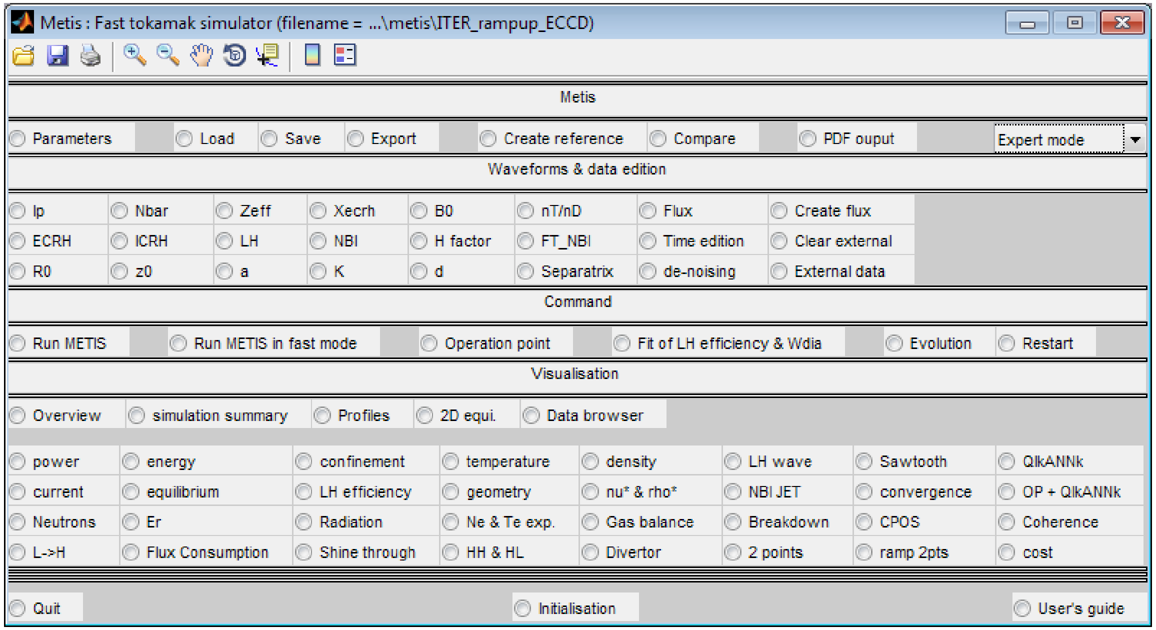
DE LA RECHERCHE À L'INDUSTRIE

METIS:
CORE & EDGE COUPLING



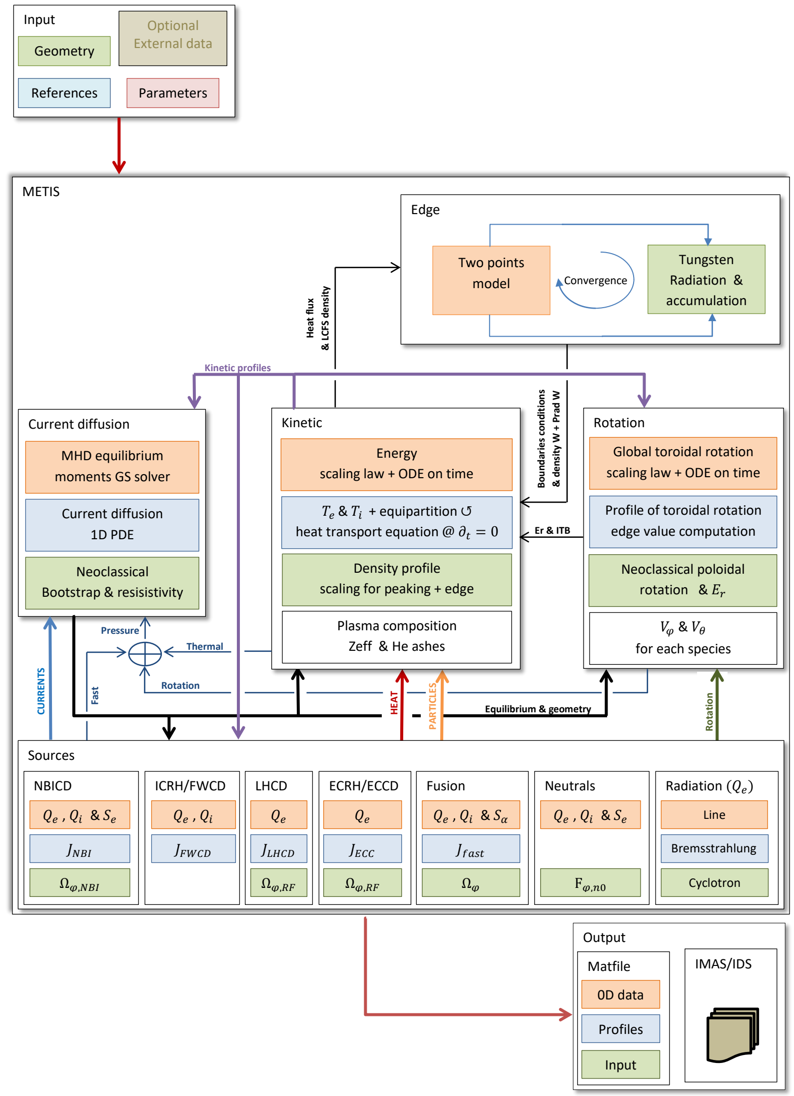
JEAN-FRANCOIS ARTAUD

TUESDAY, 22 JUNE 2021

www.cea.fr

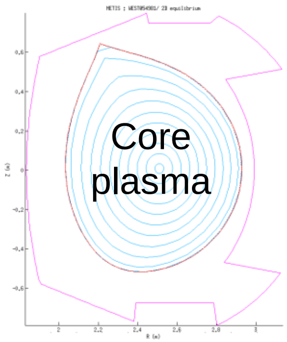
METIS CORE EDGE COUPLING OVERVIEW

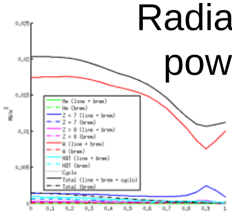
- Main goal of this model is modelling back reaction of divertor condition on core plasma through radiative power:
  - Core W profile model
  - 2-point (extended) model
  - Simplified W source from divertor
- Mainly an “heuristic” model:
  - Many free parameters
  - Scaling laws
- Dedicated to:
  - Plasma control studies
  - Experiment analysis

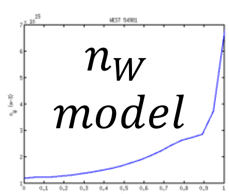


OVERVIEW CORE/EDGE COUPLING IN METIS

Parameters $(\lambda_q, ...)$







$n_{e,u}$

P_{LCFS}

$T_{e,u}$

$C_{W,LCFS}$

Extended 2-point model

$$2n_t T_t = n_u T_u$$

$$T_u^{7/2} = T_t^{7/2} + \frac{7}{2}\frac{q_\parallel L}{\kappa_{0e}}$$

$$q_\parallel = \gamma n_t k T_t c_{st}$$

+ additional cumulative effects

$T_{e,u}$ $n_{e,t}$ $T_{e,t}$

Tungsten source model

Sputtering → Prompt redeposition → Screening

TUNGSTEN PROFILE IN METIS

$$n_W(t,x) = \left(C_W\, G(t) + C_{W,offset} + C_{W,LH}\, P_{LH} + C_{W,IC}\, P_{IC} + C_{W,EC}\, P_{EC} + C_{W,NBI}\, P_{NBI}\right)$$

$$n_{e,a}(t)\left(\frac{n_e(t,x)}{n_{e,a}(t)}\right)^{\gamma_n} e^{\sigma\, \overline{Z_W} I(t,x)}$$

Back reaction from divertor **normalized to LCFS density (METIS)**

C_W , γ_n , σ, $C_{W,offset}$, … are user defined constants

Contamination/ decontamination factor (neoclassical like + rotation + heat):

