# Design of next step tokamak: Consistent analysis of plasma flux consumption and poloidal field system

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**Abstract.** A consistent and simple approach to derive plasma scenarios for next step tokamak design is presented. It is based on successive plasma equilibria snapshots from plasma breakdown to end of ramp-down. Temperature and density profiles for each equilibrium are derived from a 2D plasma model. The time interval between two successive equilibria is then computed from the toroidal field magnetic energy balance, the resistive term of which depends on n, T profiles. This approach provides a consistent analysis of plasma performance, flux consumption and PF system, including average voltages waveforms across the PF coils. The plasma model and the Poynting theorem for the toroidal magnetic energy are presented. Application to ITER-FEAT and to M2, a Q=5 machine designed at CEA, are shown.

## 1. Introduction

In the design of next step tokamaks a consistent analysis of plasma performance, flux consumption and Poloidal Field (PF) system is only performed at the final step, when a time-dependent code is run, including energy transport and flux diffusion (e.g. TSC [1]). Presently, in preliminary analysis plasma performance is evaluated using 0D or 1D plasma power balance codes (e.g. PRETOR [2]). The flux consumption is computed by the empirical Ejima formula [3] for current ramp-up and from an approximated loop voltage formula for flat-top.

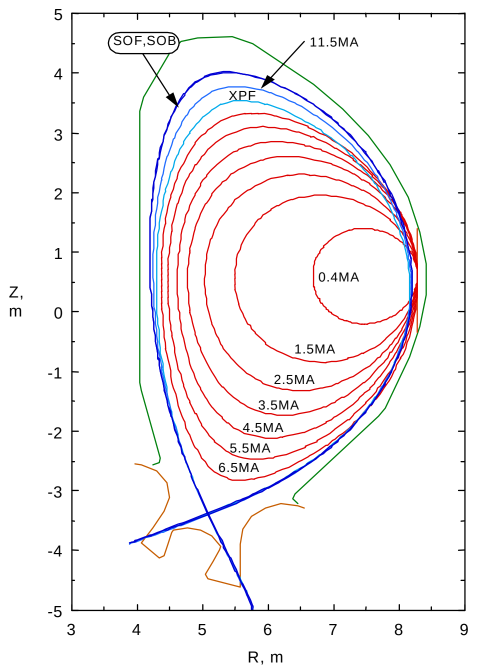


*Fig. 1. Successive plasma equilibria snapshots for the analysis of the ITER-FEAT inductive scenario [4]*

The poloidal field system analysis is based on successive plasma equilibria snapshots (fig.1) which provide the waveforms of the currents in the PF coils during the scenario. But the voltages across the PF coils cannot be derived from the snapshot sequence analysis since the Ejima approach doesn't provide the time interval between two successive equilibria.

The method we propose is based on the coupling of plasma performance analysis, and equilibrium computation. The coupling is done by volume and time integrated toroidal energy balance between the successive equilibria snapshots of a scenario (Poynting theorem). This balance allows to derive flux consumption and time interval between two successive equilibria thus allowing to analyze the influence of heating / current drive and bootstrap current fraction on flux consumption and PF coils voltages.

## 2. Poynting theorem for snapshot plasma scenarios

In axisymmetric configurations poloidal and toroidal fields and currents are cross coupled in Maxwell equations so that Poynting's theorems can be written for the total, toroidal and poloidal magnetic fields energies. The flux surface averaged Poynting's theorem for a tokamak plasma related to the toroidal magnetic field energy conservation can be derived from the neo-classical Ohm's law: $\langle \mathbf{E}.\mathbf{B}\rangle = \eta\langle(\mathbf{j}-\mathbf{j_N})\mathbf{B}\rangle$ combined with Ampere, and Faraday laws, it reads:

$$\left\langle \nabla.\left(\frac{\mathbf{B_t}\times\mathbf{E_p}}{\mu_0}\right)\right\rangle = \eta\frac{f'}{\mu_0}\left(f\,p' + \frac{\langle B^2\rangle}{\mu_0}f' - \langle \mathbf{j_N}.\mathbf{B}\rangle\right) + \frac{f\,f'}{\mu_0}\left\langle \frac{1}{R^2}\frac{\partial\psi}{\partial t}\right\rangle + \left\langle \frac{\partial}{\partial t}\left(\frac{B_t^2}{2\mu_0}\right)\right\rangle$$

where **E**, **B** are the electric and magnetic fields (angle brackets indicate the flux surface average); **j** is the total current density and $\mathbf{j_N}$ is any current not driven by the inductive electric field including the bootstrap current. $\eta$ is the parallel neo-classical resistivity. $B_0$ is the toroidal field at $R_0$, "t" (resp. "p") indices indicate toroidal (resp. poloidal) field components. f is the diamagnetic function, $\psi$ is the poloidal flux function and p is the total plasma pressure. The prime denotes derivation with respect to $\psi$ .

