2014.03.05, 17th プラズマ若手

原型炉炉心プラズマの出力制御シミュレーション研究

徳永晋介

日本原子力研究開発機構

Introduction

原型炉炉心プラズマ制御の主な課題

- プラント規模での一定の経済性実証

  エネルギー消費、長時間運転・稼働率、メンテナンス性

- プラズマの強い自律性

  高い自己加熱・自発電流比率 → 相対的に非力な外部制御

- 計測・制御装置の限定

  熱・中性子負荷のために、使用可能な機器が限定

  トリチウム増殖率確保のためにポートは最低限ぎりぎり

Introduction

DDAにおける炉心制御研究

- どう制御するか、だけではなく、制御のためにどうしても絶対必要なものは何か
- オペレーションポイントの設定は適切か
- 他の設計要素とのトレードオフを具体化
- 個々の要素技術開発に対する目標設定

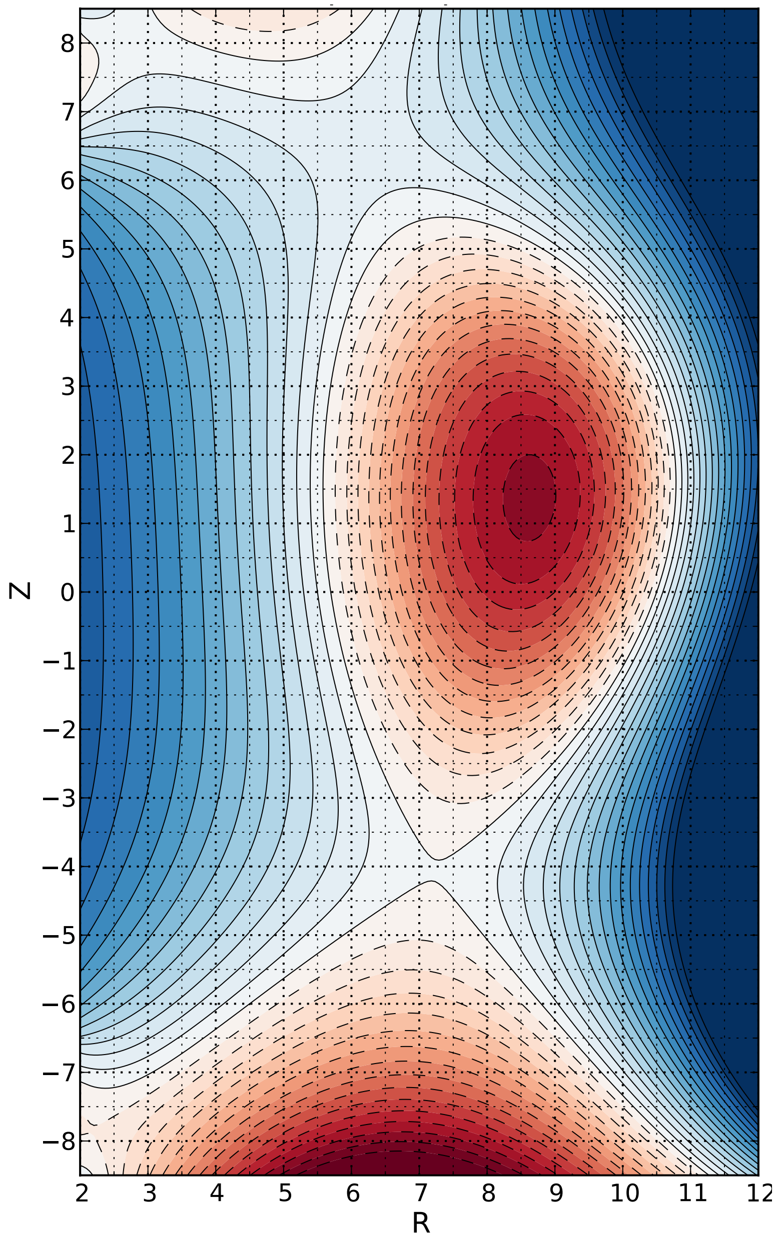
摺り合せの繰り返し、トライ＆エラー

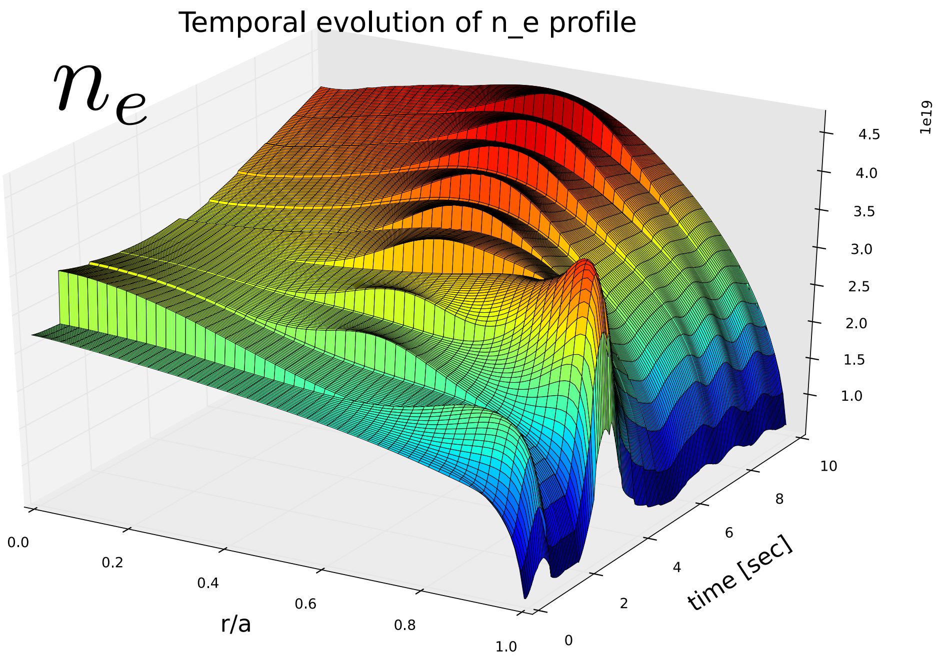
装置そのものの変更も含めた広大なパラメータサーベイ

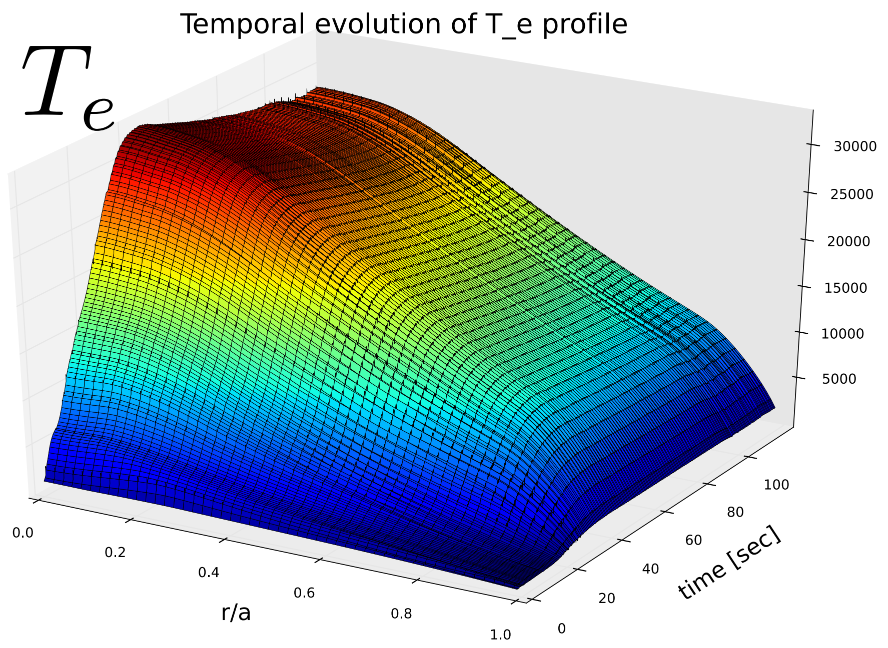
Introduction

ＡＴＬＡＳコードについて

- 炉設計用途に適した道具として、高速性重視、独立性の高いモジュールにより構成。
- 1D輸送(NC, anomalous, fusion, radiation, neutral)、2D平衡(GS)、ハードウェア(NB, puff, pellet, RF, coil)、計測(line-density, neutron), SOL/div(Multilayer1D).
- 120sec 放電計算：
  約600sec on MBP.
  On WS, 360sec.





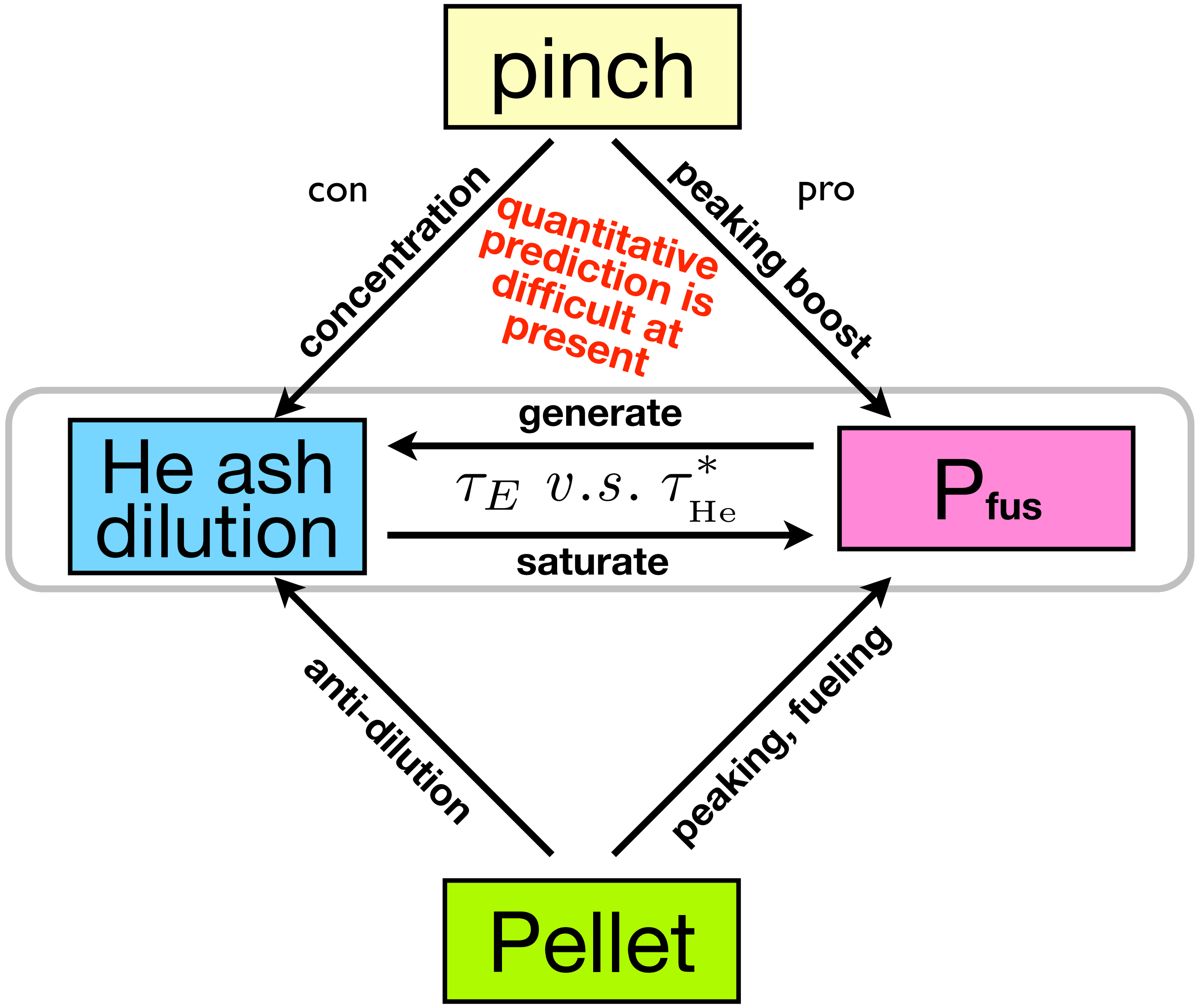


核融合出力制御　ターゲット

- Fusion Output: **1.5~2.0GW**
- I_p: 14[MA], R: 8.2[m], a: 2.4[m] , B_T: 5.27[T]
- pedestal width: 0.15a , Density at ped. top ~**0.7** n_{GW}
- T_{axis}: 35[keV], <T>: 20[keV]
- ELMy H-mode, HH98y2: 1.3-1.5
- Pedestal is formed by a L-H transition model at given position (r/a=0.85). χ_{anom} is adjusted to meet target HH.
- Density at pedestal top is kept by **puff feedback control**. Thus Outgoing net DT flux is under control.

