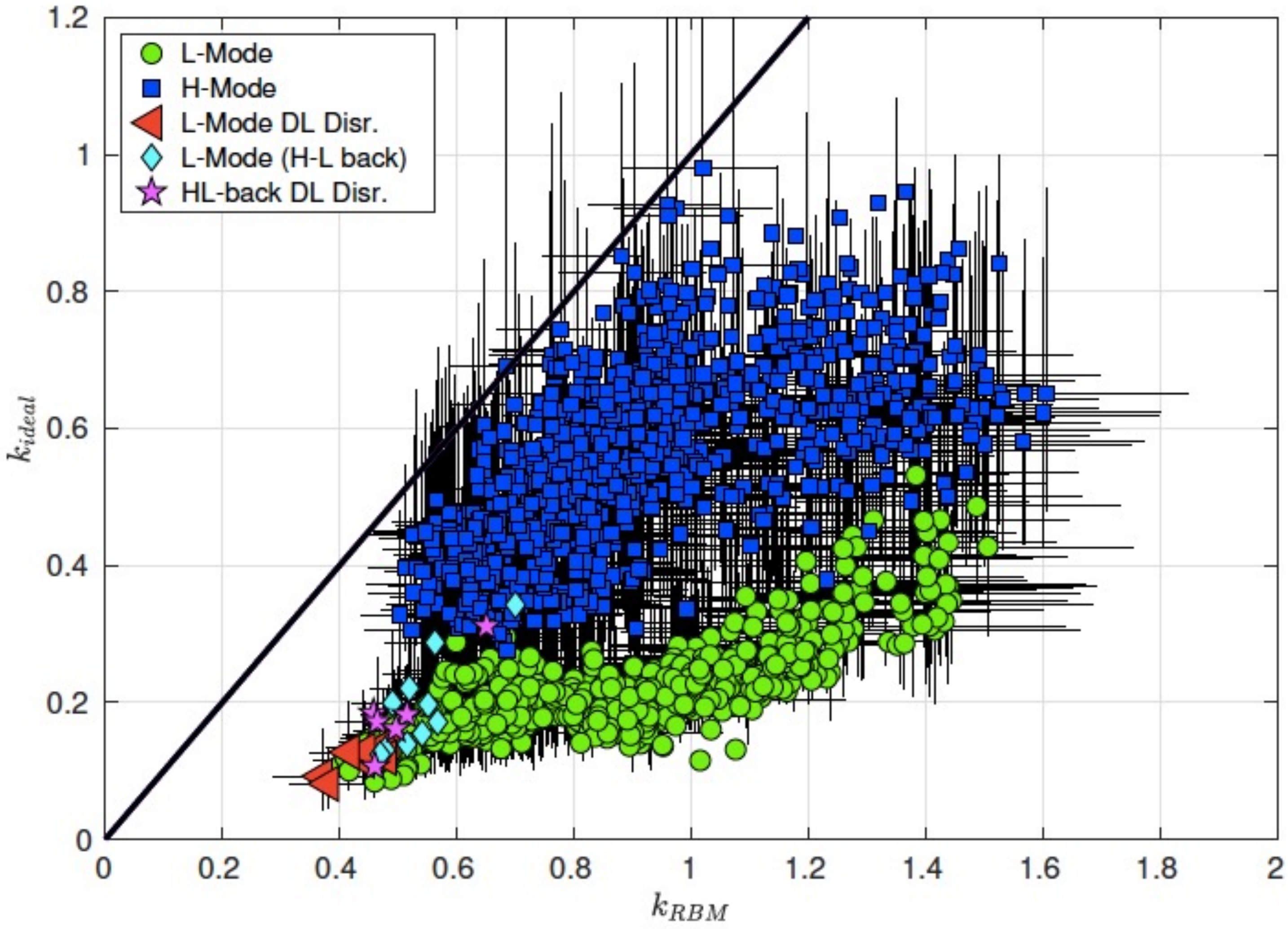
we resolve for the Greenwald density fraction at the separatrix (μ_e =1/3672)

$$\frac{n_{\mathrm{e,sep}}}{n_{\mathrm{GW}}} = 0.11 \frac{\sqrt{\alpha_{\mathrm{c}}}}{\hat{\kappa}^2} \sqrt{\frac{T_{\mathrm{e,sep}}}{Z_{\mathrm{eff}}}} \lambda_p^{\frac{1}{4}} R_{geo}^{\frac{1}{4}}. \tag{G.4}$$

H-Mode – ideal ballooning limit (k_{RBM}=k_{ideal})