A control surface $S_c$ is chosen which includes all the plasmas of a given scenario (the inner side of the the first wall is a good choice for $S_c$) . Let's define $V_c$ as the volume enclosed by $S_c$ and $A_c$ as the domain enclosed by $S_c$ in the poloidal plane; $A_p$ is the plasma cross section in the poloidal plane. The Poynting theorem is volume integrated over $V_c$ and time integrated between an initial equilibrium at $t_i$ and a final equilibrium at $t_f$ with $\Delta t = t_i - t_f$. Let M(X) be the value of X averaged over the initial and final equilibria and $\Delta$(X) be the variation of X between initial and final equilibria ($M(X) = (X^f + X^i)/2$, $\Delta(X) = X^f - X^i$). The time interval $\Delta t$ between the two equilibria can be approximated by:

$$\Delta t \approx \frac{M(R_0 B_0)\Delta\left(\int_{A_C}\frac{f}{R}dA\right) - \int_{A_C}\frac{M(ff')}{\mu_0 R^2}\Delta(\psi)dA - \Delta\left(\int_{A_C}\frac{RB_t^2}{2}dA\right)}{M\left(\int_{A_P}R\eta f'\left(f\,p' + \frac{B^2}{\mu_0}f' - \mathbf{j_N}.\mathbf{B}\right)dA\right)}$$

The initial and final plasma temperatures and densities profiles are needed to compute the denominator, which is the "resistive dissipation" term of the toroidal energy balance. The profiles are taken as generalized parabolic profiles: $x(\overline{\psi}) = x_0(1-\overline{\psi}^2)^{\alpha_x}$ where $\overline{\psi}$ is the normalized poloidal flux function. The equilibrium total pressure profile is obtained by integration of the "pressure" term of plasma current density. The density and temperature profiles of the plasma species are consistently derived from the total equilibrium pressure. The plasma species include electrons, D, T ions, fast and thermal alphas, one intrinsic and one seeded impurity. The fraction of thermal alpha is calculated assuming that the ratio of the alpha apparent confinement time to the energy confinement time $\tau^*_{\alpha t}/\tau_E$ is fixed. The fraction of fast alpha is obtained as the solution of a simplified Fokker-Planck equation.

## 3. Plasma scenarios of ITER-FEAT and M2

The consistent analysis of performance, flux consumption and PF system was used to derive inductive scenarios for ITER-FEAT [5] and M2, a Q=5 machine designed at CEA [7].

- **ITER-FEAT** is a Q ≥ 10, ≈ 400s inductive plateau machine with high neutron fluence.

- **M2** is a Q ≈ 5, ≈ 500s inductive plateau machine with low neutron fluence. The rationale for the conceptual design of M2 at CEA was to analyze how a reduction of the amplification factor and of the neutron fluence requirement impacts on the size. Limiting the total DT operation of the machine to 700 hours (i.e. ≈5000 shots) the shielding requirements are kept to a minimum. Two versions of M2 were studied: **M2S** a super-conducting machine and **M2C** a copper magnets machine. They both have the same plasma parameters since the larger radial extension of M2C TF coils is compensated by the smaller shielding radial extension.

TAB. I: MAIN PARAMETERS OF ITER-FEAT AND M2

| | **R**(m) | **a**(m) | **A** | $\mathbf{B_0}$(T) | $\mathbf{I_p}$(MA) | $\kappa_{95}$ | $\delta_{95}$ |
|---|---|---|---|---|---|---|---|
| **ITER-FEAT** | 6.2 | 2.00 | 3.1 | 5.30 | 15 | 1.70 | 0.35 |
| **M2** | 5.0 | 1.43 | 3.5 | 5.43 | 9 | 1.63 | 0.35 |

Starting from the breakdown plasma, the successive equilibria of a complete scenario are determined by tuning, for each equilibrium:

- the flux linkage of the plasma with the PF coils (this is done by adding to PF coils cur
- rents PF current distributions that generate no magnetic field in the vacuum vessel).
- the pressure profile (i.e. heating power)

The goal of the equilibrium tuning is to find an optimized scenario which:

- minimize the cost of the current drive devices and of the PF coils power supplies
- maximize the plasma performances and the flat top duration.
- while keeping the plasma parameters in a safe operating space ($\beta_N$, Greenwald density and L-H transition limits).

