Status of radiation transport in EIRENE

Ray Chandra

20 November 2023

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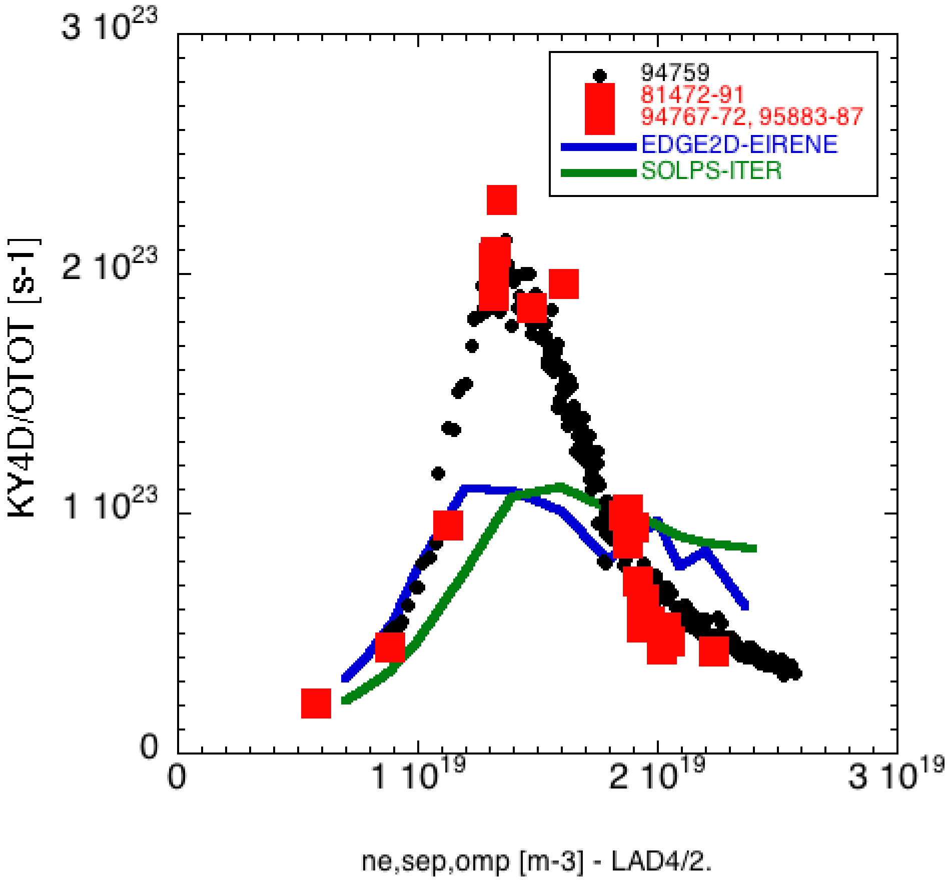
Several outstanding issues with code runs and physics models currently investigated