- The 2nd criterion is $k_{ideal} = k_{RBM}$
- This establishes a *soft* limit as possibly expected

$$\frac{\hat{\beta}\sqrt{\omega_{\mathrm{B}}}}{C} \equiv k_{\mathrm{ideal}}^2$$



Ideal Ballooning Limit: critical α_c from MHD

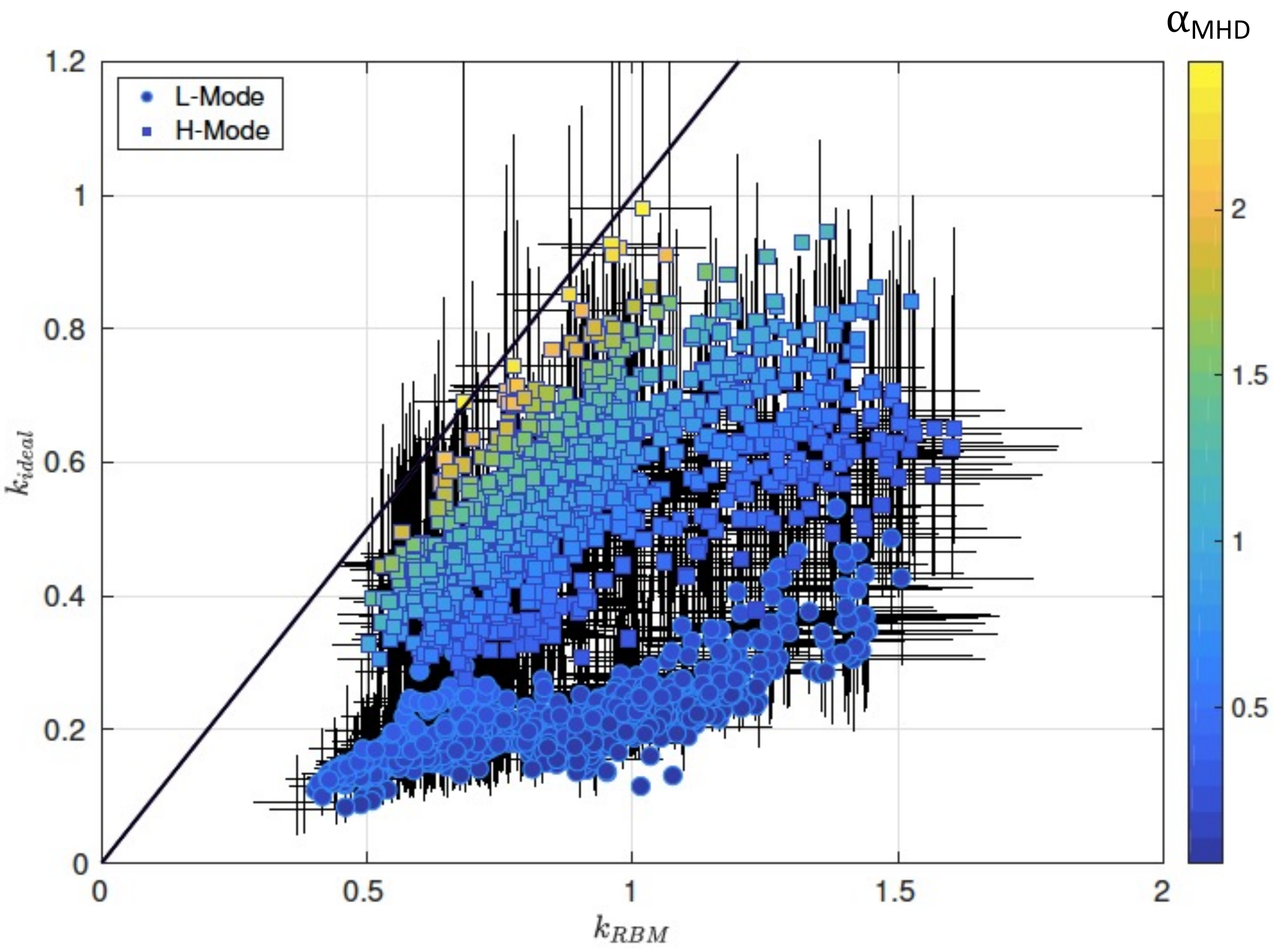
- $k_{ideal} = k_{RBM}$ is the same as

  $\alpha_{MHD} = \alpha_c$ when $k_{\|}^2 \equiv \alpha_c$

- Thus we use an analytical formula derived for IBM also for the L-Mode DL and LH/HL transition

$$\boxed{\alpha_c = \kappa_{geo}^{1.2}\,(1 + 1.5\,\delta)}$$

- L.C. Bernard et al., NF 23 (1983) for D3D discharges (LCFS)



Comparison to H_{98} vs n_{GW} studies (Greenwald in H-Modes)

In order to compare $k_{\text{ideal}} = k_{\text{EM}}$ to Greenwald density n_{GW} we refine the approach presented in [23]. Using the mean value of the data base for α_c =2.37 gives

$$\alpha_{\text{MHD}} = \frac{R_{geo}q_{cyl}^2}{\lambda_p}\frac{p_e}{B_{tor}^2/(2\mu_0)} = \frac{4\mu_0 R_{geo}q_{cyl}^2\, n_{sep}\, T_{sep}}{1.2(1+3.6\,\alpha_t^{1.9})\rho_{s,\text{pol}}B_{tor}^2} = \alpha_c \qquad \text{(I.1)}$$