In practice for each snapshot equilibrium the operating space in the $\langle n_e \rangle$, $\langle T_e \rangle_n$ plane is determined. Examples for the EOB equilibrium of ITER-FEAT (resp. M2) are shown on fig.2 (resp. fig.3). The following parameters were used for the determination of the operating space:

- no fast alpha, $\tau^*_{\alpha t}/\tau_E$ =5 for thermal alphas
- profiles: $n(\overline{\psi}) = n_0\left(1-\overline{\psi}^2\right)^{\alpha_n}$ $T(\overline{\psi}) = T_0\left(1-\overline{\psi}^2\right)^{\alpha_T}$, with $\alpha_n = 0.01$ and $\alpha_T = 1.05$
- constant intrinsic (Be), seeded (Ar) impurities fractions ( $f_{Be} = 2\%$, $f_{Ar} = 0.12\%$ )
- H mode scaling for $\tau_E$ : $\tau_{E,IPB98(y,2)}$ for ITER-FEAT (fig.2), $\tau_{E,IPB98(y)}$ for M2 (fig.3)
- ITER-FEAT H-L power threshold expression [5]

The operating space is limited by the $\beta_N \approx 2.5$ contour, the Greenwald density limit and the H-L transition contour (fig.2 and 3).

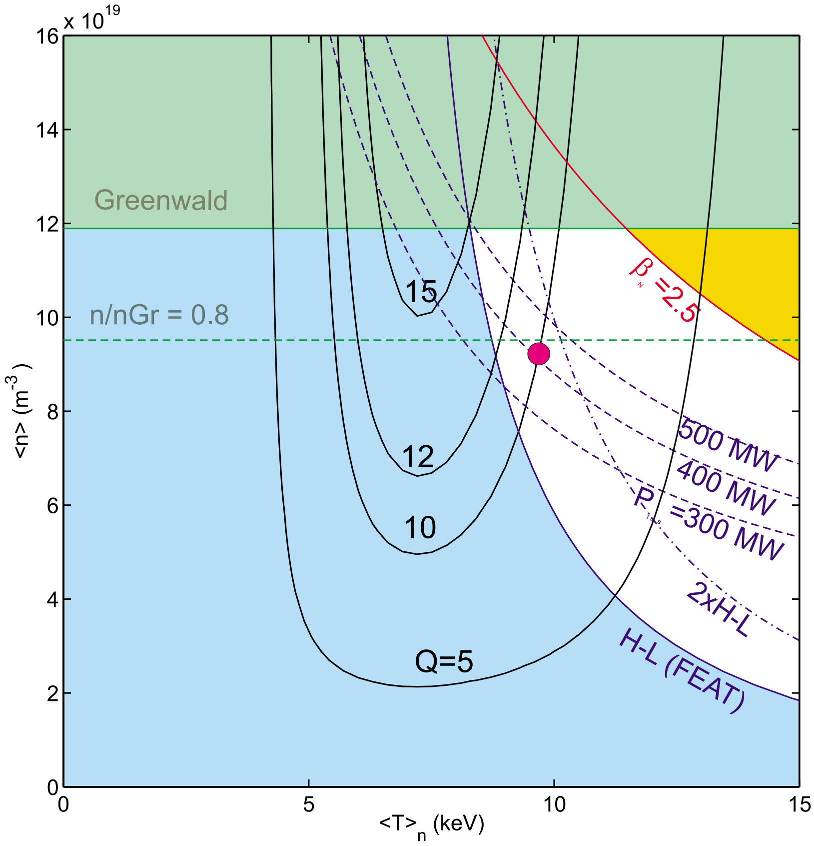


*Fig. 2. Q and $P_{fusion}$ contours for FEAT inductive scenario [5]*

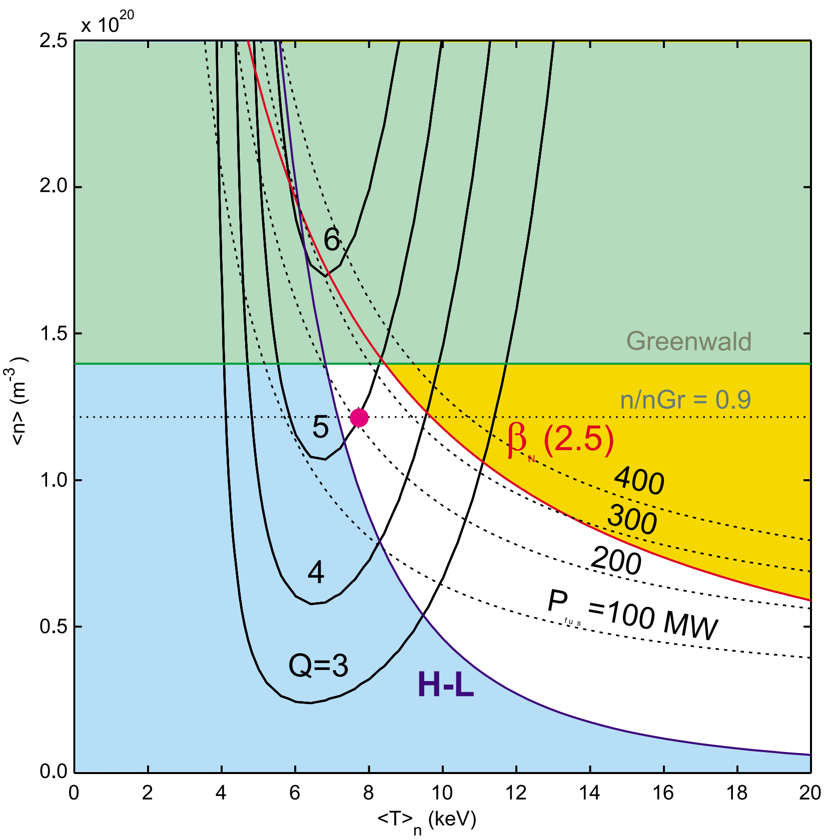


*Fig. 3. Q and $P_{fusion}$ contours for M2 inductive scenario [7]*