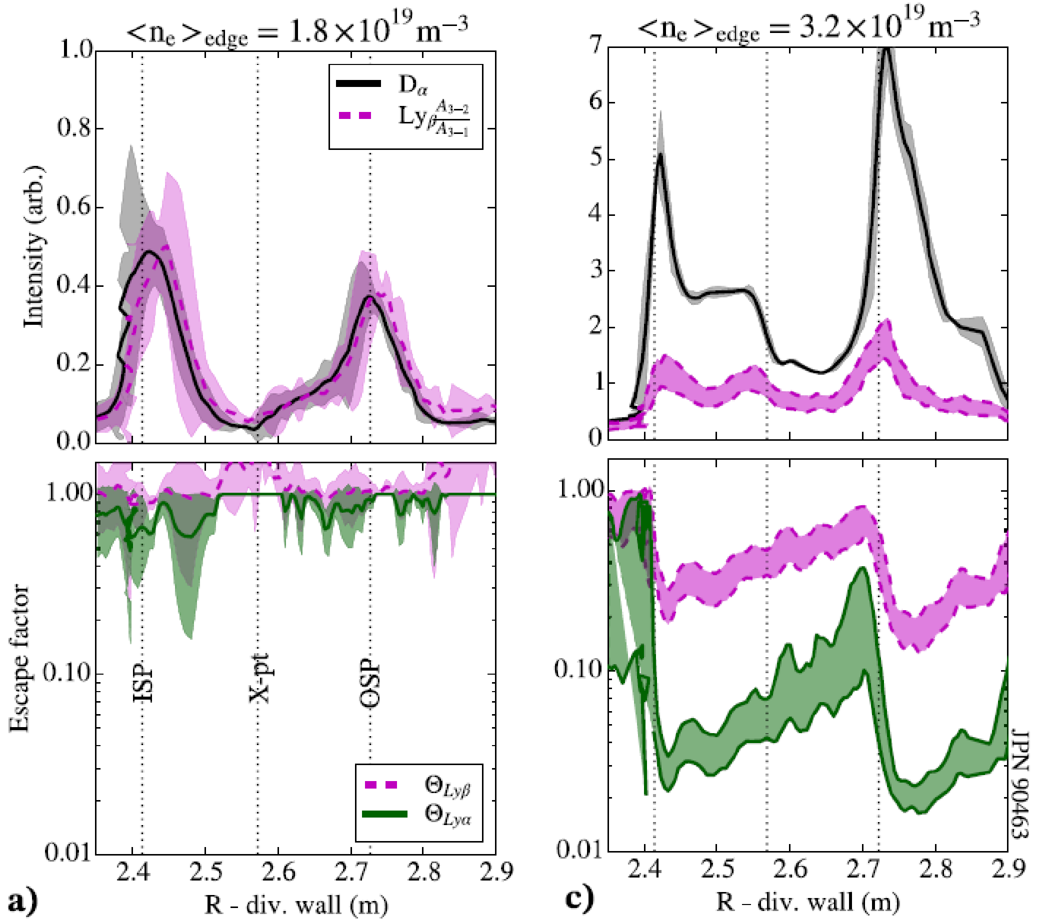
N. Horsten et al.



- Separatrix location → $n_{e,sep,omp}$
- Fixing $n_{e,sep,omp}$ vs fuelling/pumping
- Impact of vibrationally resolved molecules (c.f., U. Fantz, JNM 2001)
- Increase of I_{div} due to inclusion of Ly-a opacity (c.f., B. Lomanowski, PPCF 2020)
- Transport of molecular ions
- Necessary grid resolution for detached conditions

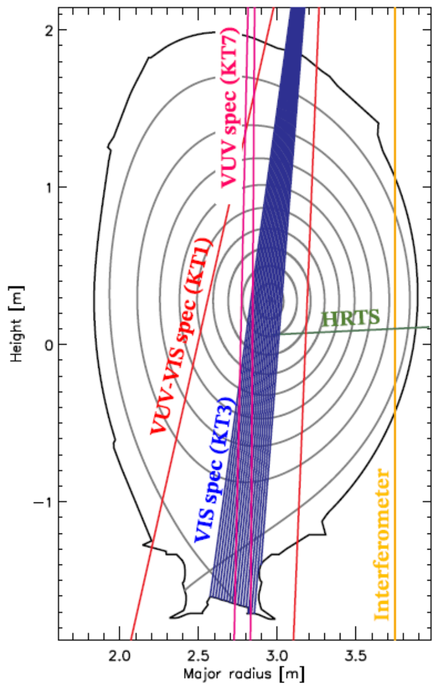
M. Groth, IAEA-TM CR Properties W & H, Vienna, Austria (2021)

Ly-a opacity experimentally observed with KT1 in JET D L-mode



B Lomanowski et al., Plasma Physics and Controlled Fusion 62, 6:065006 (2020)

- Constant $\frac{Ly_\beta}{D_\alpha}$ in the optically thin case
- 94-98% Ly_α absorption at high densities



- Ad-hoc opacity factors in the model (constant, not self-consistent):

Photon transport using EIRENE!