$$\frac{dI}{dx} = C_{\Omega,W}\, u_\Omega + \frac{\frac{dn_i}{dx}}{n_i} + \left(1 - \frac{1}{\overline{\overline{Z_W}}} - k_{neo} - C_{H,W}\, h_{e,i}\right)\frac{\frac{dT_i}{dx}}{T_i}$$

$C_{\Omega,W}$ and $C_{H,W}$ user defined constants

$$u_\Omega = -\frac{\frac{d\Omega}{dx}}{R_{axe}\, v_{th,W}} \qquad h_{e,i} = \frac{q_{e,i}}{q_e + q_i}$$

2-POINT MODEL IN METIS (1/5): OVERVIEW

- Stangeby formulation:

  "The Plasma Boundary of Magnetic Fusion Devices, Institute of Physics Publishing, Bristol 2000"

  - Inputs (control parameters) :
    - LCFS electron density
    - power crossing the LCFS
  - Outputs:
    - Electron temperature and density at target
    - Electron temperature at LCFS
    - Various flux
- Extended formulation:
  - Additional effects can be taken into account
  - Can be switched on or off

2-POINT MODEL IN METIS (2/5): EXTENDED FORMULATION (MAIN EFFECT)

- Neutral friction / momentum losses:
  - User defined
  - Analytical model (Self S A and Ewald H N 1966 Phys. Fluids 9 2486 cited in C S Pitchery and P C Stangeby, Plasma Phys. Control. Fusion 39 (1997) 779–930)
  - Recycling fraction at the target / neutral density (P.C. Stangeby NF 51,2011, 063001)
  - Wisitsorasak / Pegourié additional term (Plasma and Fusion Research: Volume 14, 3403150, 2019)
- Radiative losses (R. Clark et al, Journal of Nuclear Materials, vol 220-222,1995,p 1028-1032):
  - ADAS cooling rate
  - Non-coronal Equilibrium State (A. A. Mavrin , J Fusion Energ, DOI 10.1007/s10894-017-0136-z)
  - Carbon blow effect (M. Warrier, R. Schneider and X. Bonnin, Computer Physics Communications 160 ,2004, 46-48)

2-POINT MODEL IN METIS (3/5): EXTENDED FORMULATION (ADDITIONAL)