Peaking Control

- DEMO should achieve and maintain AIMED Fusion Output by the use of limited apparatuses.
- Pellet Fueling is a promised measure to control core density.
- Inward Particle Pinch has been observed in Tokamaks.
  pros: fuel peaking;
  cons: He ash concentration



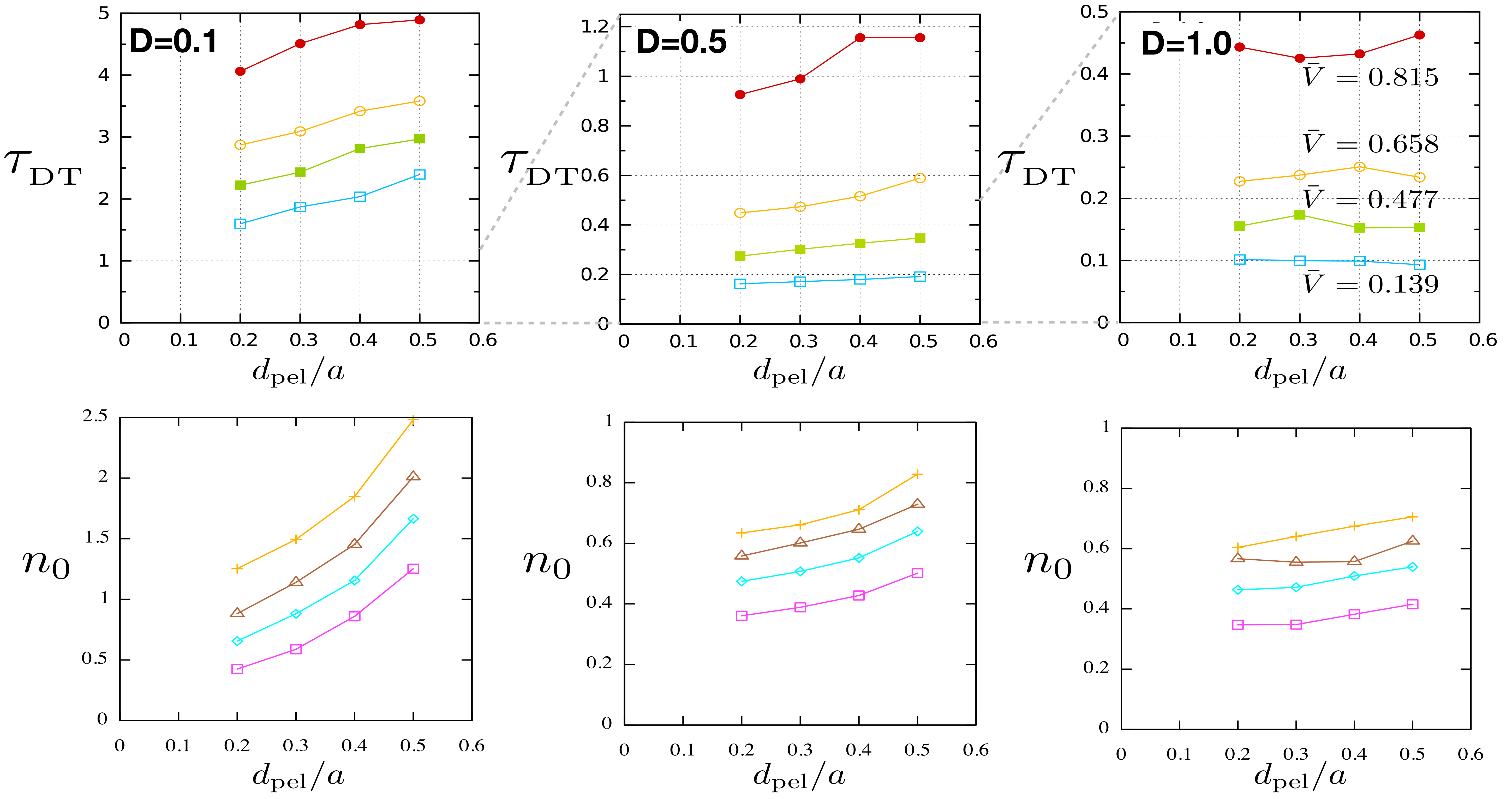
- Output Control by fueling means to keep BOTH Peaking and Purity of fuel on target. Diffusivity and pinch velocity of particle transport have still some ambiguity. How far can pellet-control recover the peaking and purity deviation from expectation?

燃料密度・純度制御 - Strategy

$$N_{\mathrm{DT}} = \tau_{\mathrm{DT}}\Gamma_{\mathrm{DT}}$$

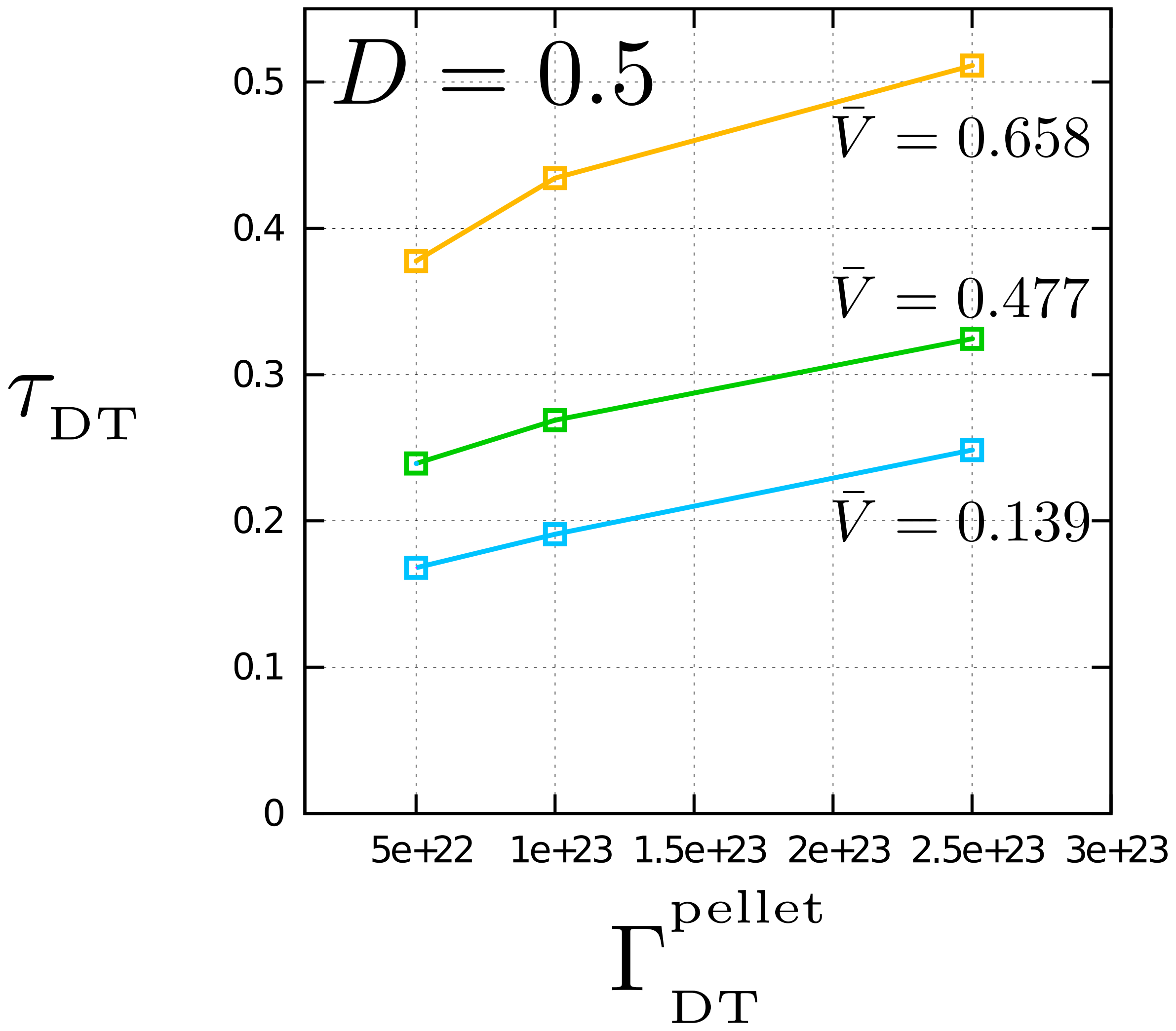
	interim target	knobs	engineering correspondence	side effect
I	τ_{DT}	d_{pel} & Γ_{pel}	**Pellet Speed** **Pellet Size***	**Perturbation** **Cooling effect** **Large Tritium Inventory** **Demand more pump**
II	Γ_{DT}	Γ_{pel}	**Pellet Frequency***	**Cooling effect** **Demand more pump**
III	τ^*_{He}	R_{He}	**Pumping Speed** **Divertor Shape**	R_{DT} **should decrease too** **Divertor load could be sacrificed**