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Line radiation trapping in EIRENE by including Line photons as test-particles

- Analog description → *D. Reiter et al., Plasma Physics and Controlled Fusion 44, 8:1723–37 (2002)*

- Requirements:
  1. Photon sources – for line radiation, excited species of atoms

  2. Rate coefficients – spont. Emission, absorption: line shape

  3. Reflections – simple specular model

- Result → line absorption tallies Q_{ext}

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Solving the population of H excited states with collisional-radiative model within EIRENE – h_colrad.f

- Based on *K. Sawada et al., Journal of Applied Physics 78, 2913 (1995)*

$$\begin{bmatrix} \frac{dn_{\mathrm{D}_2}}{dt} \\ \frac{dn_{\mathrm{D}_3}}{dt} \\ \vdots \\ \frac{dn_{\mathrm{D}_n}}{dt} \end{bmatrix} + \underbrace{\begin{bmatrix} M_{22} & M_{23} & \cdots & M_{2n} \\ M_{32} & & \ddots & M_{3n} \\ \vdots & & & \vdots \\ M_{n2} & & \cdots & M_{nn} \end{bmatrix}}_{\mathbf{M}} \begin{bmatrix} n_{\mathrm{D}_2} \\ n_{\mathrm{D}_3} \\ \vdots \\ n_{\mathrm{D}_n} \end{bmatrix} = \underbrace{\begin{bmatrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{bmatrix}}_{\boldsymbol{C}} n_{\mathrm{D}_1} + \underbrace{\begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_n \end{bmatrix}}_{\boldsymbol{F}} n_{\mathrm{D}^+} + \begin{bmatrix} \Gamma_{\mathrm{D}_2} \\ \Gamma_{\mathrm{D}_3} \\ \vdots \\ \Gamma_{\mathrm{D}_n} \end{bmatrix}$$

- **M, C, F** are ne,te dependent rate coefficients, explicitly coded in h_colrad.f up to n=34

- Q_{ext} inserted as Γ_{D_n}

- In steady-state:

$$\begin{bmatrix} n_{\mathrm{D}_2} \\ n_{\mathrm{D}_3} \\ \vdots \\ n_{\mathrm{D}_n} \end{bmatrix} = \boldsymbol{C}\mathbf{M}^{-\mathbf{1}} n_{D_1} + \boldsymbol{F}\mathbf{M}^{-\mathbf{1}} n_{D^+} + \begin{bmatrix} \Gamma_{\mathrm{D}_2} \\ \Gamma_{\mathrm{D}_3} \\ \vdots \\ \Gamma_{\mathrm{D}_n} \end{bmatrix} \mathbf{M}^{-\mathbf{1}} = \boldsymbol{R}_{\mathbf{1}} n_{D_1} + \boldsymbol{R}_{\mathbf{0}} n_{D^+} + \boldsymbol{R}_{\boldsymbol{ext}}$$

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New plasma ionization balance and neutral H mfp from modified effective ionization rate coefficient, S_{eff}

$$S_{eff} = S_1 + \underbrace{\sum_n \left(C_{1,n} - R_{1,n} \left(F_{n,1} + \frac{A_{n,1}}{n_e} \right) \right)}_{S_{eff,cr}} + \underbrace{\sum_n \left(Q_{ext,n} - R_{ext,n} \left(F_{n,1} + \frac{A_{n,1}}{n_e} \right) \right)}_{S_{eff,ph}}$$

- 'Extra' ionization contribution from photon re-absorption, $S_{eff,ph}$
- $S_{eff,cr}$ normally read from AMJUEL or ADAS files, in this case S_{eff} calculated internally

Individual test cases for photon tracing and h_colrad

Testing h_colrad:

- EIRENE 2D grid with ne and Te varied along x and y dimensions
- Ne, 20 points, ~1e8 – 1e16 cm3
- Te, 200 points, ~0.5 – 1e4 eV

Testing photon tracing:

- EIRENE 1D cylindrical grid with 20 radial points
- Homogeneous T_H = 1 eV, n_H = 10^{14} cm^{-3} , R = 5 cm
- Simulated Ly-a and Ly-b photons (2e6) with volumetric sources ($H_{(n=2,3)}$ as bulk ions)
- Line shape only doppler broadening