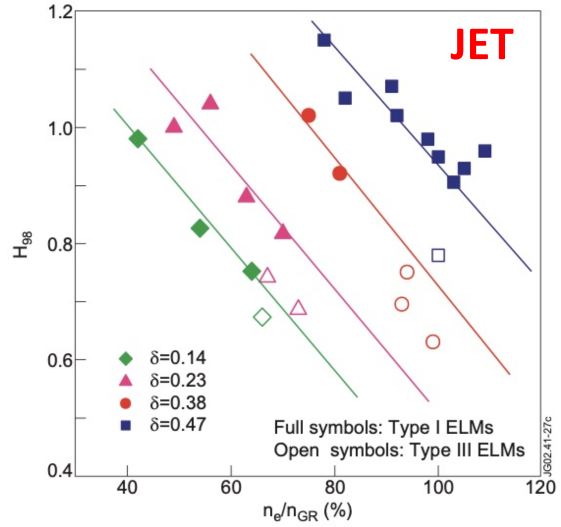
Resolving for the Greenwald density (using Eq. G.3) leads to

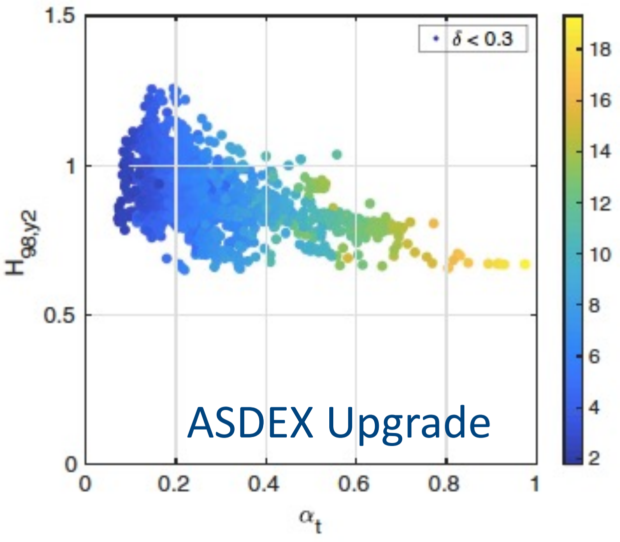
$$\frac{n_{e,\text{sep}}}{n_{\text{GW}}} = (1+3.6\alpha_t^{1.9})\frac{1.35}{\sqrt{T_{e,\text{sep}}}}\frac{\alpha_c R_{geo}}{\hat{\kappa}^2 a_{geo}} \approx (1+3.6\alpha_t^{1.9})\frac{5.5}{\sqrt{T_{e,\text{sep}}}} \qquad \text{(I.2)}$$

The latter equation shows that for high heated, good confinement plasmas with high separatrix temperatures ($T_{e,\text{sep}} \approx$ 130eV) $\alpha_t \to 0$ and thus the Greenwald density n_{GW} will approach

$$\frac{n_{e,\text{sep}}}{n_{\text{GW}}} \approx \frac{5.5}{\sqrt{T_{e,\text{sep}}}}(1+0) = \frac{5.5}{\sqrt{130eV}} = 0.48$$

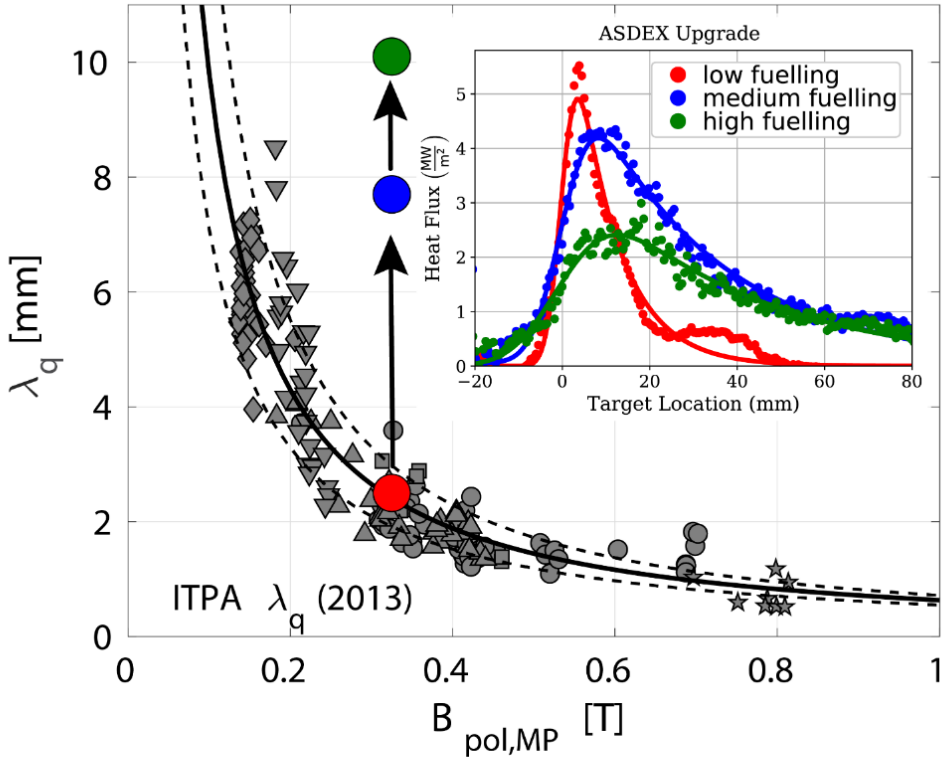
G.Saibene et al. PPCF (2002)