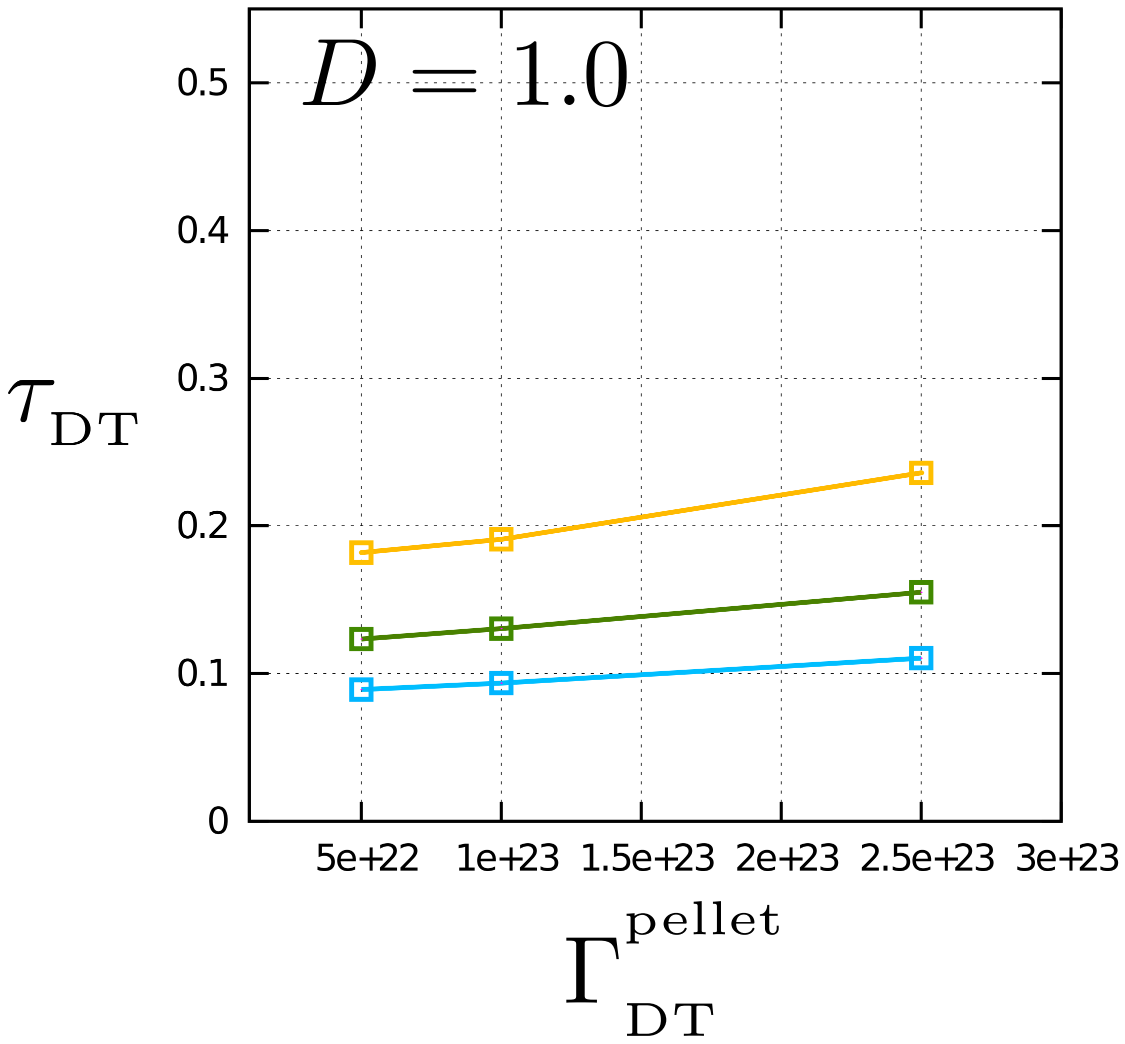
ペレット侵入深さ tau_DT



- Because of roughly linear dependence τDT on dpel, peaking density increases nonlinearly. V-tilde appears as offset.

燃料供給 Gamma_p

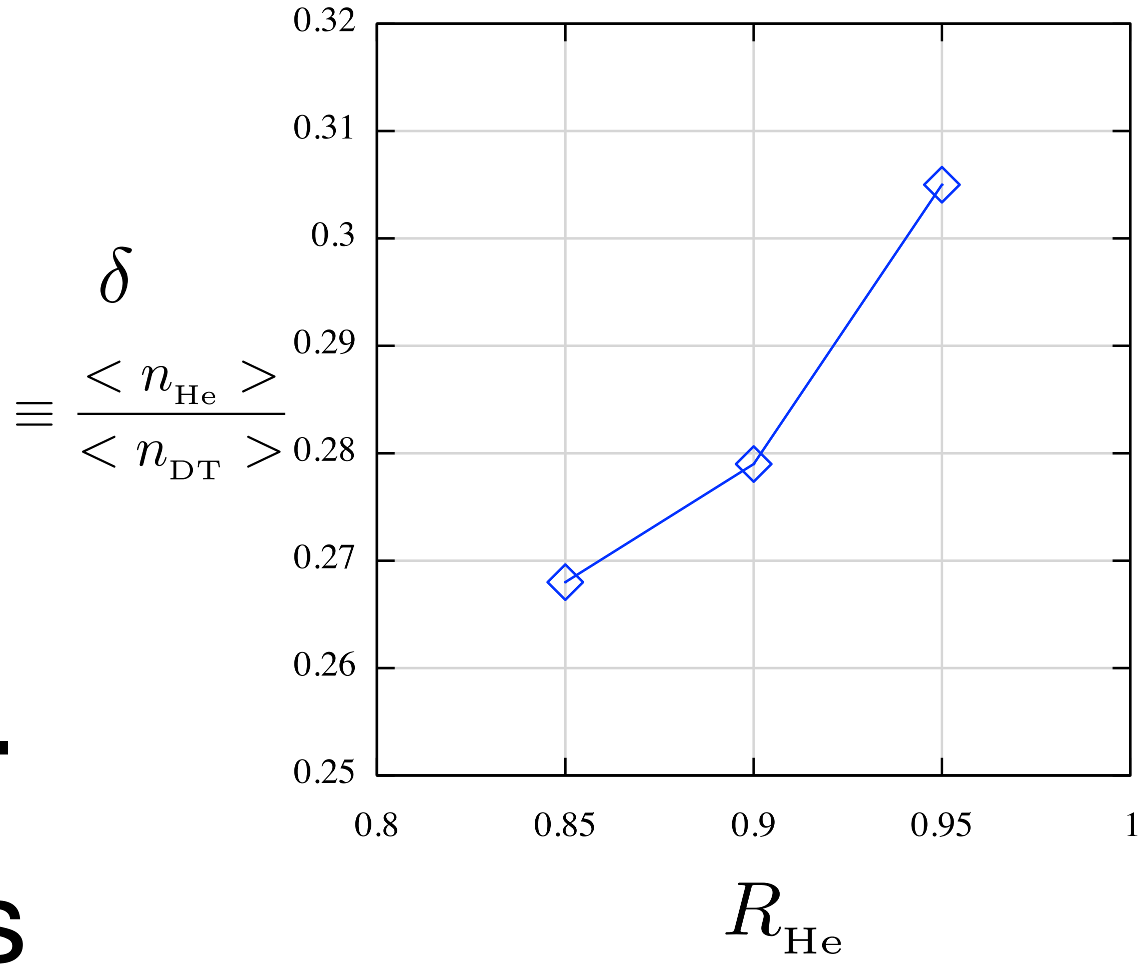




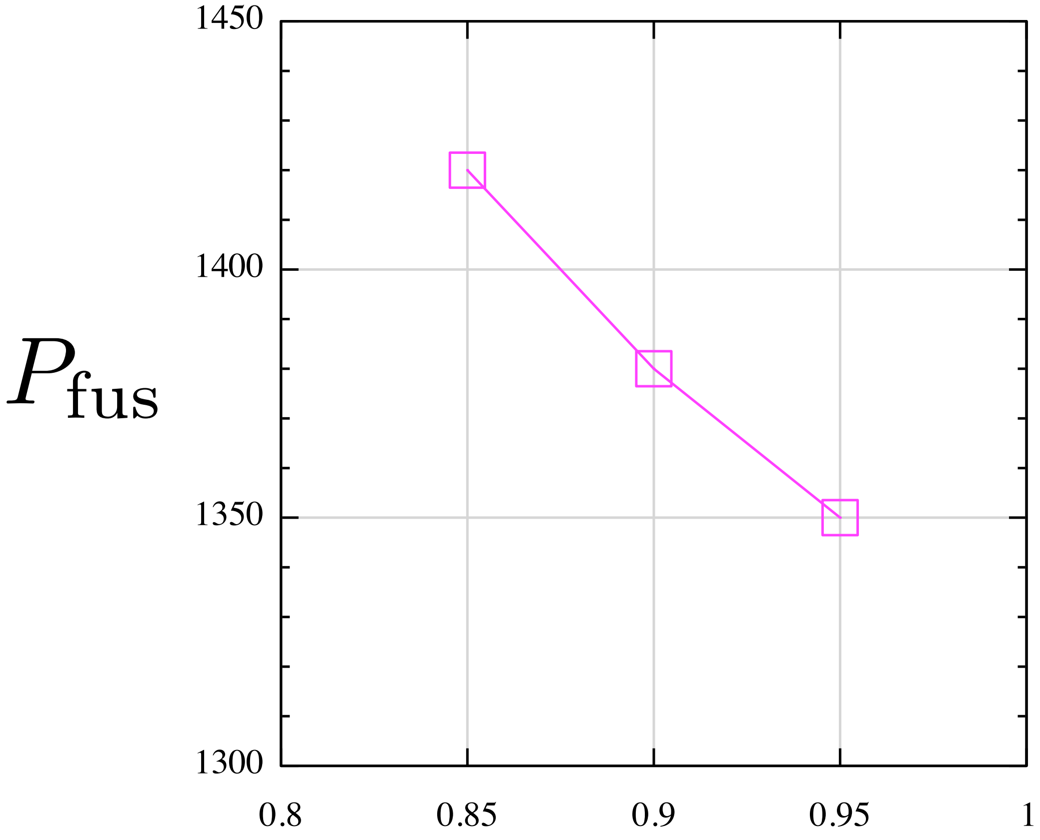
- Amount of pellet fueling affects on confinement time as well as fueling depth. They lead to difficulty of control design based on simple context of 0D analysis : $N_{\mathrm{DT}} = \tau_{\mathrm{DT}}\Gamma_{\mathrm{DT}}$.

He灰排気効率 R_He

- Effect of He recycling rate on He dilution rate is not so large at least initial phase of steady state. Double of pumping rate does not results half of dilution.



- Fusion output slightly increases as recycling rate decreases. Namely, less recycling He rate results more production He rate, then the dilution rate is determined as the result of fusion-recycling interaction.



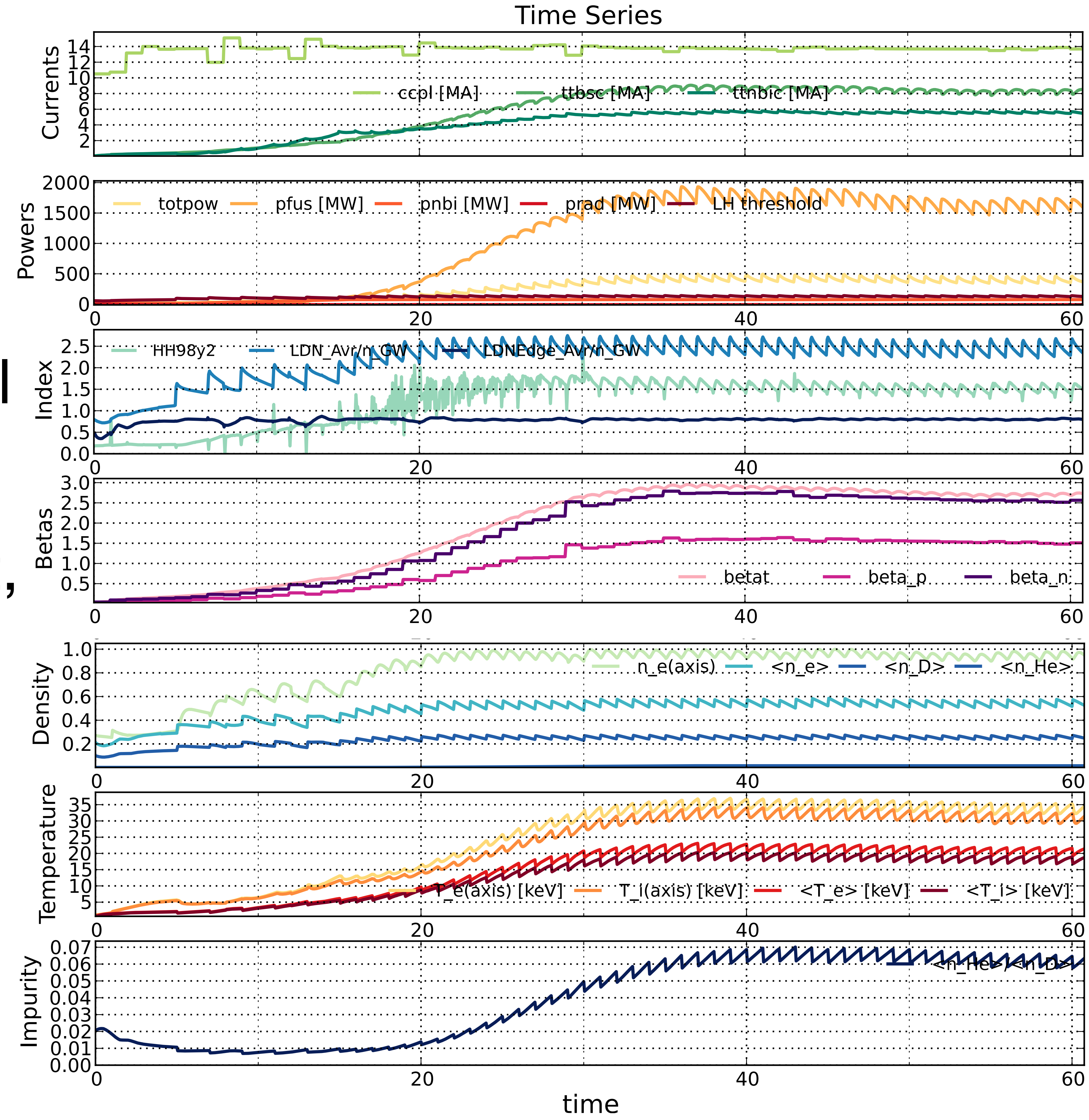
Simulation Results:: I more d_{pel}

$D = 0.5, \bar{V} = 0.139, R_{\mathrm{DT,\,He}} = 0.91$

larger D, weak V

pel: 2x10^23, 1Hz, d=0.6

- Target fusion output is achieved by larger dpel and pellet size.
- Because of huge pellet, the system is considerably oscillating.
- needed pellet speed is 44km/s. Obviously outrageous.