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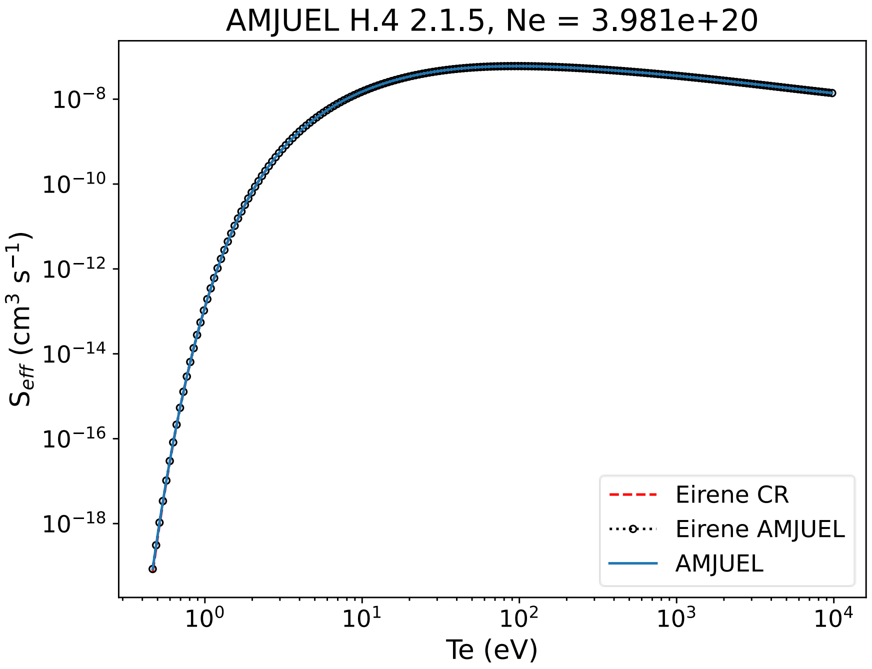
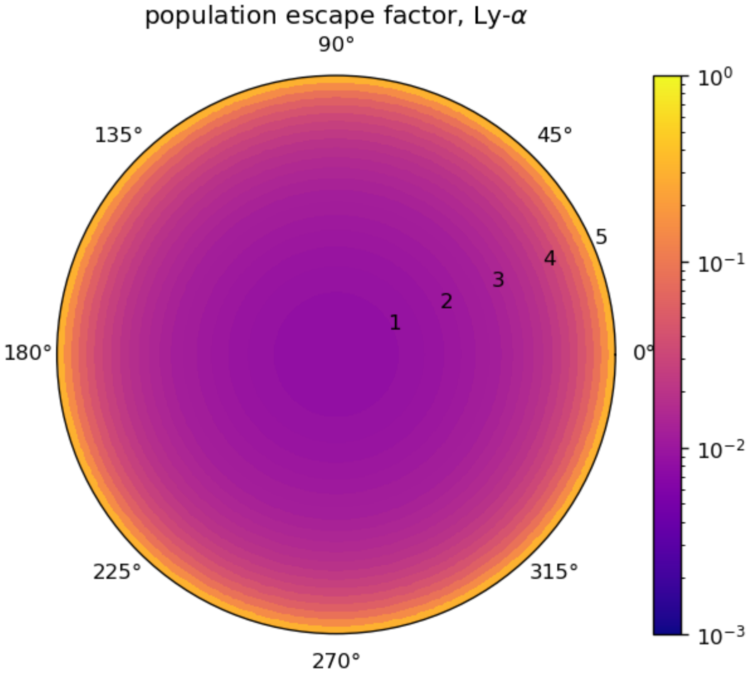
Individual test cases for photon tracing and h_colrad

Testing h_colrad:



Testing photon tracing:



TSVV-5 Code Camp 21-25 November 2022

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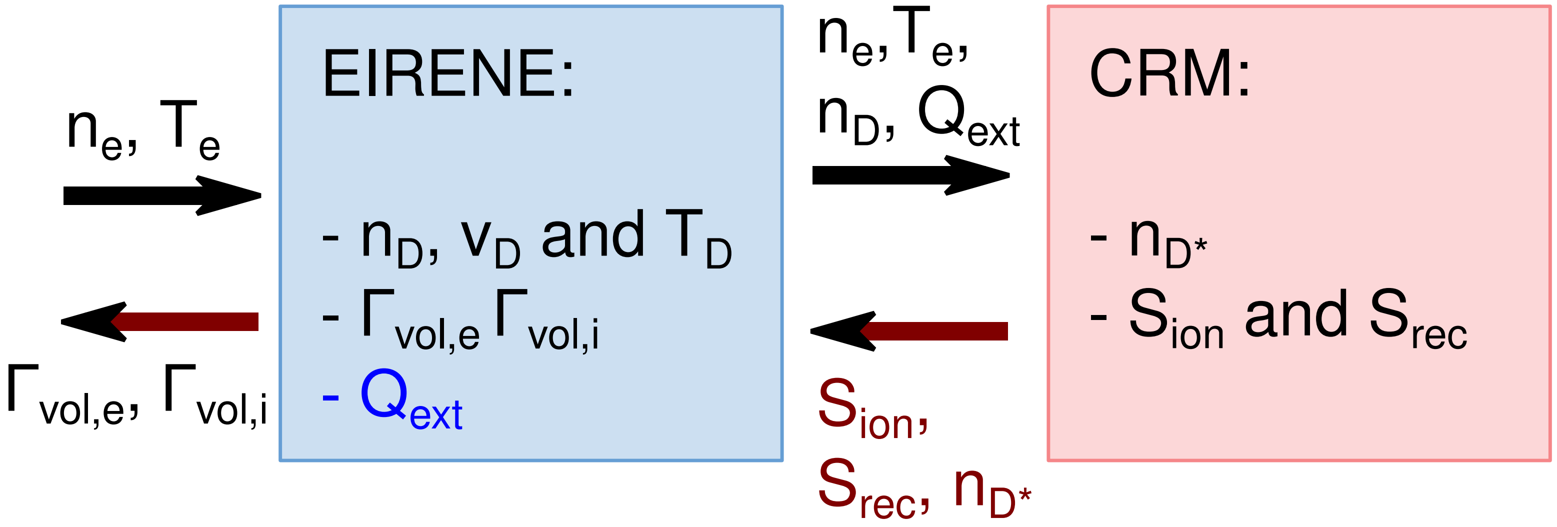
Photon-gas coupling for self-consistent $Q_{ext} \rightarrow S_{eff} \rightarrow n_H$



- EIRENE provides Q_{ext} to CRM, CRM provides S_{eff} and n_{D*} (photon sources) to EIRENE
- First implementation in EIRENE version coupled to EDGE2D (March 2023)

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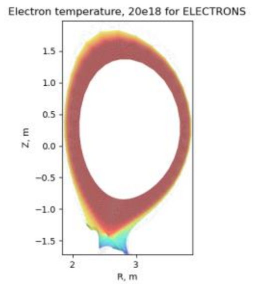
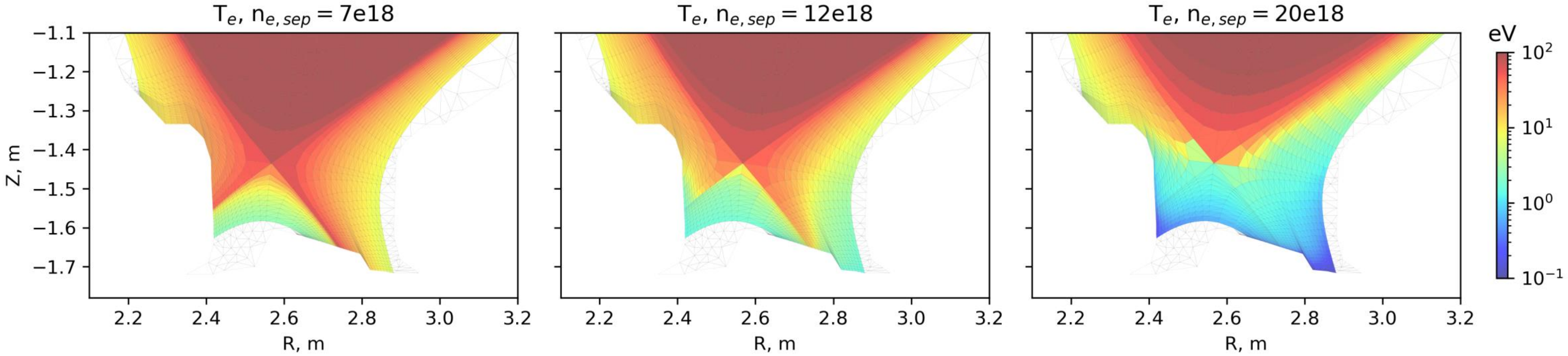
Radiation transport applied to static plasma solutions from JET81472 D+Be EDGE2D-Eirene runs[1]