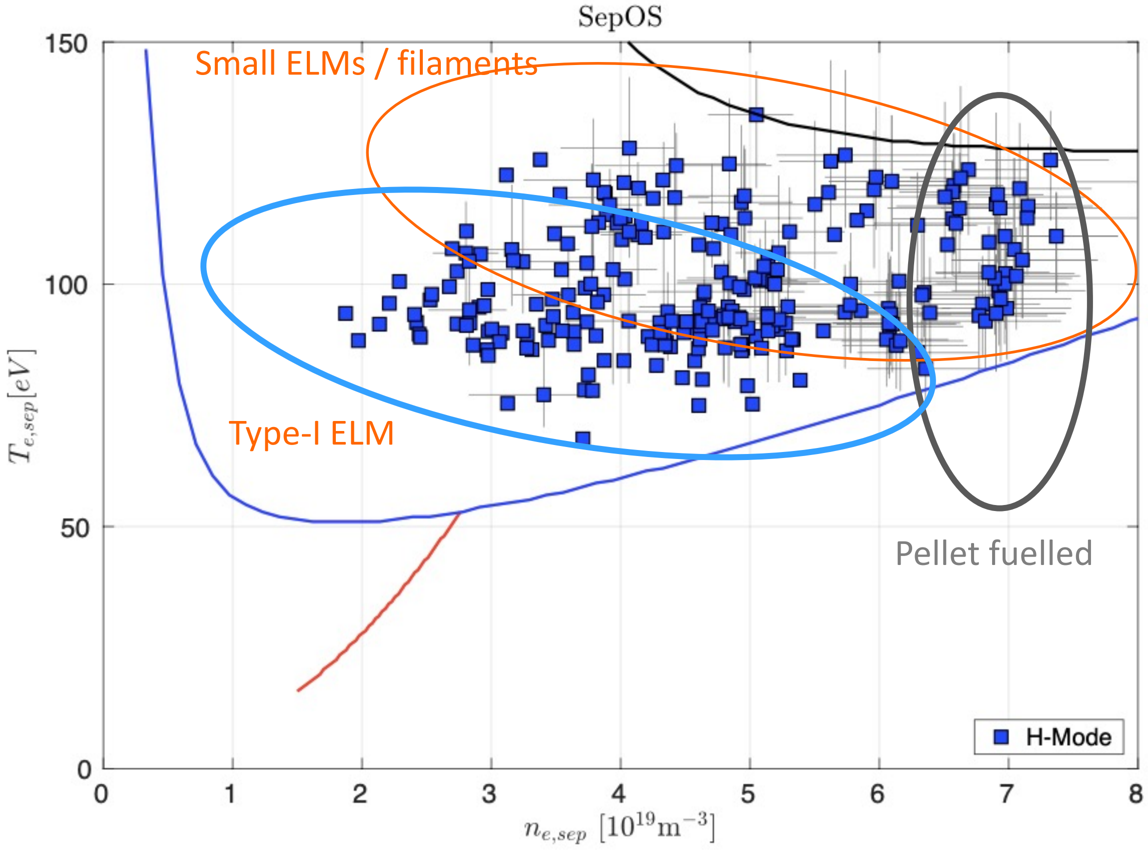




Quasi-Continuous-Exhaust, QCE discharges:

- Broadened power width
- No type-I ELMs
- Small ELMs / filaments
- How does pedestal degrade?





Faitsch et al, Nucl Mat and Energy **26** (2021) 100890

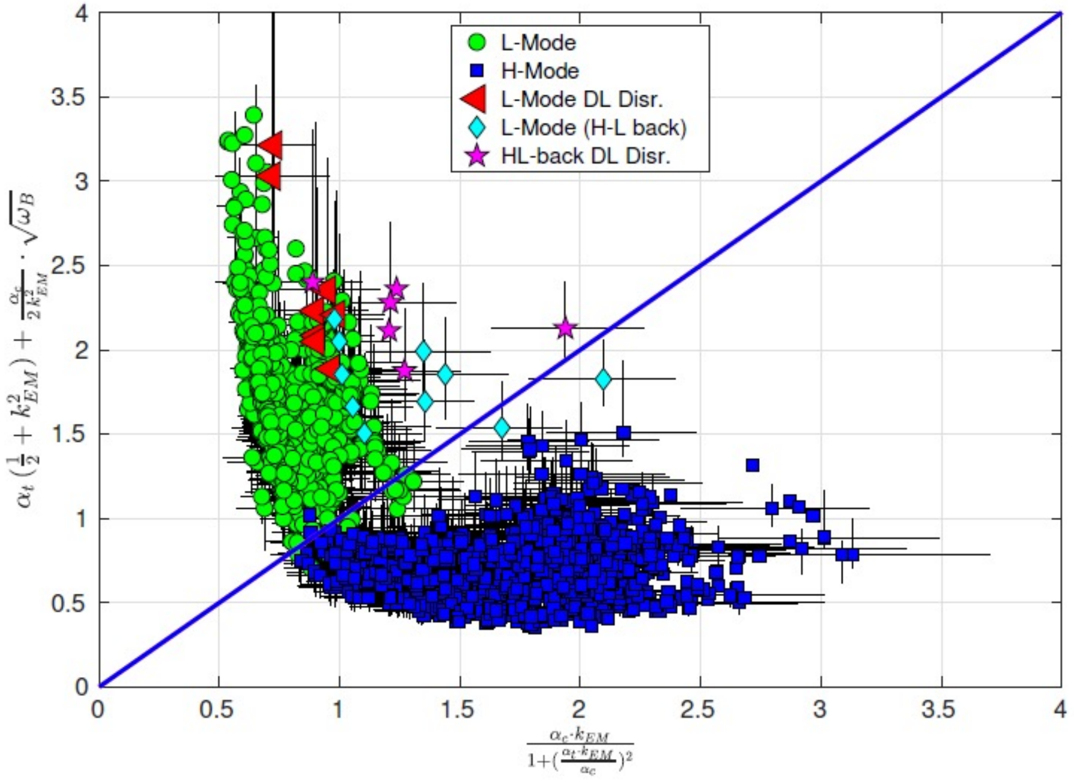
Conditions close to separatrix determine H-Mode sustainment