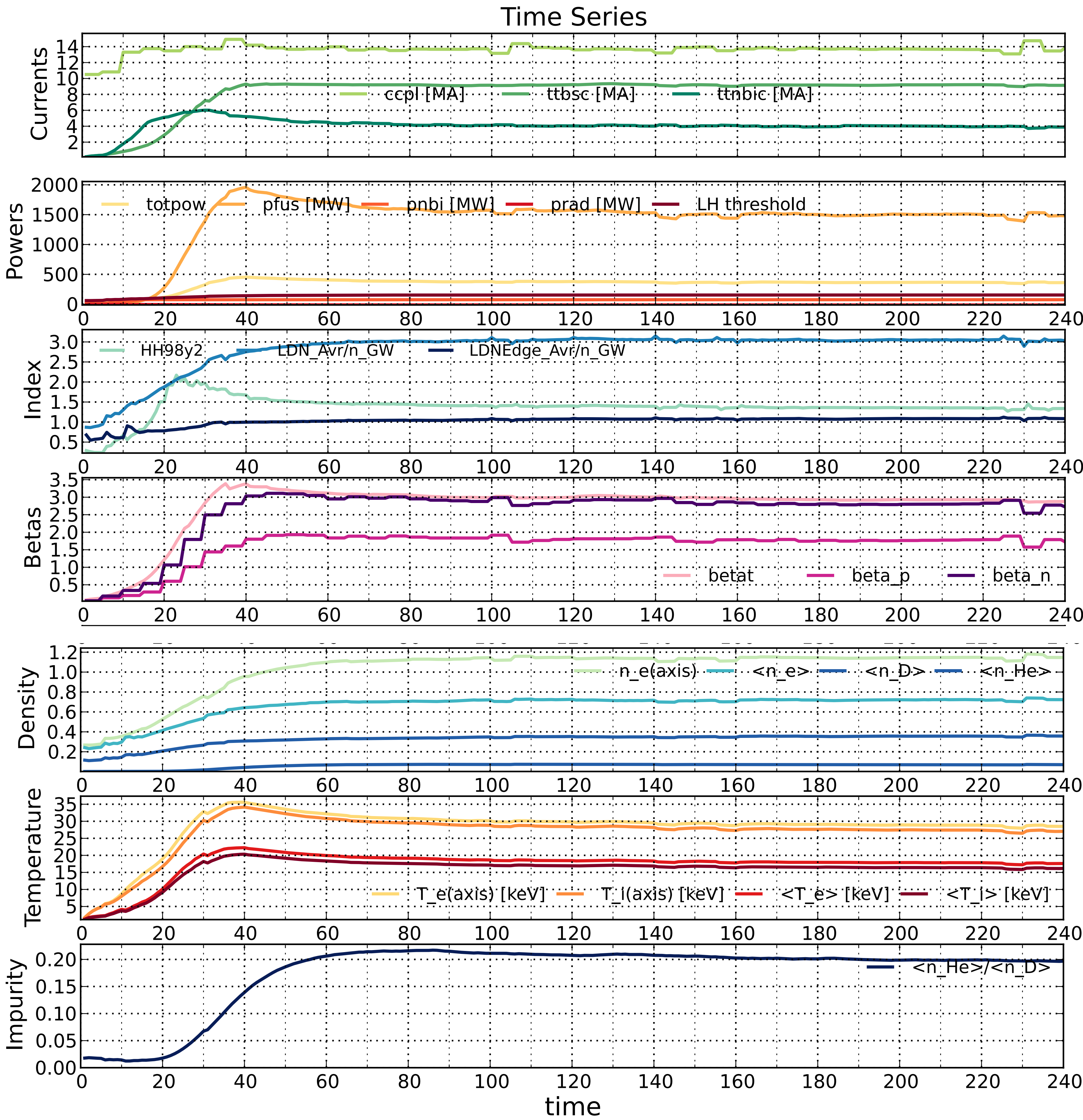
Simulation Results:: II more Γ_{pel}

$D = 0.1, \bar{V} = 0.477, R_{\mathrm{DT,\,He}} = 0.91$

moderate D, moderate V

pel: 2x10^22, 10Hz, d=0.4

- For severer case (D=1.0, weak pinch) no plausible solution found without deepening deposition point.
- Because of too-much fueling, edge density exceeds $f_{GW}=1$.