- supersonic flow / detachment

  (JET-P(64) 05 , P. H. Harbour and A. Loarte)

- kinetic correction / flux limitation

  (W. Fundamenski, PPCF 47 2005 p R163-R208)

- Radial position of the target / flux expansion

  (T.W. Petrie et al, Nuclear Fusion 53,2013, 113024)

- Impurities concentration in divertor (radiation & sputtering):
  - User defined concentration enrichment in divertor for light impurities

    (N,Ar, …) as defined in METIS composition

2-POINT MODEL IN METIS (4/5): PARAMETERS DEFINITION

- The key parameter: radial decay length
  - User defined
  - Scaling law:
    - H-mode: Goldston model for lambda_q Nucl. Fusion 52 (2012) 013009
    - L-mode: F.D. Halpern et al , Nuclear Fusion 53 (2013) 122001
- Connection length:
  - Depend on configuration defined in METIS
  - Can be increased to take into account X-point.
- sheath transmission factor (γ): formula 25.46 in Stangeby book.
- Power fraction
  - only one side (LFS or HFS)
  - User defined fraction

2-POINT MODEL IN METIS (5/5): PARAMETERS DEFINITION

- $T_{i,u} \neq T_{e,u}$

$$4 n_t T_t = f_{mom} f_{i/e} n_u T_{eu} \qquad \& \qquad f_{i/e} \equiv 1 + T_{iu} / T_{eu}$$

f_{mom} is a user defined parameter (≤ 1)

(P.C. Stangeby and A.W. Leonard 2011 Nucl. Fusion 51 063001)

- Fraction of power going to electron (P.C. Stangeby and A.W. Leonard 2011 Nucl. Fusion 51 063001)
  - $f_{pe} = 0.5$ (standard 2-point model)
  - $f_{pe} = q_{e,LCFS} / \left(q_{e,LCFS} + q_{i,LCFS}\right)$
- Turbulence heat flux spreading (D Nille et al, Plasma Phys. Control. Fusion 61 (2019) 085016; A. Scarabosio et al, Journal of Nuclear Materials 463 (2015) 49–54)

TUNGSTEN SOURCE FROM DIVERTOR (1/4): OVERVIEW

Back reaction from divertor

$$G(t) = Y_p(t)\, S_r(t)\, \left(1 - F_r(t)\right)$$

Sputtering **Screening** **Prompt-redeposition**

- Each term can be switched on or off in METIS

TUNGSTEN SOURCE FROM DIVERTOR (2/4): SPUTTERING

$$Y_p(t) = \sum_{j\in\{species\}} \frac{n_j(t,1)}{n_{e,a}(t)}\, y_{j\to W}\left(E_j(t)\right)$$ + enrichment effect of low Z in divertor

$$E_j(t) = T_{e,t}(t) + (2+\Gamma_H) * T_{i,t}(t) - 0.5\, Z_j\, T_{e,t}(t)\, ln\left(\frac{2\pi\, m_e}{m_j}\left(1+\frac{T_{i,t}(t)}{T_{e,t}(t)}\right)\right)$$

$$T_{i,t}(t) = \eta_t T_{e,t}(t)$$ Γ_H is 1 for the isothermal case and $\frac{5}{3}$ for the adiabatic case

- Model for the sputtering yield :
  - Janev R.K. et al Journal of Nuclear Materials 290-293 (2001) 104-106
  - Warrier M. et al., Computer Physics Communications 160 (2004) 46-68

TUNGSTEN SOURCE FROM DIVERTOR (3/4): SCREENING

$$S_r(t) = e^{-\left(\frac{T_{leak}(t)}{T_{e,t}(t)}\right)^2} \qquad T_{leak}(t) = 3.8\ 10^{-9}\ \overline{Z_W}\left(T_{SOL,eff}(t)\right)\sqrt{n_{e,t}(t)\Delta s(t)}$$

$$\Delta s(t) = \frac{\sqrt{\dfrac{2\ e\ T_{e,t}(t)}{m_{eff}(t)}}}{n_{e,t}(t)\left(\langle\sigma v\rangle_{i,e}(t) + \langle\sigma v\rangle_{i,i}(t) + \langle\sigma v\rangle_{cx}(t)\right)\mu_t(t)}$$

$$T_{SOL,eff}(t) = f_{SOL,eff}\, T_{e,a} + \left(1 - f_{SOL,eff}\right) T_{e,t}$$

$\mu_t(t)$ is the angle of magnetic field line (2-point model)

- Simplified version of model described in (including only temperature dependence):
  - Stangeby P.C.: “ The Plasma Boundary of Magnetic Fusion Devices” (Institute of Physics Publishing, Bristol 2000)

TUNGSTEN SOURCE FROM DIVERTOR (4/4): PROMPT-REDEPOSITION

$$F_r = f_{ERO}\left(\frac{l_{W,ion}}{\rho_{W^+}}\right) \qquad l_{W,ion} = \frac{\sqrt{\frac{2\,e\,T_{e,t}}{m_W}}}{\langle\sigma v\rangle_{W,ionised}\left(T_{e,t}\right)\,n_{e,t}}$$