- $n_{e,sep}$ = 0.6e19 – 2.2e19
- Ly-alpha and Ly-beta as test-particles
- Shown for low-recycling, high-recycling and detached ($n_{e,sep}$ = 0.7e19, 1.2e19, 2.0e19)



[1]M. Groth et al., *Journal of Nuclear Materials* 463 (August 2015): 471–76, https://doi.org/10.1016/j.jnucmat.2014.12.030.

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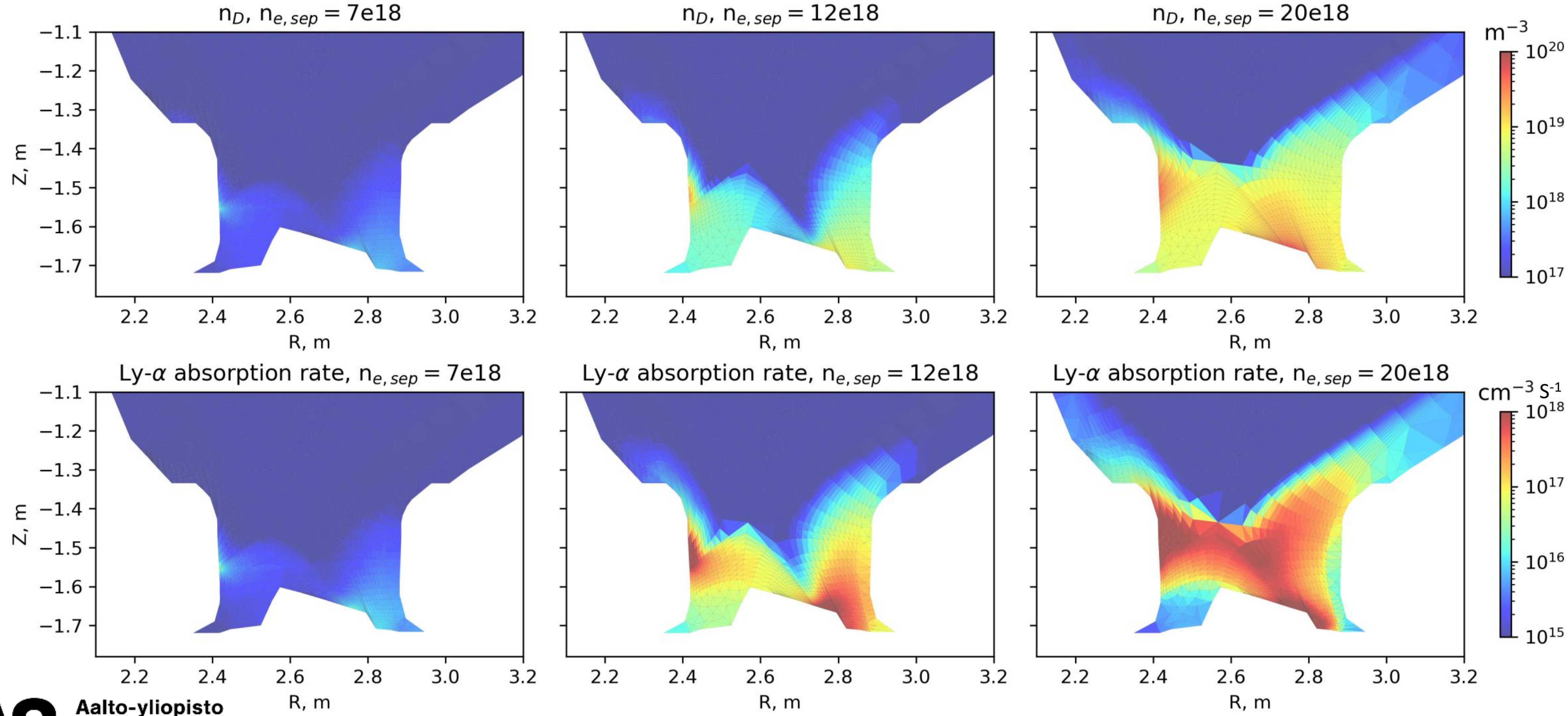
Expected high Ly-alpha absorption rate at high neutral D density