H-mode sustainment when:

$$\frac{\alpha_c k_{\mathrm{EM}}}{1+(\frac{\alpha_t}{\alpha_c}k_{\mathrm{EM}})^2} > \alpha_t\left(\frac{1}{2}+k_{\mathrm{EM}}^2\right)+\frac{1}{2}\frac{\alpha_c}{k_{\mathrm{EM}}^2}\sqrt{\omega_B}.$$

stabilising: energy transfer into an **established** shear flow (H-Mode)

destabilising: effect of turbulence from electron free energy, kinetic energy and ion free energy



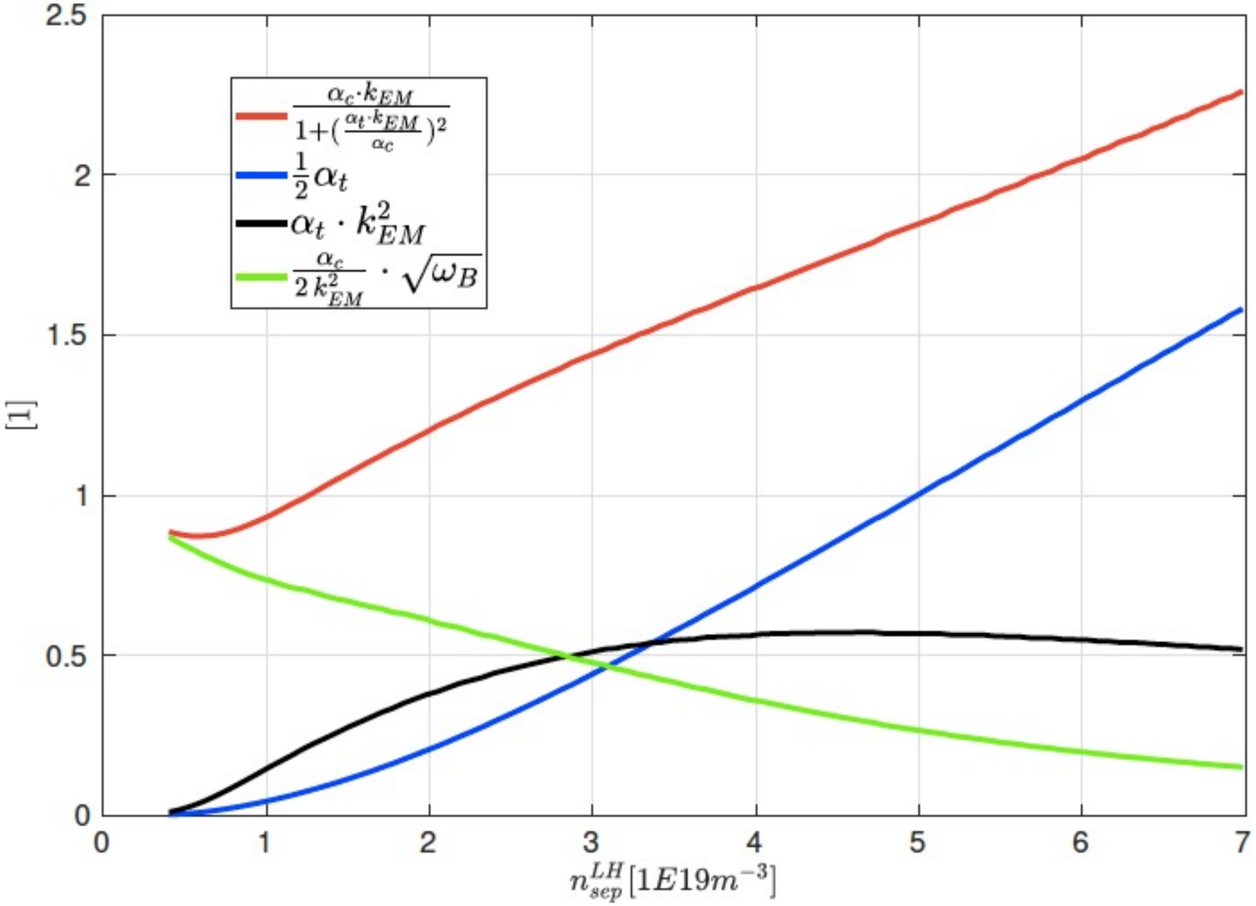
Electron-beta vs. Ionen-pressure gradient