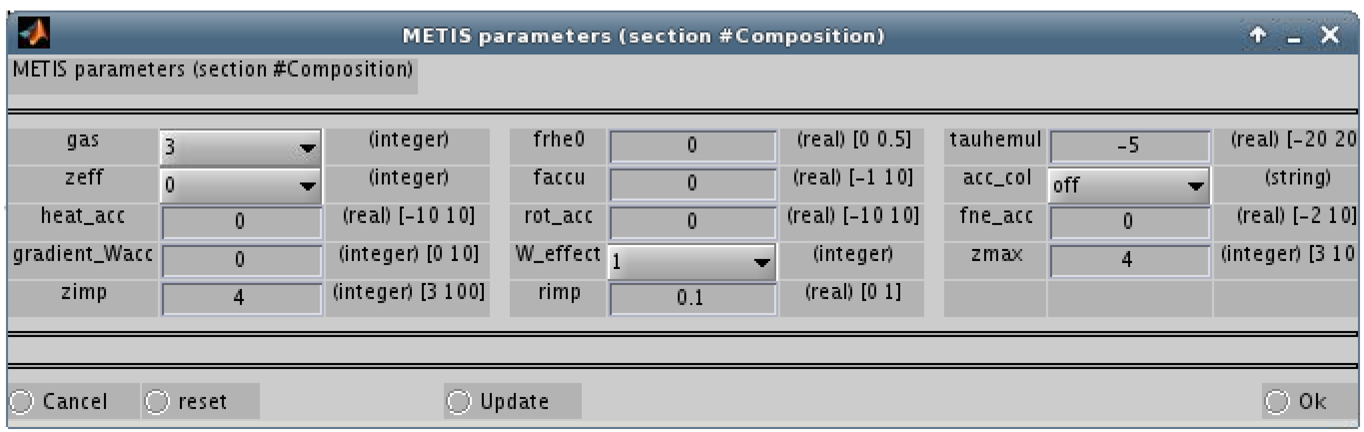
ρ_{W^+} is the tungsten ionised one time Larmor radius

x	0	0.2	0.6	2.2	3.2	6	1000
$f_{ERO(x)}$	1	0.85	0.65	0.3	0.25	0.15	0.1

- Fit of ERO code data:
  - Stangeby P.C. NF 51 (2011) 063001
  - Naujoks D. et al NF 36 (1996) 671

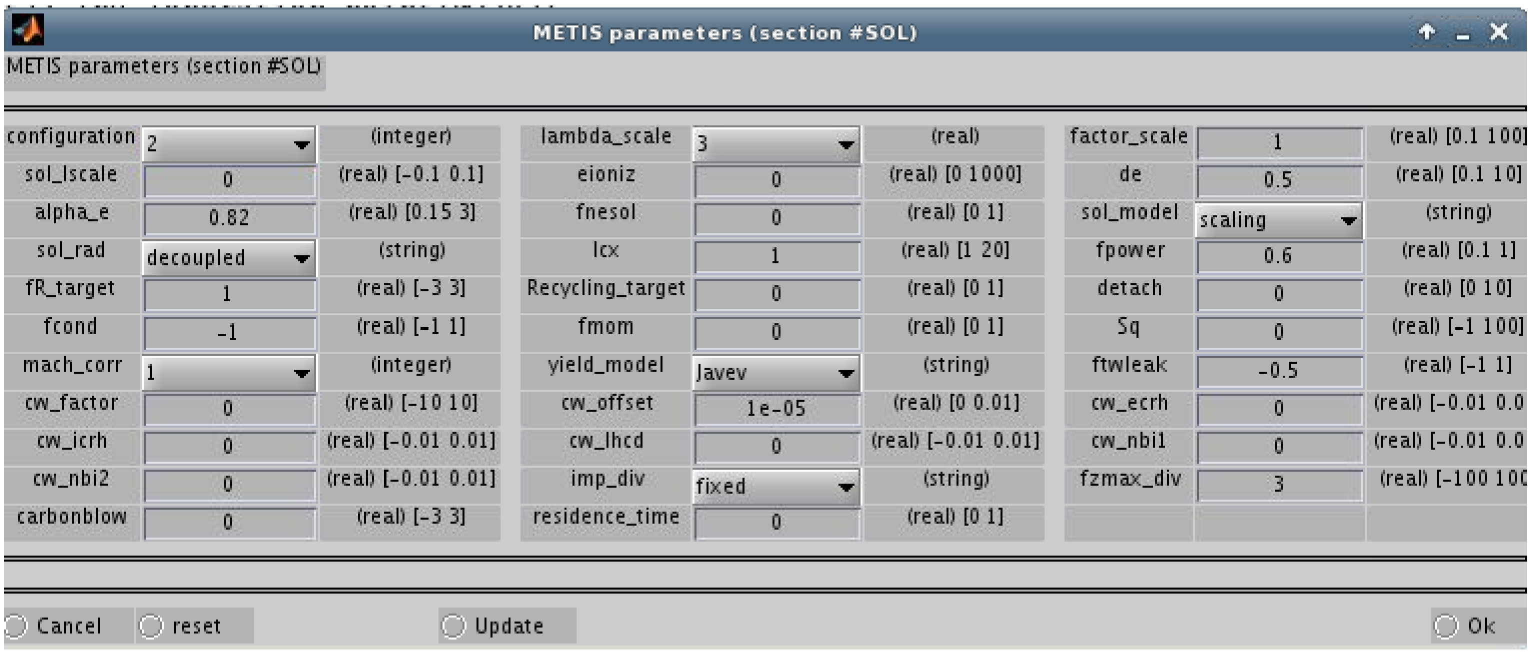
HOW TO TUNE THE MODEL (1/2)