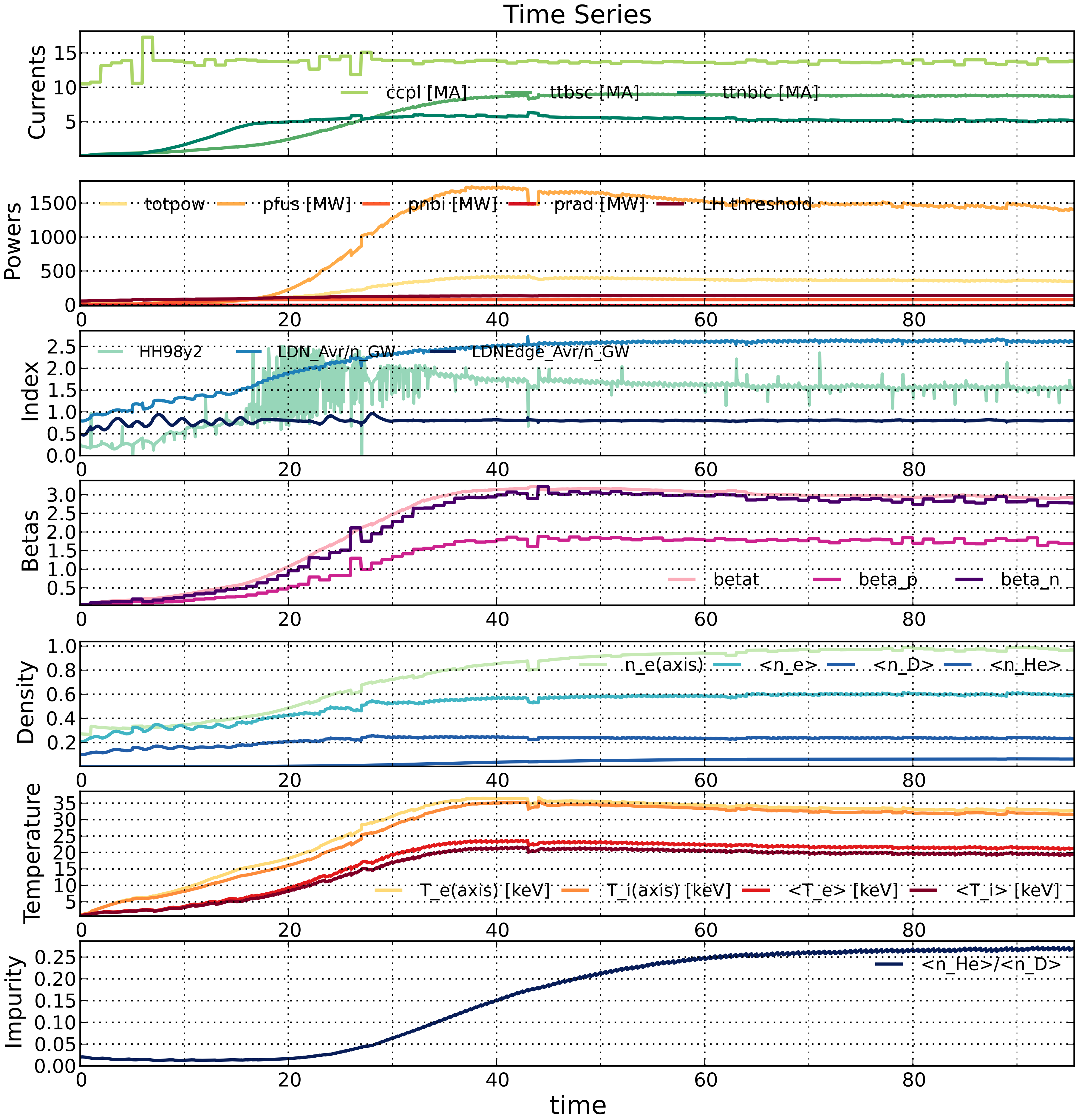
Simulation Results:: III less R_{He}

$$D = 0.1, \bar{V} = 0.477, R_{\mathrm{DT,\,He}} = 0.85$$

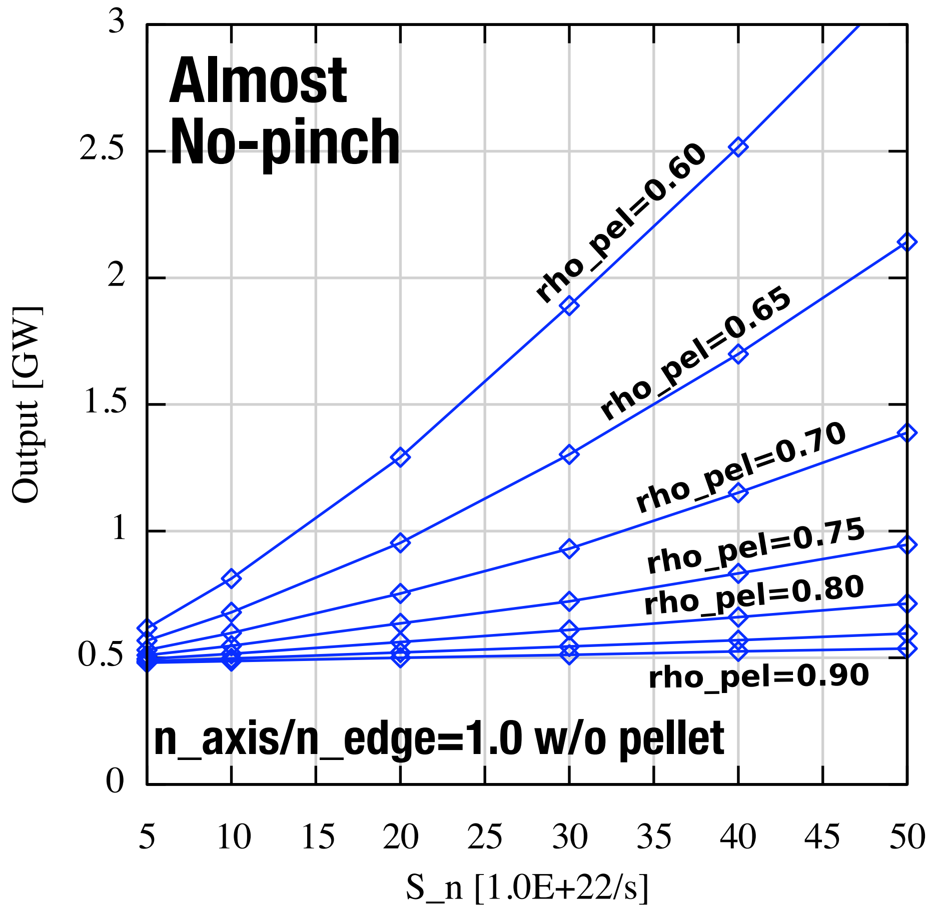
moderate D, moderate V

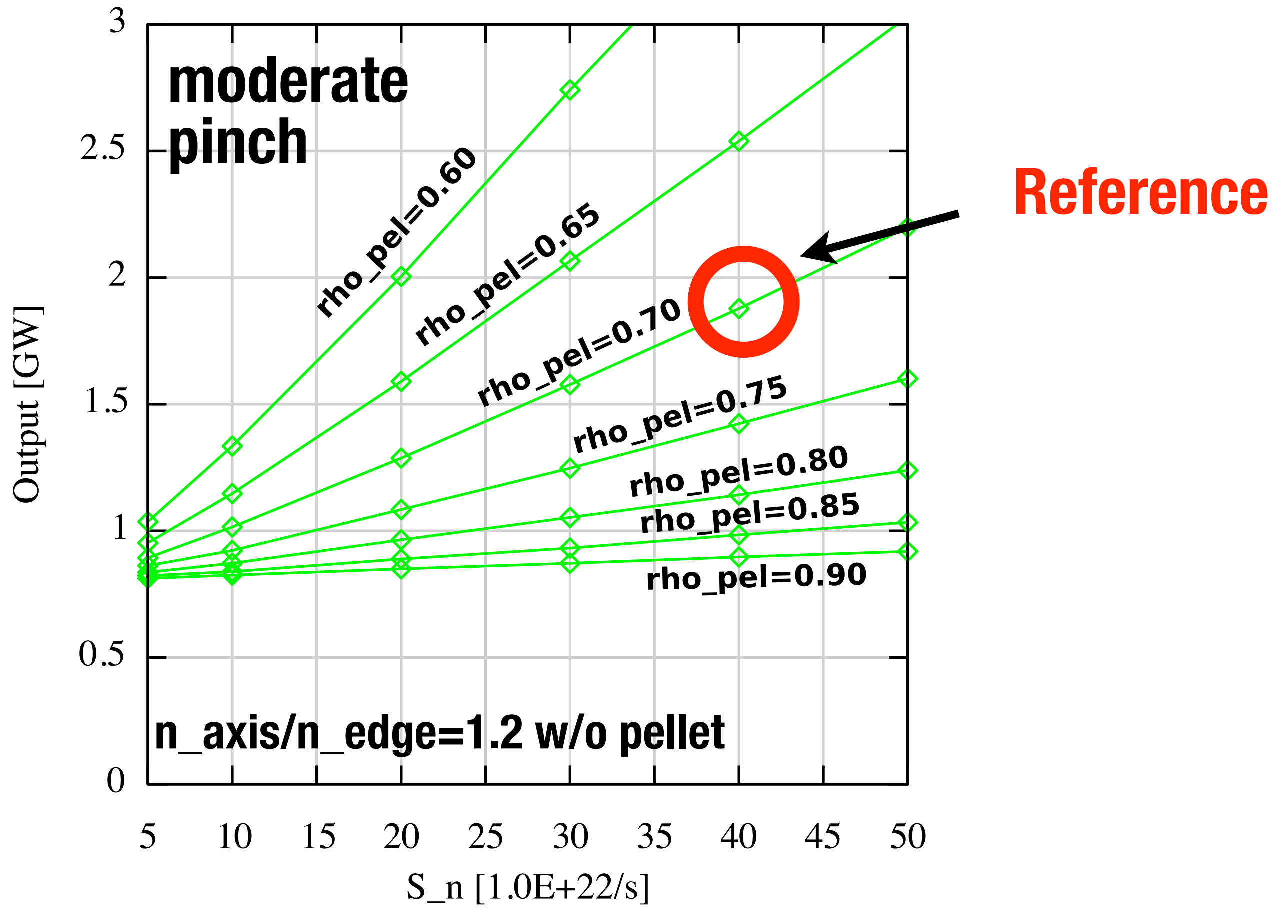
pel: 5x10^22, 2Hz, d=0.4

- Target output is achieved with half amount of fueling of case II.
- He dilution ratio is high in spite of low-recycling rate. Longer calculation in progress.