- For **low α_t** values the LH (or HL) transition criterion is about fullfilled when

$$k_\perp^3 > \frac{1}{2}\sqrt{\frac{2\lambda_{pi}}{R}\frac{T_e}{T_i}}$$

- For **high α_t** values HL (back-) transition citerion is about fullfilled when

$$k_\perp > \frac{\alpha_t}{\alpha_c}(k_\perp^2 + \frac{1}{2})$$

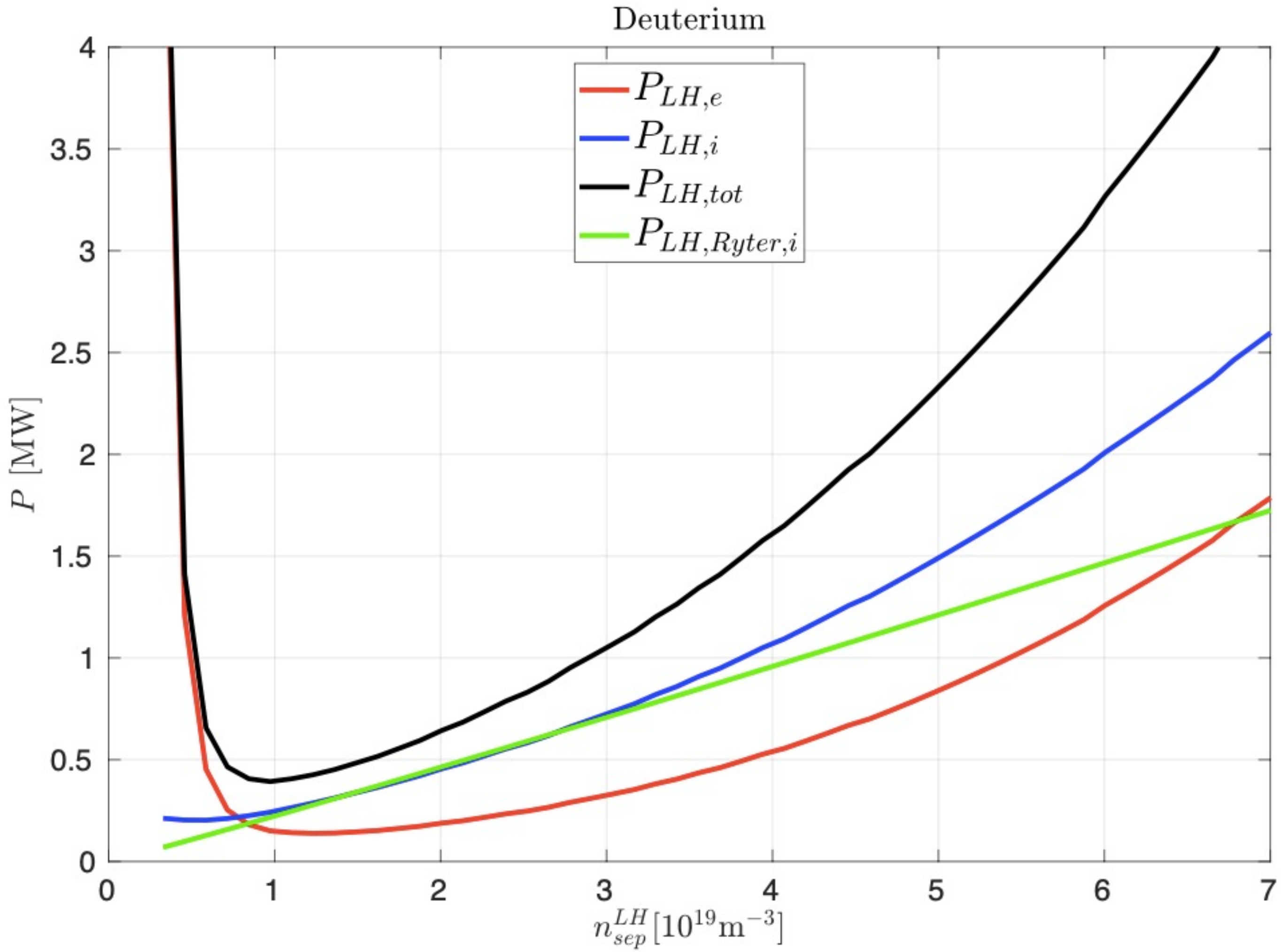


Exercise: comparison to *ion heat flux studies in AUG*

- Assuming an equal share of Q_i and Q_e at minimum density as reported by Ryter in NF 2014
- Electron channel is non-monotonic vs density, minimum density at observed values
- Important implication: Q_i & Q_e share will depend on machine size