- Tungsten profile model can be tune in “Composition” section of METIS parameters:
  - W_effect switch on/off model for tungsten with profile effect in METIS
  - faccu, heat_acc and rot_acc tune the neoclassical like model for accumulation
  - fne_acc is the exponent of the dependence on density profile
  - acc_col switch from fixed k_neo factor (-3/2) to analytical expression.

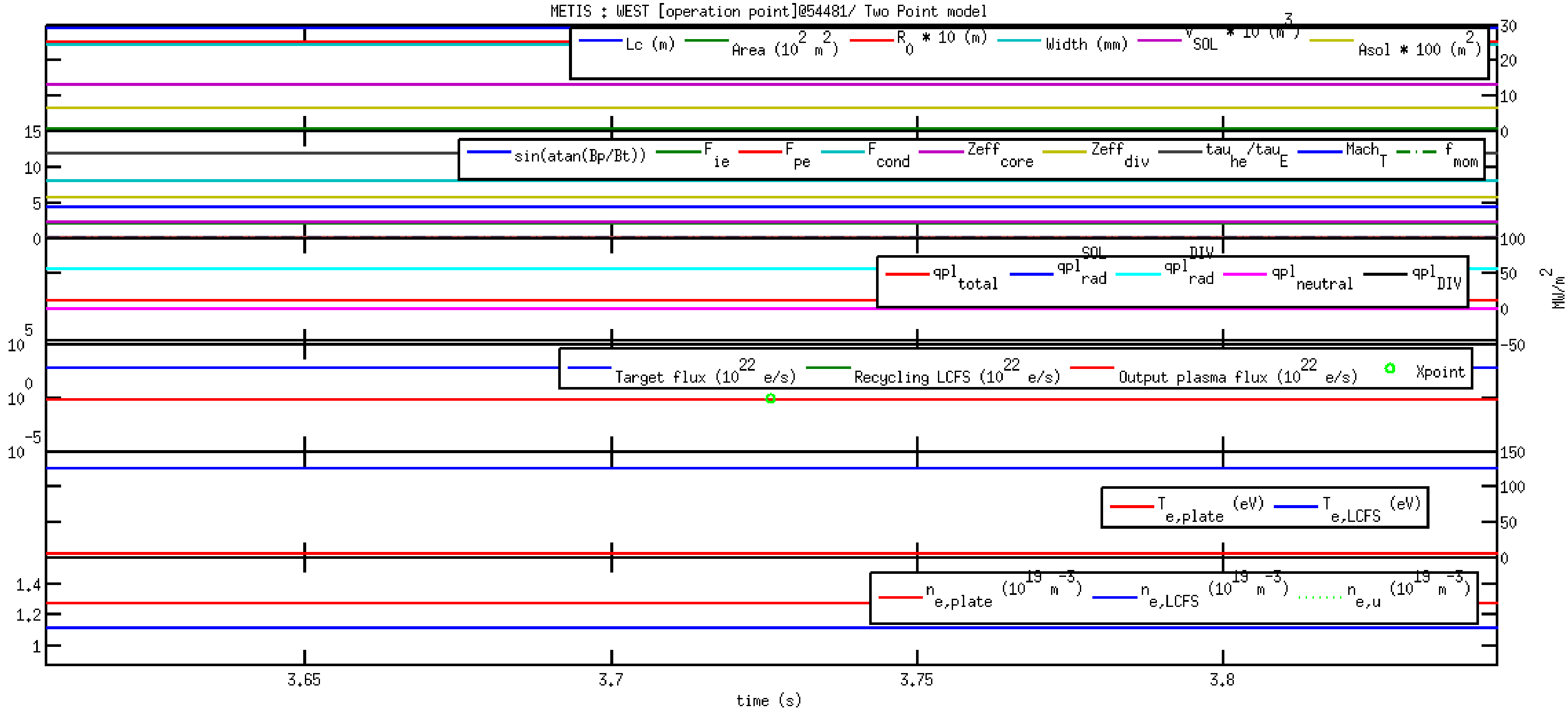


HOW TO TUNE THE MODEL (2/2)