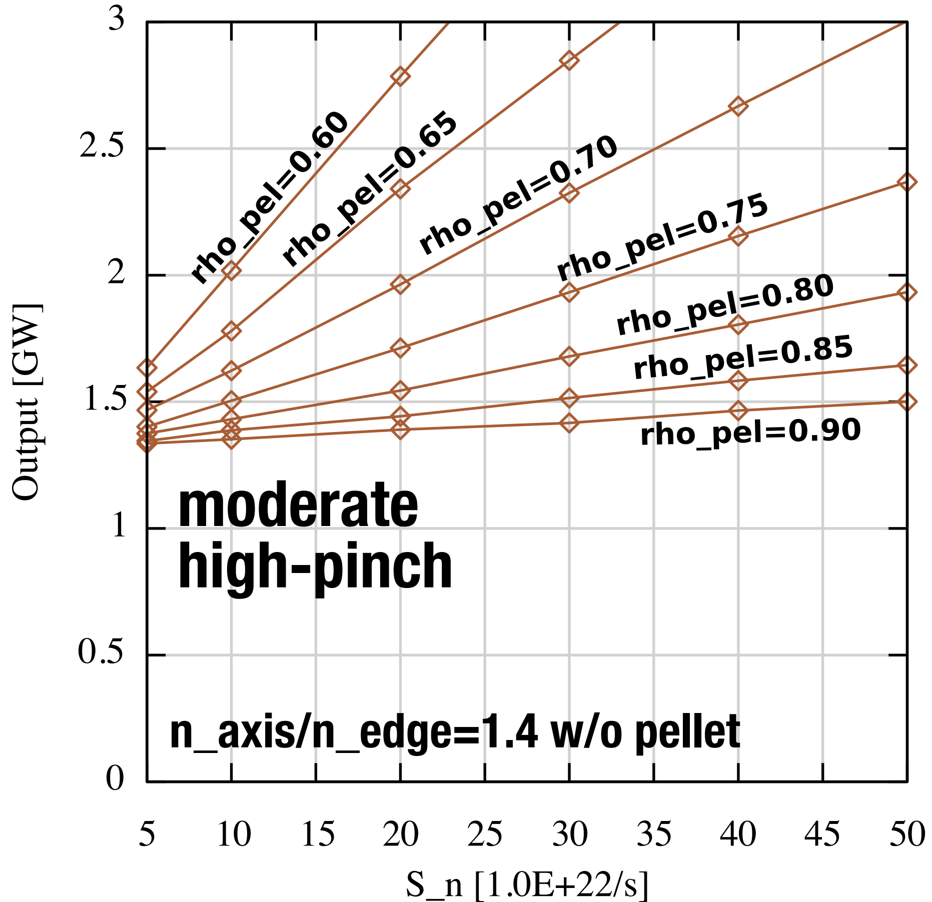


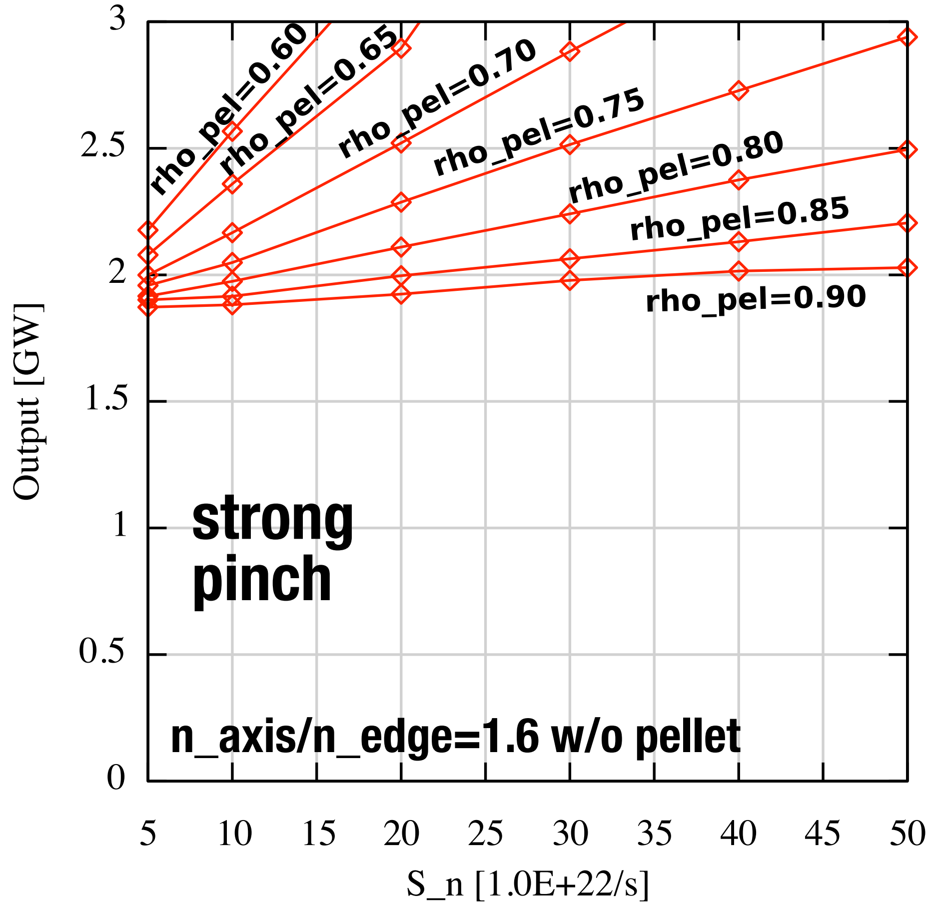
Parameter Scan





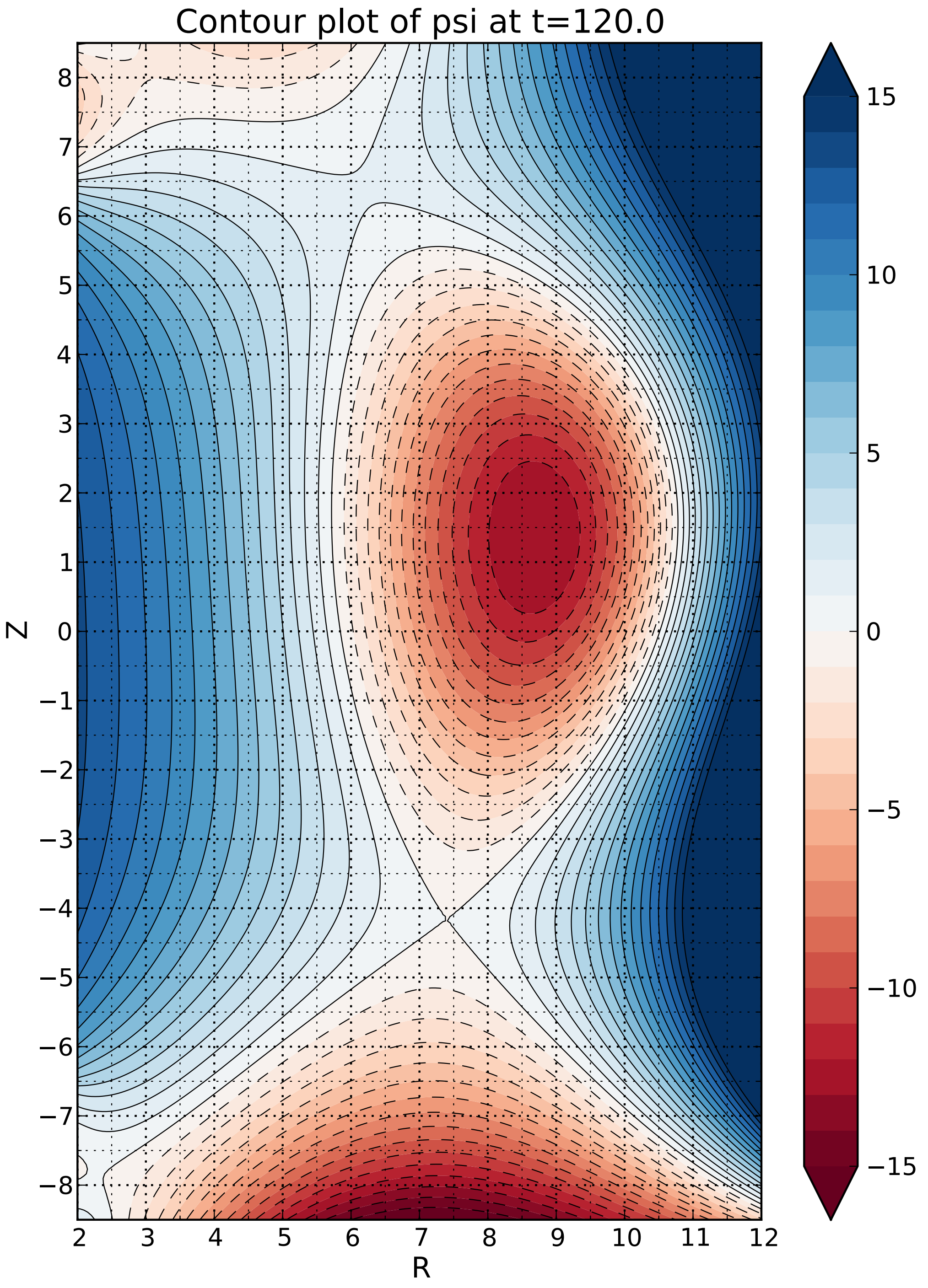
S_n = pellet size × frequency (5Hz, fixed)

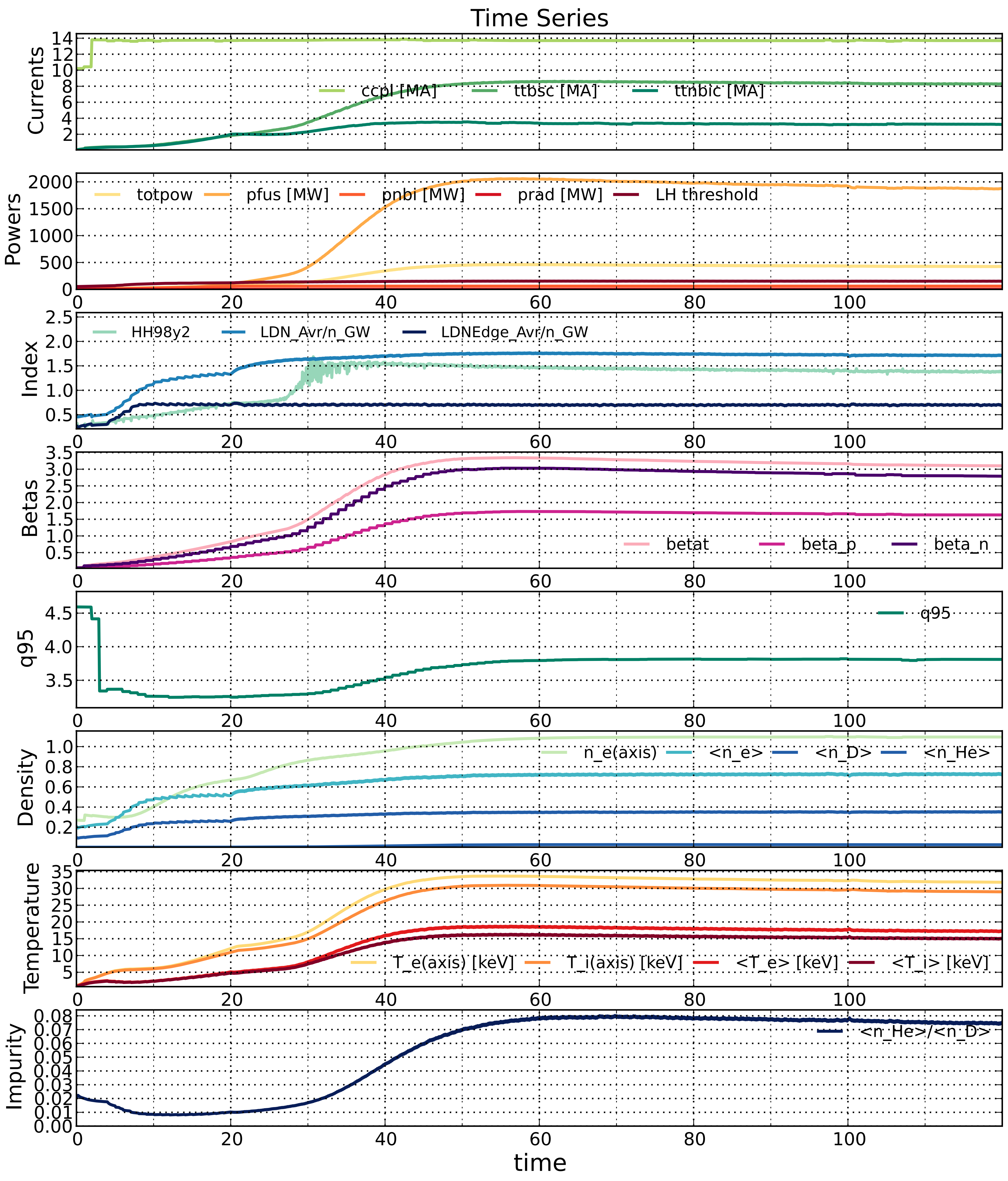




核融合出力制御

Recent Reference Case





Power Balance Analysis 1

$$\langle P_{\rm ohm} + P^{\sf e}_{\rm aux} + P^{\sf e}_{\alpha} - P_{\rm EP} - P_{\rm rad}\rangle - \frac{3}{2}\frac{\langle n_{\sf e} T_{\sf e}\rangle}{\tau^{\sf e}_{E}} = 0$$

$$\langle P^{\sf i}_{\rm aux} + P^{\sf i}_{\alpha} + P^{\sf i}_{\rm EP}\rangle - \frac{3}{2}\frac{\langle n_{\sf i} T_{\sf i}\rangle}{\tau^{\sf i}_{E}} = 0$$

Power balance eqs.

$$n = n_{\sf e} = n_{\sf D} + n_{\sf T} + 2n_{\sf He} \qquad n_{\sf He} = {\rm f}_{\sf He}\, n,$$

$$n_{\sf i} = (1 - 2{\rm f}_{\sf He})n$$

$$Z_{\rm eff} = 1 + 2{\rm f}_{\sf He} + Z'_{\rm eff}. \qquad {\rm R}_{\sf T} = \frac{n_{\sf T}}{n_{\sf D} + n_{\sf T}} \qquad m_{\sf i} = (2 + R_{\sf T})m_{\rm p}$$

Density ratio

$$P_{\alpha} = n_{\sf D} n_{\sf T} \langle\sigma v\rangle_{\sf DT}\mathcal{E}_{\alpha} = \mathcal{E}_{\alpha} R_{\sf T}(1 - R_{\sf T})(1 - 2{\rm f}_{\sf He})^2 n^2 \langle\sigma v\rangle_{\sf DT}$$

$$\frac{{\rm f}_{\sf He}\, n}{\tau^{*}_{\sf He}} = \frac{P_{\alpha}}{\mathcal{E}_{\alpha}} \qquad {\rm f}_{\sf He} = \frac{1}{2} + \frac{1 - \sqrt{1 + {\rm g}}}{\rm g}, \qquad {\rm g} = 8\tau^{*}_{\sf He} R_{\sf T}(1 - R_{\sf T})n\langle\sigma v\rangle_{\sf DT}.$$

$$\langle\sigma v\rangle_{\sf DT} = 9 \times 10^{-22} \exp\left[-0.47595 \left|\ln\left(\frac{T_{\sf i\,[keV]}}{69}\right)\right|^{2.25}\right]$$

$$\boxed{\begin{aligned} P_{\alpha} &= P_{\alpha}(\boxed{\tau^{*}_{\sf He}, R_{\sf T}}; \boxed{n}, \boxed{T_{\sf i}}), \\ {\rm f}_{\sf He} &= {\rm f}_{\sf He}(\boxed{\tau^{*}_{\sf He}, R_{\sf T}}; \boxed{n}, \boxed{T_{\sf i}}). \end{aligned}}$$

Alpha heating

Alpha particle

$$\cancel{P_{\rm ohm}} \qquad P_{\rm brem} = \sum_{\sf s} 5.35 \times 10^{-37} Z_{\sf s}^2 n_{\sf e} n_{\sf s} \sqrt{T_{\sf e\,[keV]}}$$

$$P_{\rm rad} = P_{\rm brem} + \cancel{P_{\rm sync}} + \cancel{P_{\rm line}} \qquad = \boxed{5.35 \times 10^{-37} \boxed{n}^2 \boxed{Z_{\rm eff}} \sqrt{\boxed{T_{\sf e}}}}$$

Powers(1)

Power Balance Analysis 2

External Heating

$$P_{\mathrm{EC}} = (1 - \boxed{\phi^{\mathrm{NB}}_{\mathrm{aux}}})\boxed{P_{\mathrm{aux}}},$$

$$P_{\mathrm{NB}} = \boxed{\phi^{\mathrm{NB}}_{\mathrm{aux}}}\boxed{P_{\mathrm{aux}}}.$$

$$P^{\mathrm{e}}_{\mathrm{aux}} = (1 - (1 - \boxed{\phi^{\mathrm{e}}_{\mathrm{NB}}})\boxed{\phi^{\mathrm{NB}}_{\mathrm{aux}}})\boxed{P_{\mathrm{aux}}}$$

$$P^{\mathrm{i}}_{\mathrm{aux}} = \boxed{\phi^{\mathrm{i}}_{\mathrm{NB}}}\boxed{\phi^{\mathrm{NB}}_{\mathrm{aux}}}\boxed{P_{\mathrm{aux}}}$$

$$P^{\mathrm{He}}_{\mathrm{aux}} = \boxed{\phi^{\mathrm{He}}_{\mathrm{NB}}}\boxed{\phi^{\mathrm{NB}}_{\mathrm{aux}}}\boxed{P_{\mathrm{aux}}}.$$

alpha Heating

$$P^{\mathrm{e}}_{\alpha} = \boxed{\phi^{\mathrm{e}}_{\alpha}}\boxed{P_{\alpha}}$$

$$P^{\mathrm{i}}_{\alpha} = \boxed{\phi^{\mathrm{i}}_{\alpha}}\boxed{P_{\alpha}}$$

$$P^{\mathrm{He}}_{\alpha} = \boxed{\phi^{\mathrm{He}}_{\alpha}}\boxed{P_{\alpha}}$$

$$\boxed{\phi^{\mathrm{e}}_{\mathrm{b}}} = 1/F$$

$$\boxed{\phi^{\mathrm{i}}_{\mathrm{b}}} = \left(\frac{3\sqrt{\pi}}{4\sqrt{m_{\mathrm{e}} m_{\mathrm{p}}}}\right)\left(\frac{m_{\mathrm{b}}\boxed{T_{\mathrm{e}}}}{\mathcal{E}_{\mathrm{b}}}\right)^{\frac{3}{2}}\left(\frac{1 - \boxed{2\mathrm{f}_{\mathrm{He}}}}{2 + \boxed{R_{\mathrm{T}}}}\right)/F$$

$$\boxed{\phi^{\mathrm{He}}_{\mathrm{b}}} = \left(\frac{3\sqrt{\pi}}{4\sqrt{m_{\mathrm{e}} m_{\mathrm{p}}}}\right)\left(\frac{m_{\mathrm{b}}\boxed{T_{\mathrm{e}}}}{\mathcal{E}_{\mathrm{b}}}\right)^{\frac{3}{2}}\left(\frac{(1 - \boxed{\gamma_{\alpha}})\boxed{\mathrm{f}_{\mathrm{He}}}}{4}\right)/F.$$

$$\boldsymbol{F} = 1 + \left(\frac{3\sqrt{\pi}}{4\sqrt{m_{\mathrm{e}} m_{\mathrm{p}}}}\right)\left(\frac{m_{\mathrm{b}}\boxed{T_{\mathrm{e}}}}{\mathcal{E}_{\mathrm{b}}}\right)^{\frac{3}{2}}\left(\frac{1 - 2\boxed{\mathrm{f}_{\mathrm{He}}}}{2 + \boxed{R_{\mathrm{T}}}} + \frac{(1 - \boxed{\gamma_{\alpha}})\boxed{\mathrm{f}_{\mathrm{He}}}}{4}\right)$$