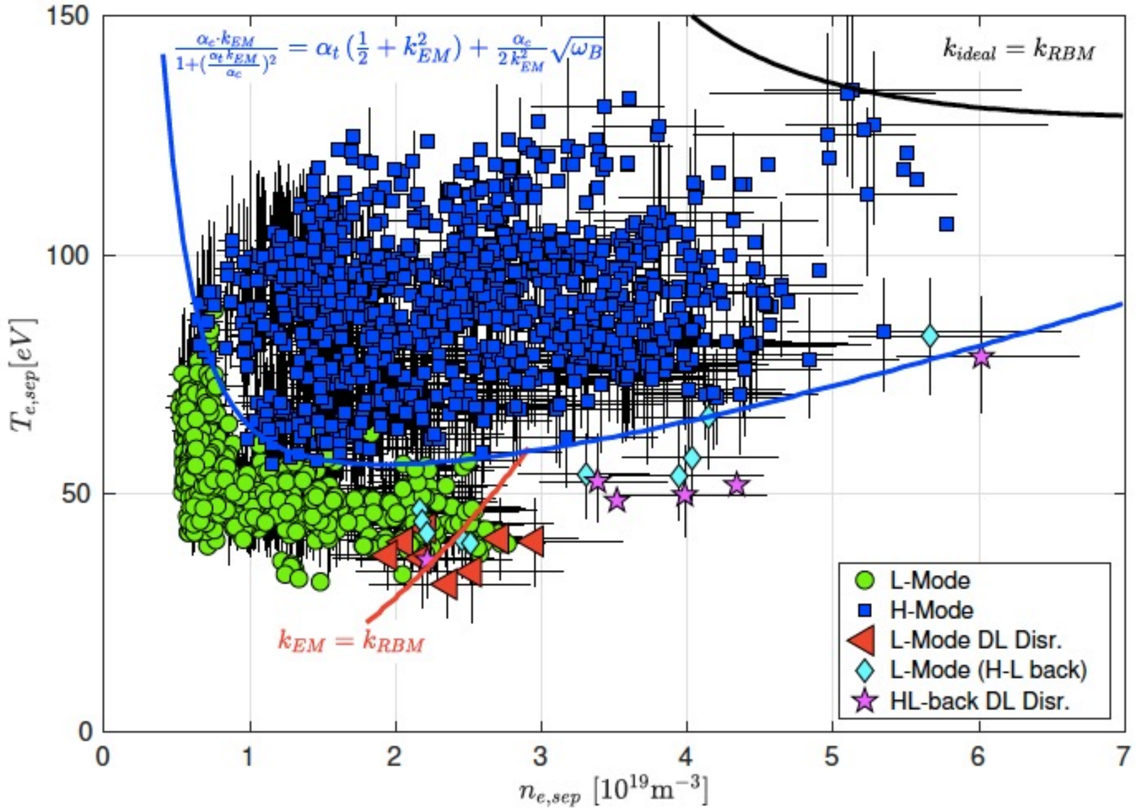
$$P^{LH}_{\mathrm{sep,i}} = 2\pi\kappa a_{geo}\, 2\pi R_{geo} n_{\mathrm{e,sep}} \chi_i \frac{T_{\mathrm{i}}}{\lambda_{Ti}}$$

$$P^{LH}_{\mathrm{sep,e}} \approx \frac{16\,\kappa_0^e\,\hat{\kappa}\,\lambda_{\mathrm{q}}\,a_{\mathrm{geo}}}{7\,\hat{q}^2_{cyl}\,R_{geo}} \cdot \left(T^{LH}_{e,sep}\right)^{\frac{7}{2}}$$



Concluding remarks:

- Boundaries for separatrix density and temperature pairs are calculated for AUG based on turbulence considerations
- Application to other tokamaks is appreciated (WEST, JET, TCV)
- Outlook: Seeded plasmas, Isotopes, Ion profiles and non-favorable configurations



Exercise: comparison to E_r-measurements at L-H

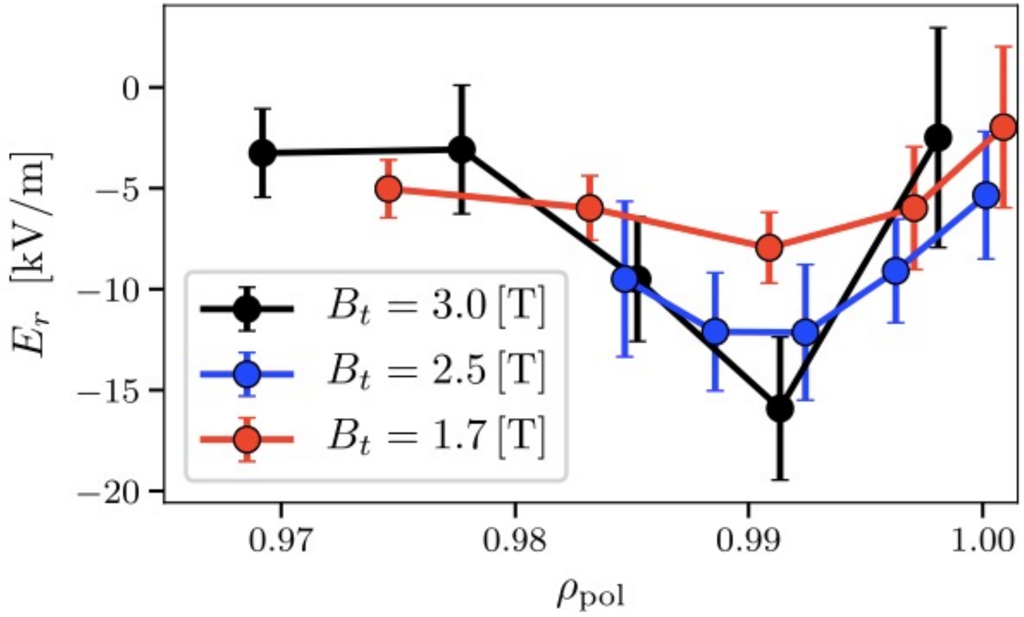
$$E_r \approx \frac{T_e}{eZ_{\text{eff}}}\left(\frac{1}{\lambda_{T_e}} + \frac{1}{\lambda_{n_e}}\right)$$