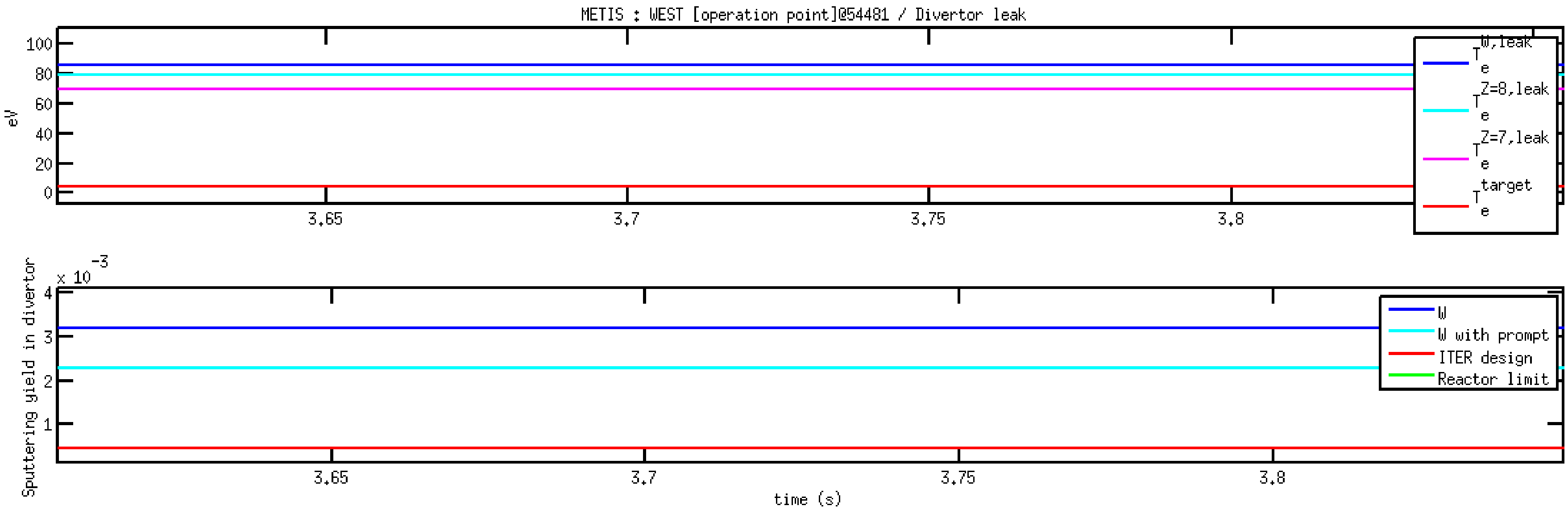
- 2-point model and tungsten source model can be tune in “SOL” section of METIS parameters:
  - sol_rad parameter must be set to “decoupled” to use 2-point model
  - sol_model must be set to “2_point” to switch on 2-point model use