Energy Transfer among species

$$P^{\mathrm{i}}_{\mathrm{EP}} \simeq \frac{e^4 \ln\Lambda}{(2\pi)^{\frac{3}{2}}\varepsilon_0^2}\frac{m_{\mathrm{e}}^{\frac{1}{2}}}{m_{\mathrm{p}}}\boxed{n}^2\frac{\boxed{T_{\mathrm{e}}} - \boxed{T_{\mathrm{i}}}}{\boxed{T_{\mathrm{e}}}^{\frac{3}{2}}}\frac{1 - 2\boxed{\mathrm{f}_{\mathrm{He}}}}{2 + \boxed{R_{\mathrm{T}}}}$$

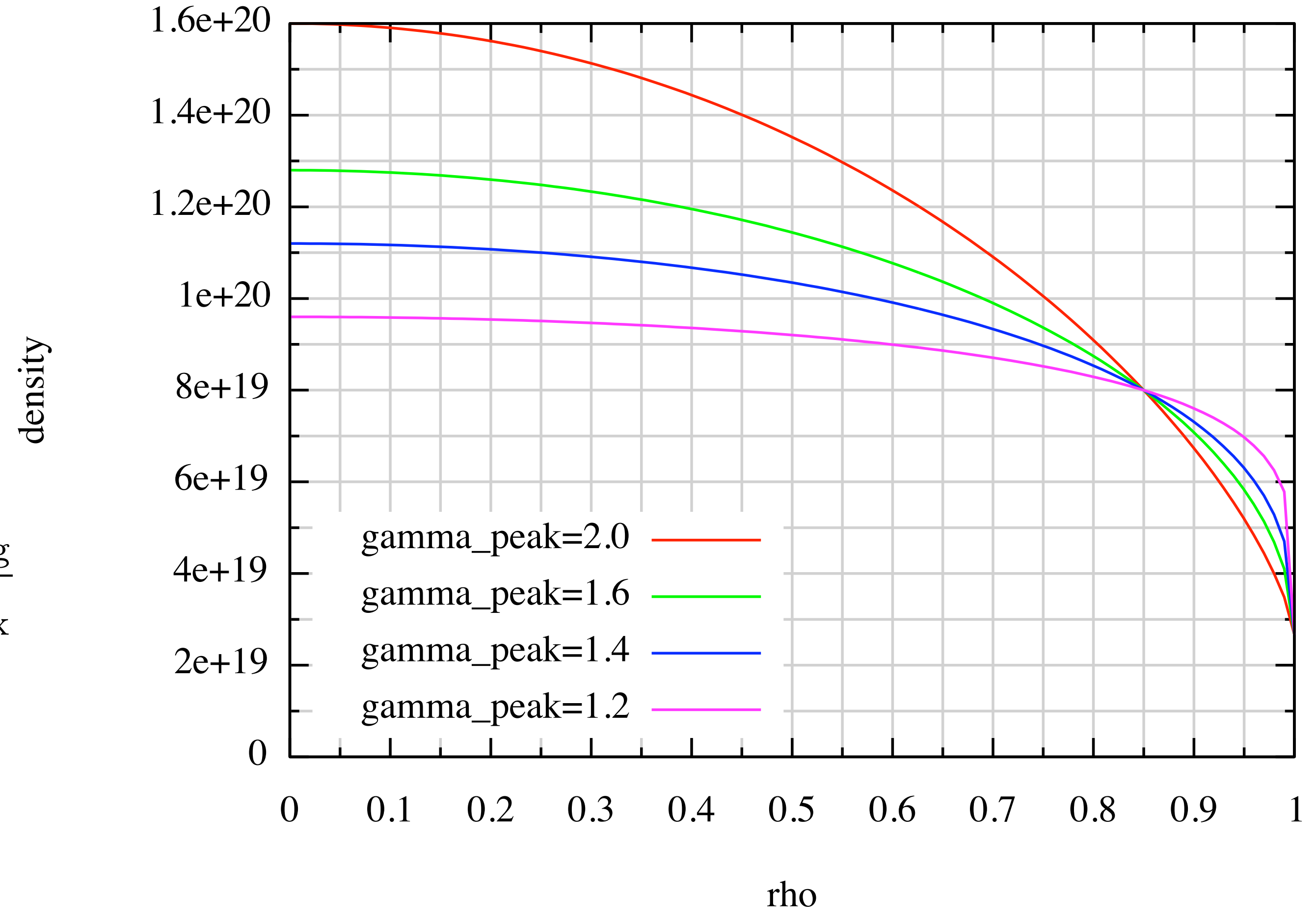
$$P^{\mathrm{He}}_{\mathrm{EP}} \simeq \frac{e^4 \ln\Lambda}{(2\pi)^{\frac{3}{2}}\varepsilon_0^2}\frac{m_{\mathrm{e}}^{\frac{1}{2}}}{m_{\mathrm{p}}}\boxed{n}^2\frac{\boxed{T_{\mathrm{e}}} - \boxed{T_{\mathrm{i}}}}{\boxed{T_{\mathrm{e}}}^{\frac{3}{2}}}(1 - \boxed{\gamma_{\alpha}})\boxed{\mathrm{f}_{\mathrm{He}}}$$

Power Balance Analysis 3

$$n(\rho) = \frac{\gamma_\mathrm{GW} n_\mathrm{GW}}{1-(1-\rho_\mathrm{ped}^2)^\nu}\left\{(\gamma_\mathrm{peak}-1)(1-\rho^2)^\nu + 1 - \gamma_\mathrm{peak}(1-\rho_\mathrm{ped}^2)^\nu\right\}$$

$$\nu \equiv \frac{\log\left(\frac{\gamma_\mathrm{spx}-1}{\gamma_\mathrm{spx}\gamma_\mathrm{peak}-1}\right)}{\log\left(1-\rho_\mathrm{ped}^2\right)}, \qquad \gamma_\mathrm{GW} \equiv \frac{n_\mathrm{edg}}{n_\mathrm{GW}}, \qquad \gamma_\mathrm{peak} \equiv \frac{n_\mathrm{axis}}{n_\mathrm{edg}}, \qquad \gamma_\mathrm{spx} \equiv \frac{n_\mathrm{edg}}{n_\mathrm{spx}}$$

エッジ条件固定 $\gamma_\mathrm{peak} \to n(r)$



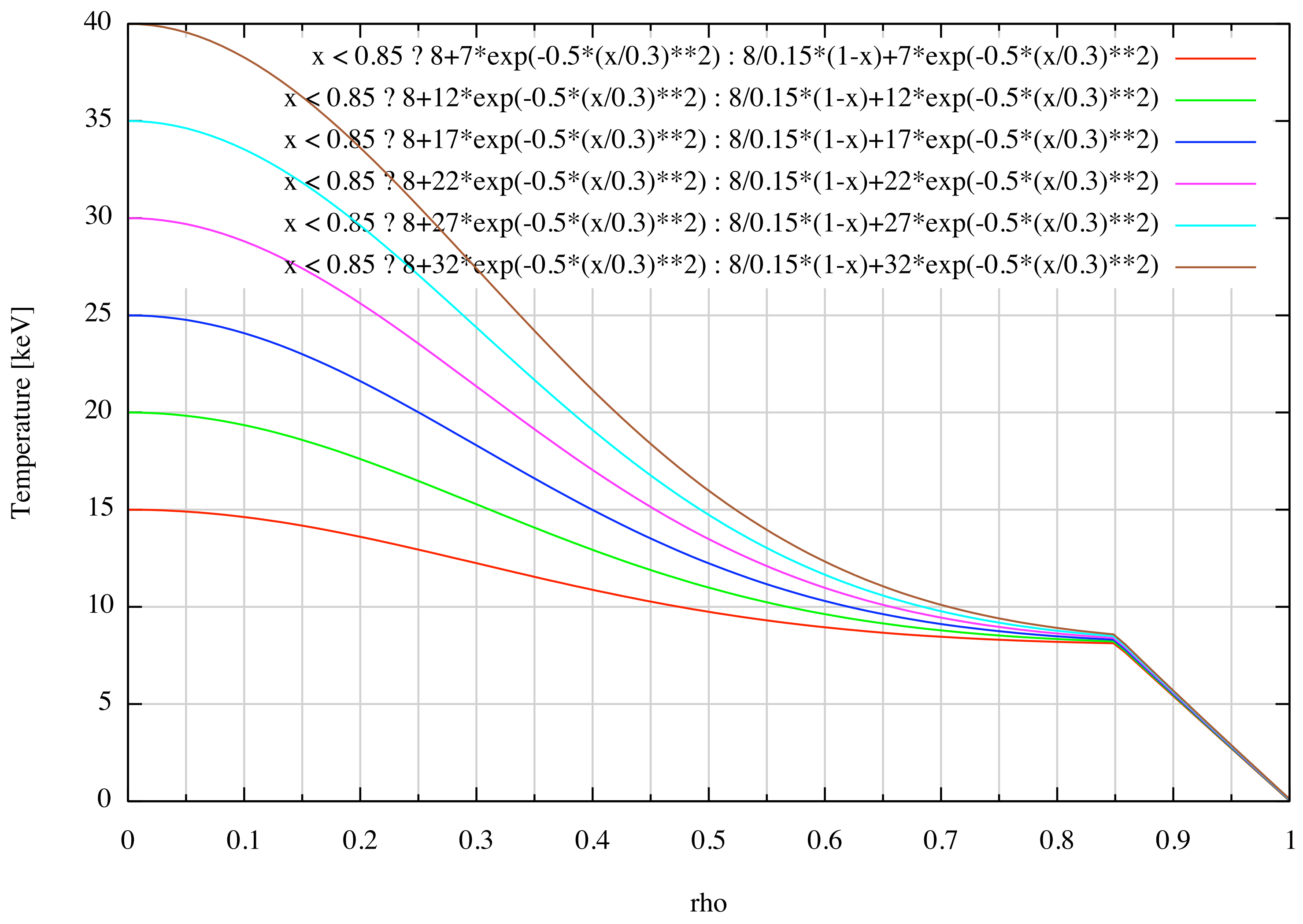
$$T_\mathsf{e}(\rho) = (T_\mathrm{axis} - T_\mathrm{edg})\exp\left(-\frac{\rho^2}{2\sigma_T^2}\right) + T_\mathrm{ped}(\rho)$$

$$T_\mathrm{edg} \equiv \frac{P_\mathrm{ped}}{n_\mathrm{edg}}, \qquad \rho_\mathrm{ped} = 1 - \frac{\Delta_\mathrm{ped}}{a}$$

$$\begin{aligned} T_\mathrm{ped}(\rho) &\equiv T_\mathrm{edg} && \text{for} \quad (0 < \rho < \rho_\mathrm{ped}) \\ &\equiv aT_\mathrm{edg}/\Delta_\mathrm{ped}(1-\rho) && \text{for} \quad (\rho_\mathrm{ped} \le \rho < 1) \end{aligned}$$