$$E_r \ = 6\text{–}12 \ \mathrm{kV}m^{-1}$$

$$R = R_{sep}\text{-}2.5\mathrm{mm} \ (\rho = 0.995)$$

$$n_{sep}^{LH} \approx \ 1\text{–}1.5 \cdot 10^{19} m^{-3}$$

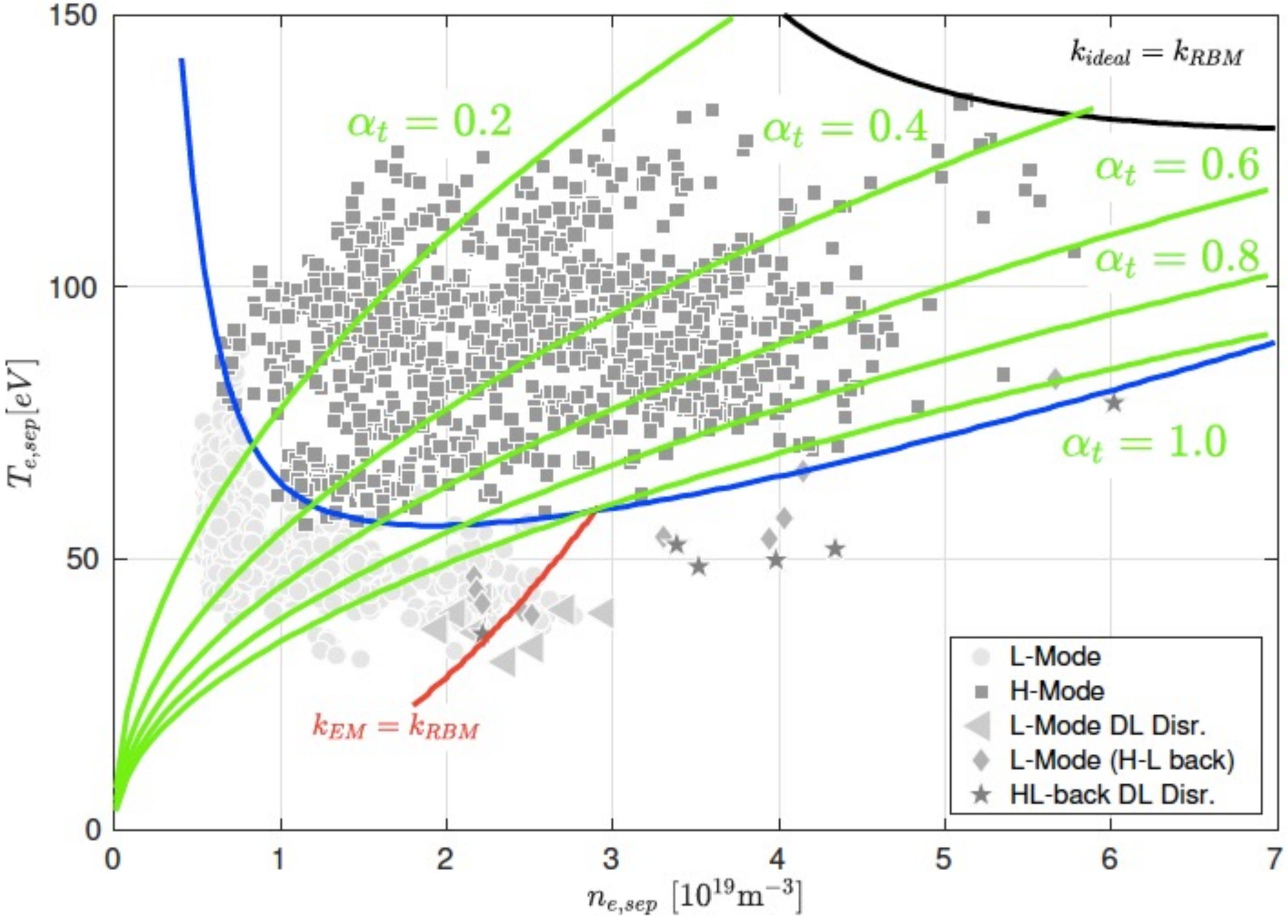
M.Cavedon et al., NF 2020



Backup: alpha_t lines

- L-Modes can be both, more interchange-dominated or more drift-wave dominated ($0.1 < \alpha_t < 2$)

- High density H-Modes fall back to L-Mode when they become interchange-dominated, H-Modes have always $\alpha_t < 1$



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