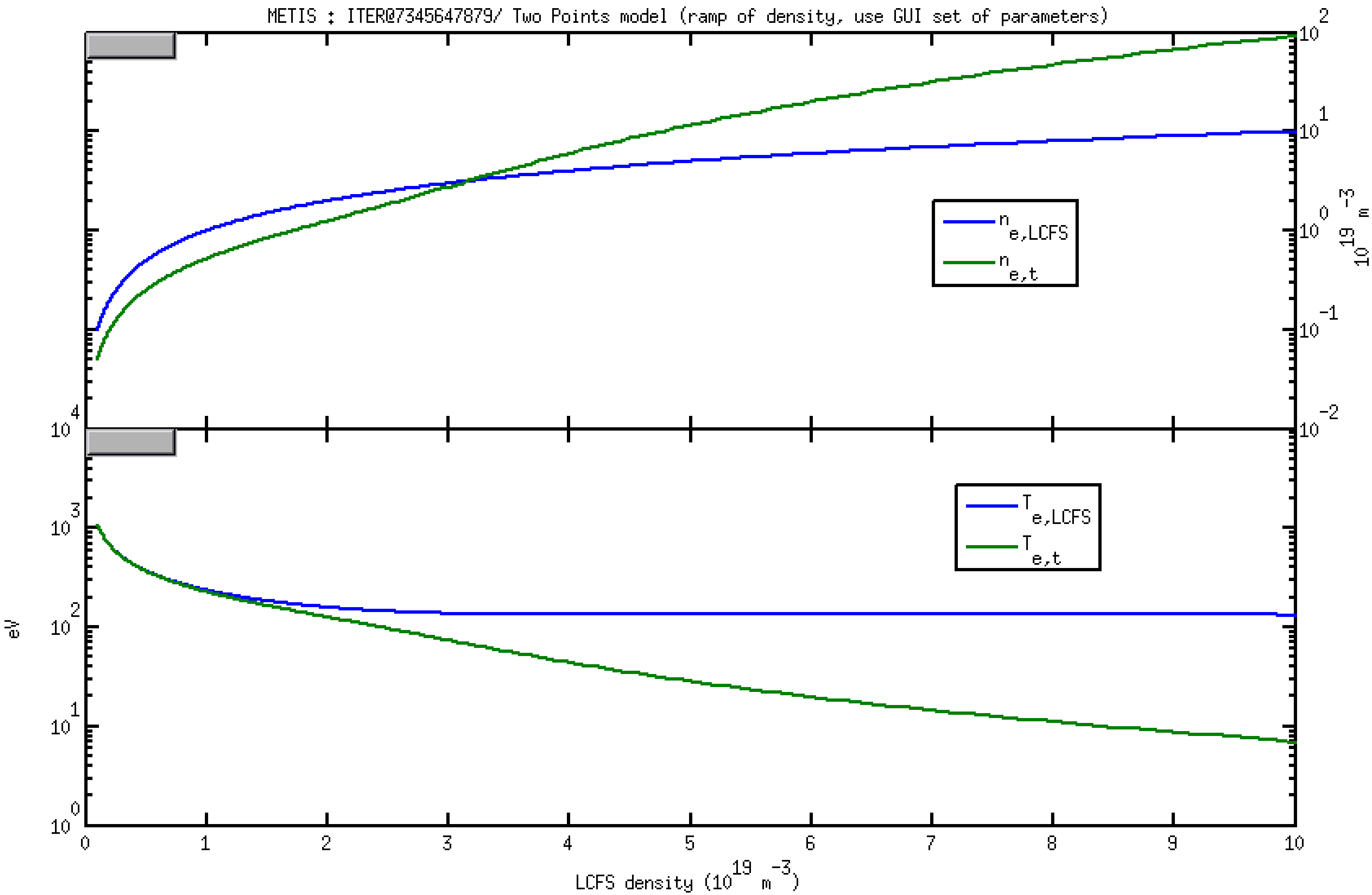
EXAMPLE: 2-POINT MODEL RESULTS



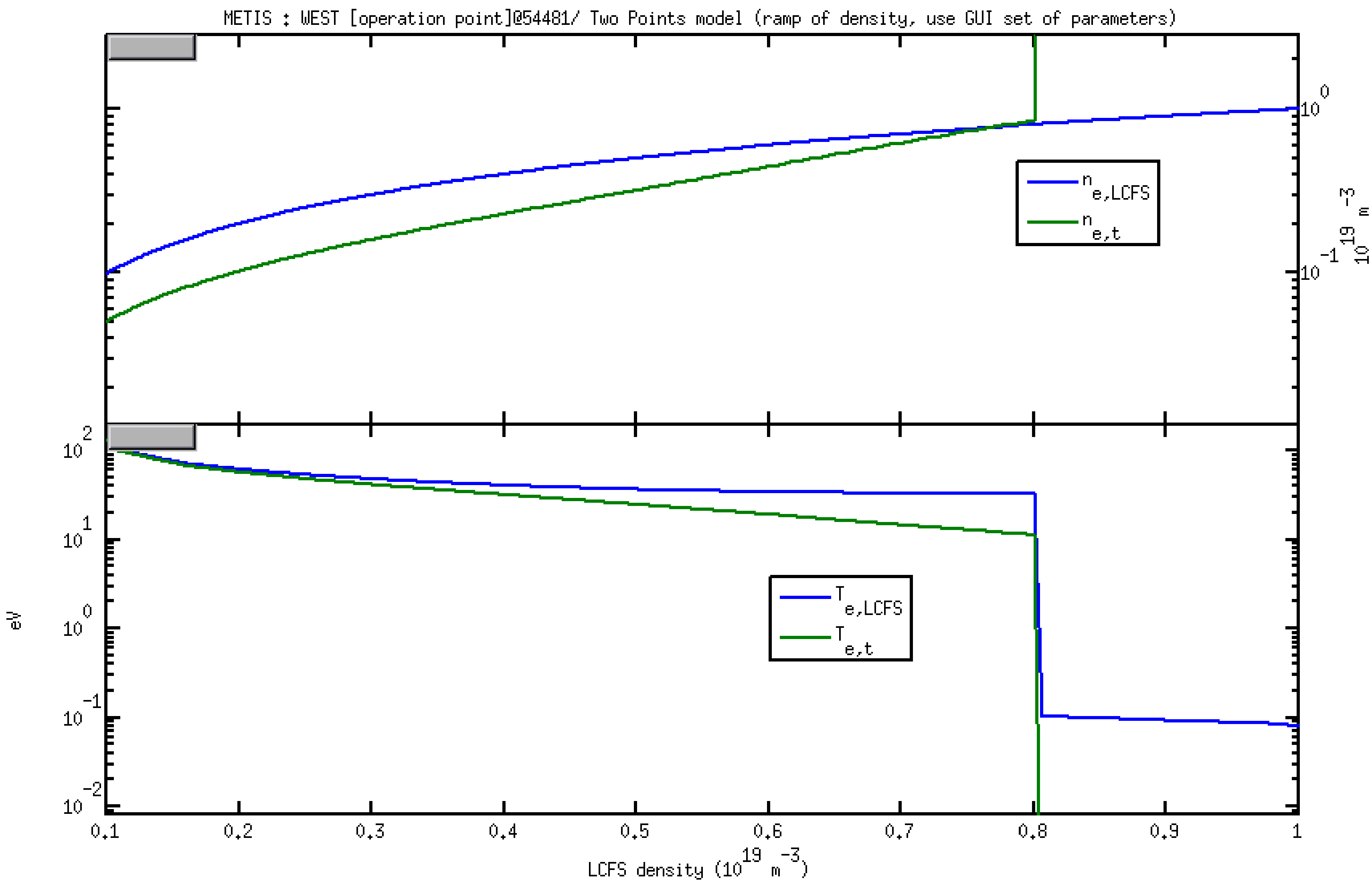
EXAMPLE: TUNGSTEN SOURCE



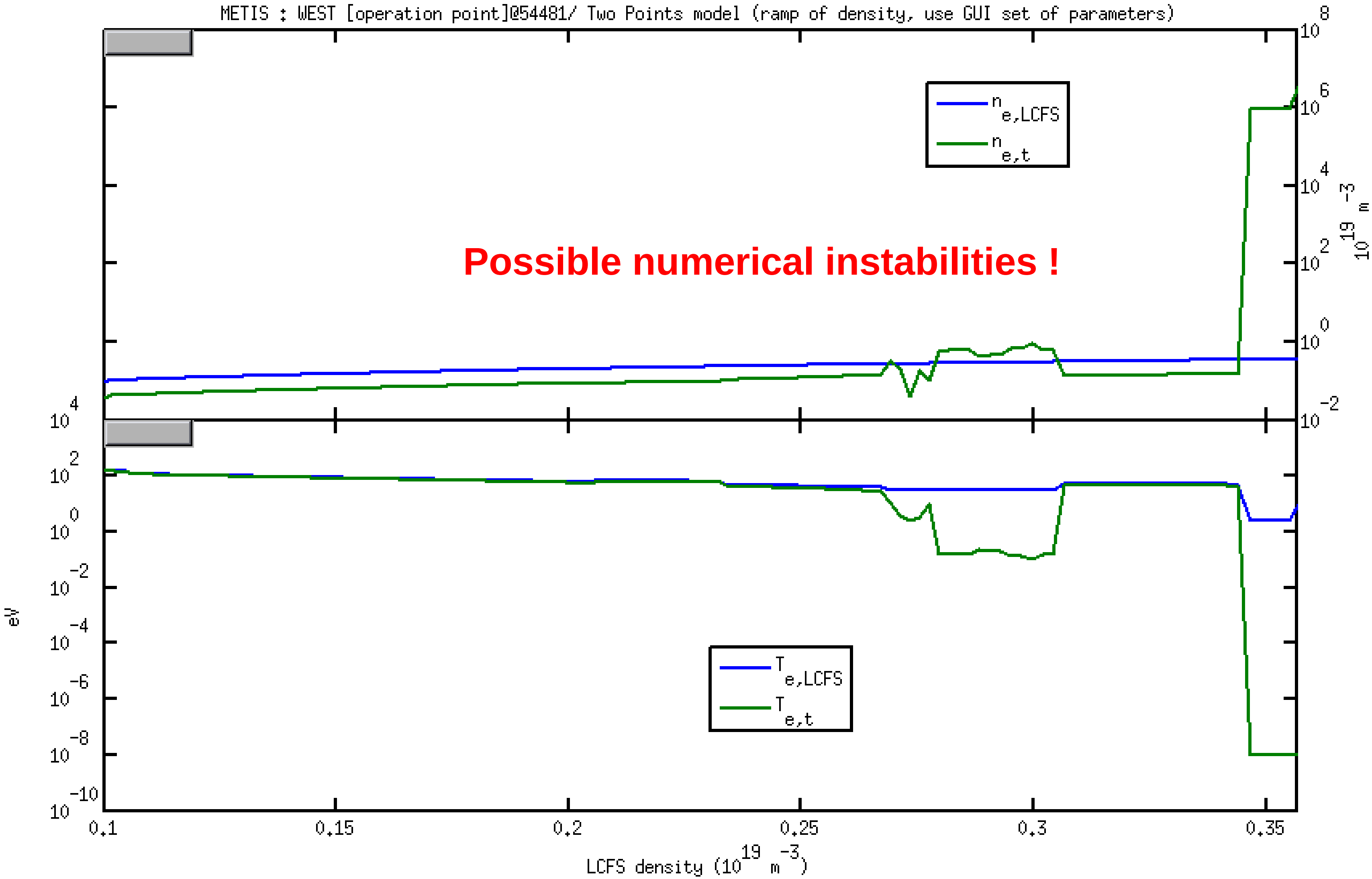
EXAMPLE: CHANGE OF REGIME



EXAMPLE: DETACHMENT LIKE BEHAVIOR USER DEFINED VALUE FOR FMOM



EXAMPLE: DETACHMENT LIKE BEHAVIOR ANALYTICAL MODEL FOR FMOM



CONCLUSIONS

- METIS is coupled to a “heuristic” model for the SOL:
  - Extended 2-point model
  - W source from the divertor to the core plasma
  - W profile model in the core plasma with ability to mimic W accumulation
- The model is versatile thank to parametrization
  - Plasma control
  - Experiment analysis
  - Low predictive capabilities (if you don’t trust scaling laws)
- The use of this model increase computational time
- Can reproduce plasma detachment:
  - But some physics is missing (especially with neutral, drift, …)
  - 0D cumulative mechanisms instead of 3D effects
- Possibility to make some scan using METIS working point mode
  - Only one time slice for steady state

Commissariat à l’énergie atomique et aux énergies alternatives
Centre de Cadarache | 13108 Saint Paul Lez Durance Cedex
T. +33 (0)4 42 25 46 59 | F. +33 (0)4 42 25 64 21

DRF
IRFM
SPPF

Etablissement public à caractère industriel et commercial | RCS Paris B 775 685 019