$$T_\mathsf{i}(\rho) = \gamma_T T_\mathsf{e}(\rho).$$

エッジ条件固定 $T_\mathrm{axis} \to T_e(r)$



Power Balance Analysis 4

$$\frac{3}{2}\frac{n_\mathsf{e}T_\mathsf{e}}{\tau_E^\mathsf{e}} = \frac{\tau_E}{\tau_E^\mathsf{e}}\frac{3}{2}\frac{n_\mathsf{e}T_\mathsf{e}}{\tau_E}, \qquad \frac{3}{2}\frac{n_\mathsf{i}T_\mathsf{i}}{\tau_E^\mathsf{i}} = \frac{\tau_E}{\tau_E^\mathsf{i}}\frac{3}{2}\frac{n_\mathsf{i}T_\mathsf{i}}{\tau_E}$$

$$\tau_E^\mathsf{e} = \gamma_\tau^\mathsf{e}\tau_E, \quad \tau_E^\mathsf{i} = \gamma_\tau^\mathsf{i}\tau_E, \quad T_\mathsf{i} = \gamma_T T_\mathsf{e} \qquad\qquad \tau_E = \tau_E^{\mathrm{IPB98y2}}$$

$$\langle P_{\mathrm{ohm}} + P_{\mathrm{aux}}^\mathsf{e} + P_\alpha^\mathsf{e} - P_{\mathrm{EP}} - P_{\mathrm{rad}}\rangle - \frac{3}{2}\frac{\langle n_\mathsf{e}T_\mathsf{e}\rangle}{\tau_E^\mathsf{e}} = 0$$

$$\langle P_{\mathrm{aux}}^\mathsf{i} + P_\alpha^\mathsf{i} + P_{\mathrm{EP}}^\mathsf{i}\rangle - \frac{3}{2}\frac{\langle n_\mathsf{i}T_\mathsf{i}\rangle}{\tau_E^\mathsf{i}} = 0$$

$$\rightarrow \quad \boxed{P_{\mathrm{aux}}}$$

$$T_\mathsf{i} = \boxed{\gamma_T}T_\mathsf{e}$$

設定パラメータ

$$\tau_E^\mathsf{e},\ \tau_E^\mathsf{i},\ \tau_{\mathsf{He}}^*,\ \phi_{\mathrm{aux}}^{\mathrm{NB}},\ Z'_{\mathrm{eff}} \quad P_{\mathrm{ped}}, \Delta_{\mathrm{ped}}, \sigma_T, n_{\mathrm{GW}},$$

スキャンパラメータ

$$\gamma_{\mathrm{peak}} \quad T_{\mathrm{axis}}$$

中間変数

$\mathrm{f}_{\mathsf{He}}, P_\alpha$, etc.

変数

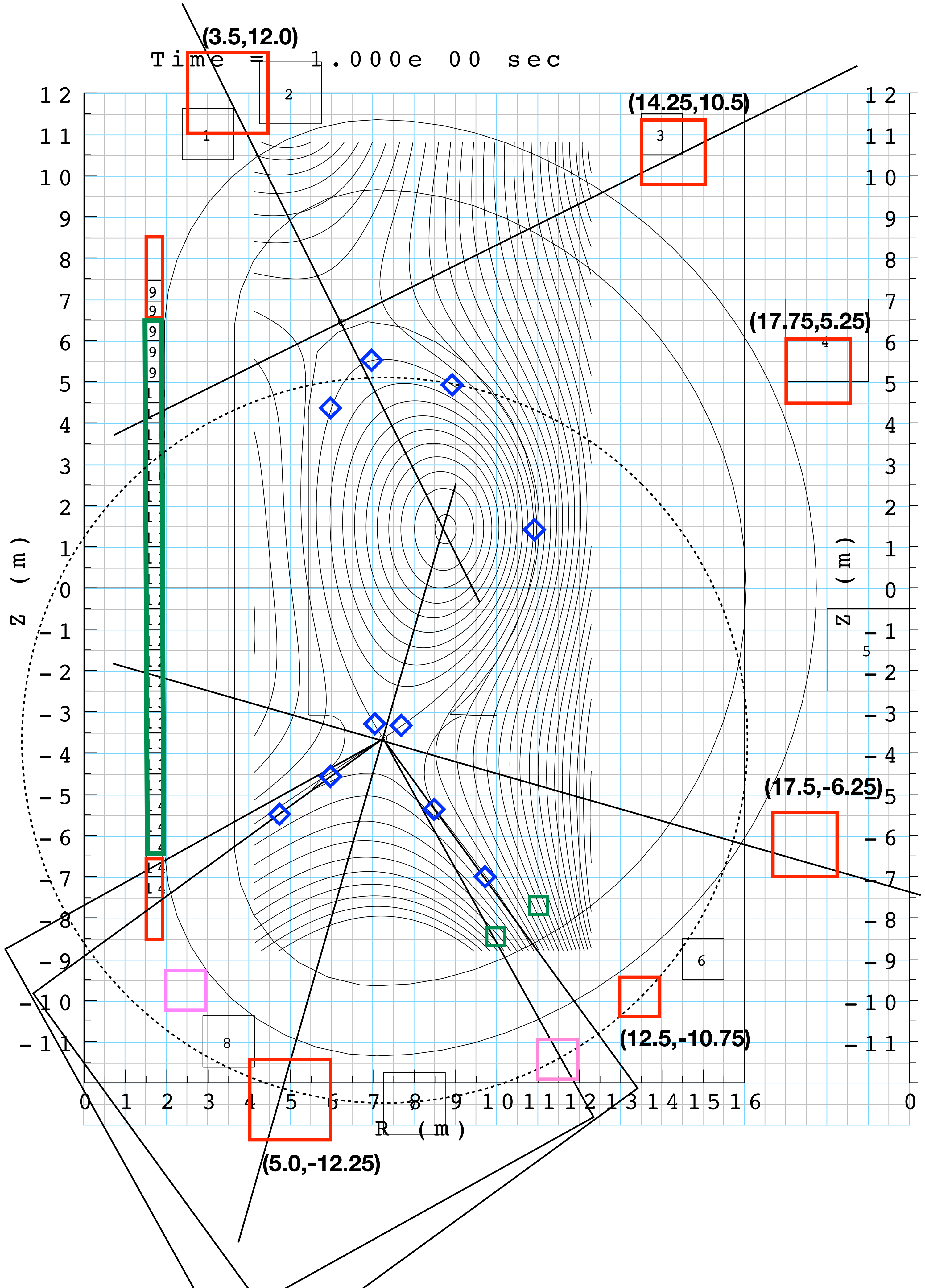
$\gamma_T,\ P_{\mathrm{aux}}$

Code Development is ongoing.

平衡制御

コイル配置の検討

- 各EFコイルの役割を明確化・できるだけ分離
- 縦方向位置、楕円度、三角度、SOL厚、X点、ストライク点
- コンビネーションロジックによる制御簡略化
- 平衡制御性評価の有効な指標が必要



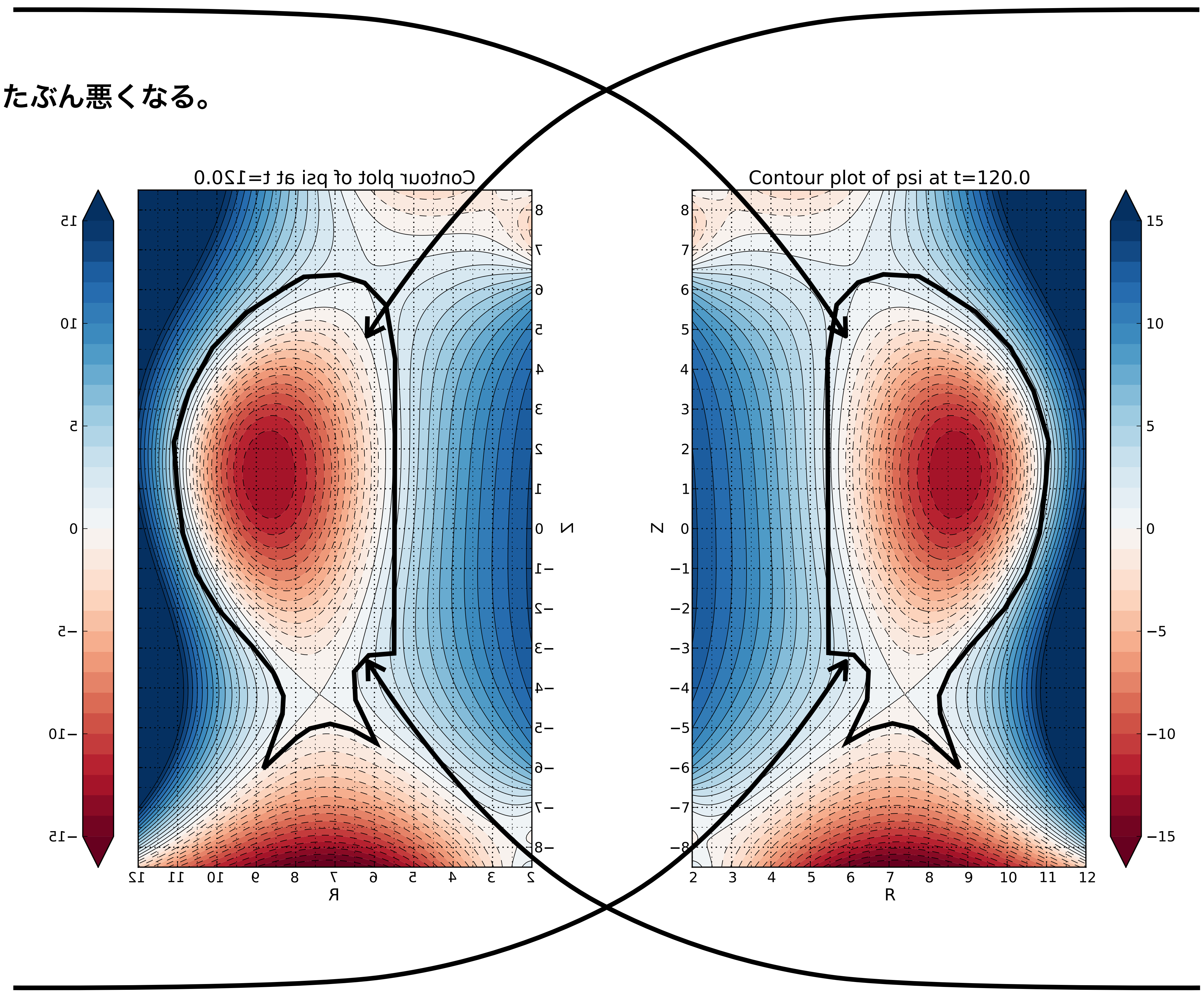
Summary

- 原型炉炉心プラズマ制御研究を目的として、大規模パラメータサーベイを目的として軽量統合コードATLASを整備した。
- 核融合出力をターゲットとして、燃料供給総量・燃料純度を介した制御シミュレーション研究を行い、その有効性と要請される制御装置性能について評価した。
- ペレットデポジション深さが最重要である一方、He還流率減少の出力への影響は限定的。
- しかしながら、現在のペレット入射装置性能からかけ離れた速度が要求される事が示された。ペレット入射装置の性能向上は、原型炉に向けて極めて重要な技術課題と言える。
- Te=Tiを想定した運転点設定の問題の改善、また炉心プラズマ性能から要求されるオペレーションを明確化する目的で、パワーバランスの定式化を行った。今後コード・可視化ツールを整備。

Ongoing and Future Works

HFS pelletクロス入射

メンテナンス性はたぶん悪くなる。



ダイバータレッグ伸張のためにトロイダルコイルをプラズマに対して縦長にすると、
HFSペレットの経路はさらに曲率が大きくならざるを得ない。