In the $<n_e>$, $<T_e>_n$ plane the time interval $\Delta t$ can be computed along a constant total plasma pressure contour (the one corresponding to the equilibrium pressure) for different values of the plasma density. In the case of the EOB equilibrium $\Delta t$ corresponds to the flat top duration. The influence of bootstrap current, heating and non inductive current drive (NICD) on $\Delta t$ are automatically taken into account. To comply with limits on the PF coils loop voltage and /or the plasma current rise $\Delta t$ can be tuned by adding NICD current, by increasing the equilibrium $\beta$ and by modifying the pressure profile. The PF Coils voltages during ramp-up for the reference inductive scenario of ITER-FEAT were computed with the CEDRES++ equilibrium finite element code and fit the reference values (fig. 4).

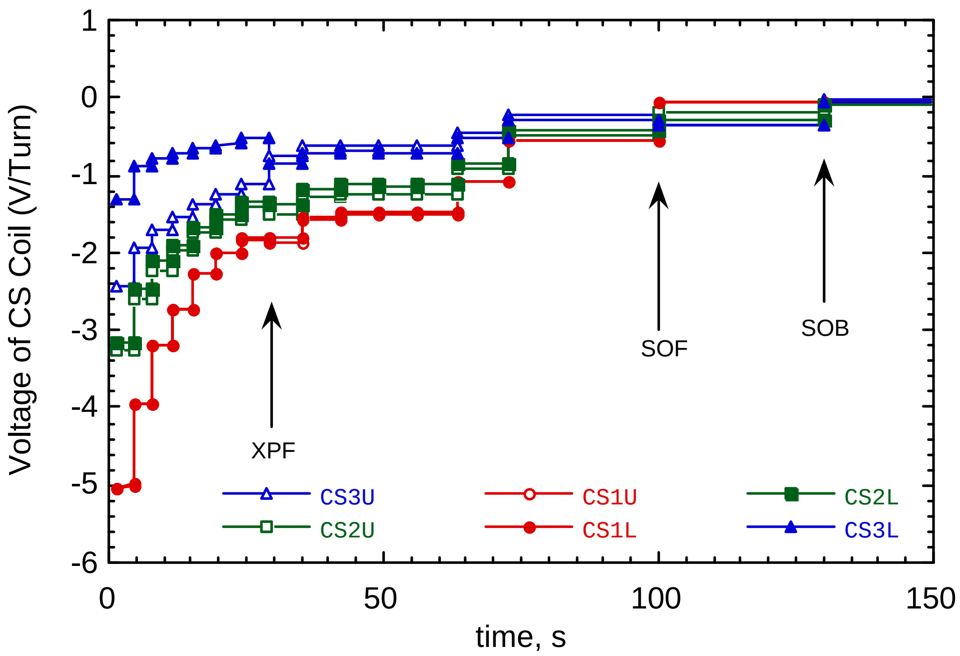


*Fig. 4 Central Solenoid voltages at ramp-up for the reference inductive scenario of ITER-FEAT* [5]

## 5. Conclusion

The coupling of plasma performance analysis with 2D equilibrium computation through toroidal magnetic field energy balance (Poynting theorem) allows to derive consistent plasma scenarios. Flux consumption analysis, poloidal field system design and plasma performance are consistently determined in a simple step by step process of plasma scenario computation. The visualization of the operating space in the $<n_e>$, $<T_e>_n$ plane at each stage make it easy to constrain the tokamak to remain in the domain of allowed parameters.

## References

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