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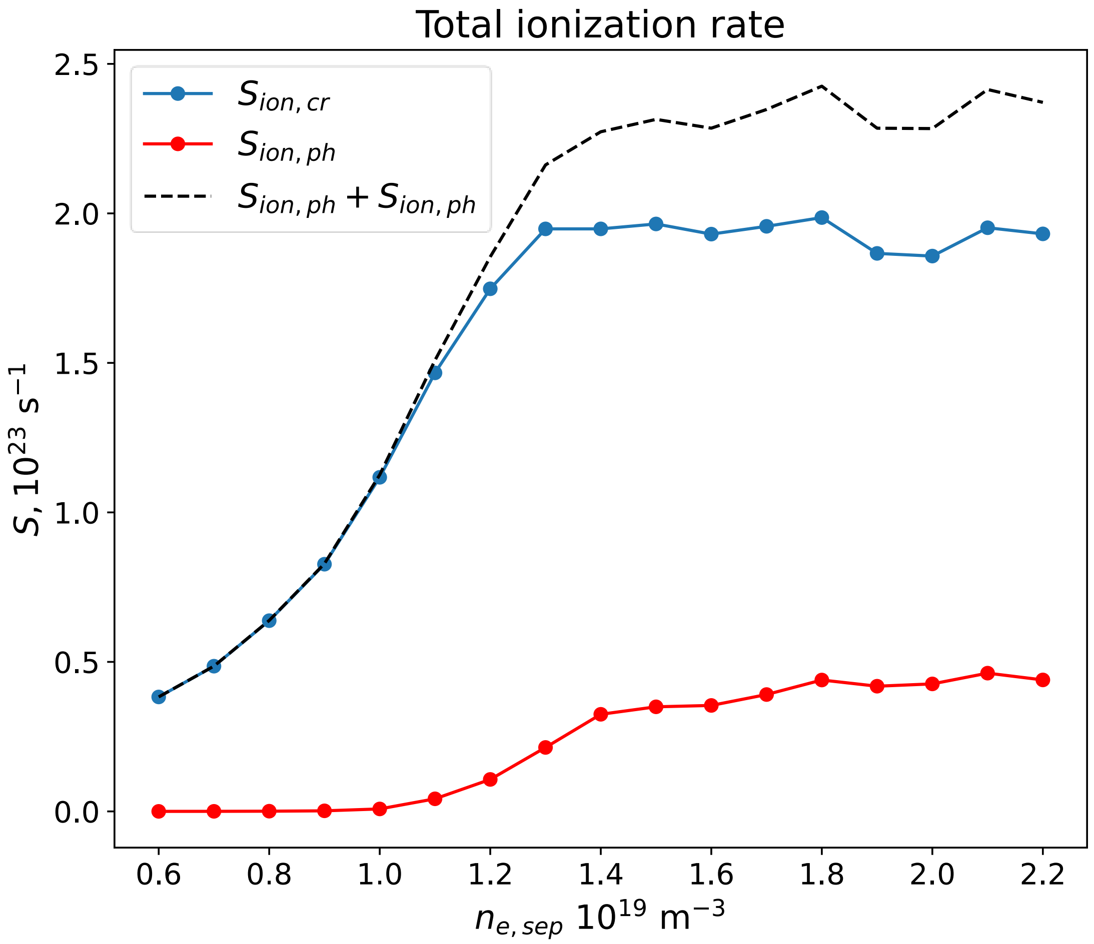
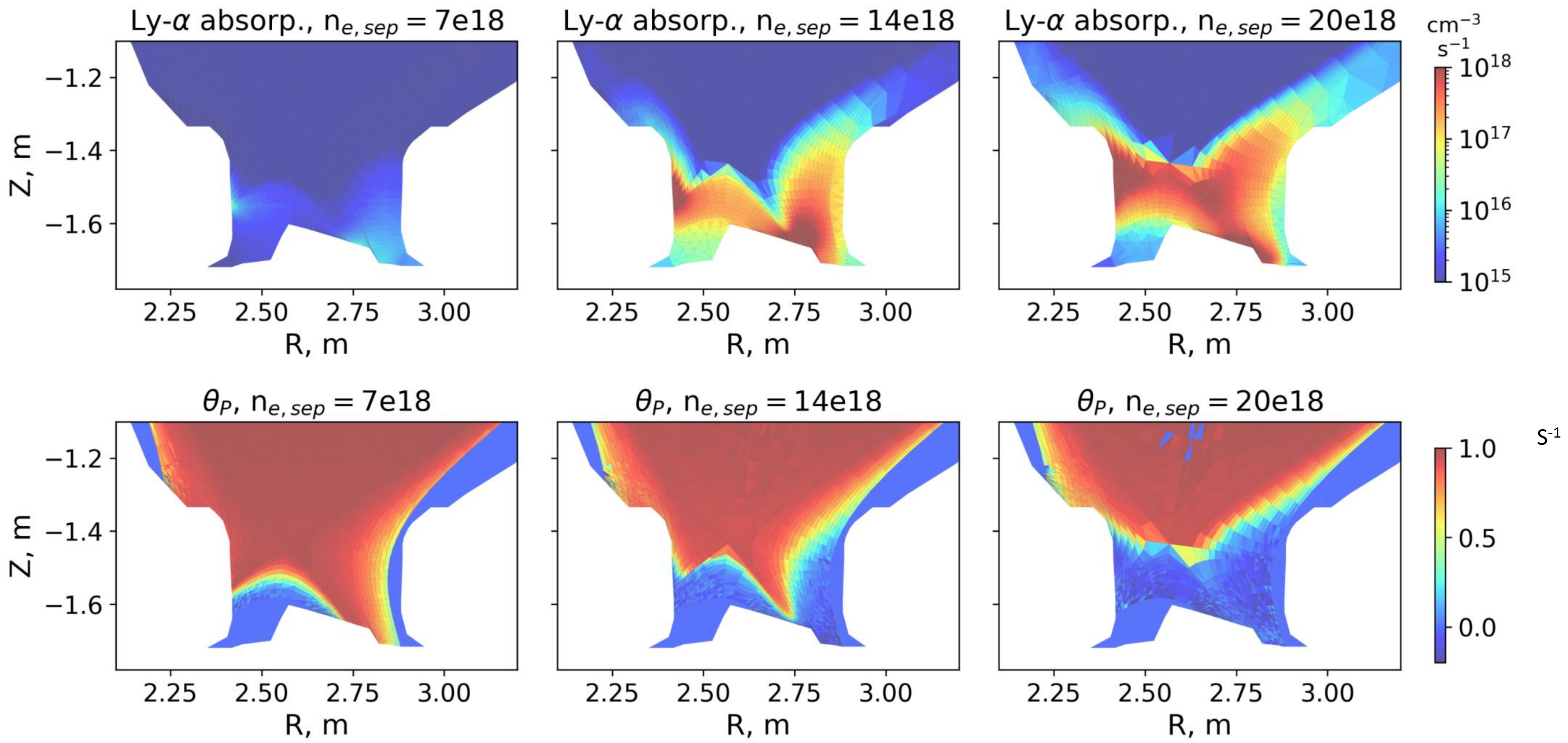
Photon absorption adds up to ~20% of total CR ionization rate in detached conditions

- Ionization rate integrated over the whole plasma volume
- No effect in low recycling regimes
- EPS 2023 poster contribution (July 2023)



Population escape factors from EIRENE → $\theta_p = 1 - \frac{abs}{ems}$



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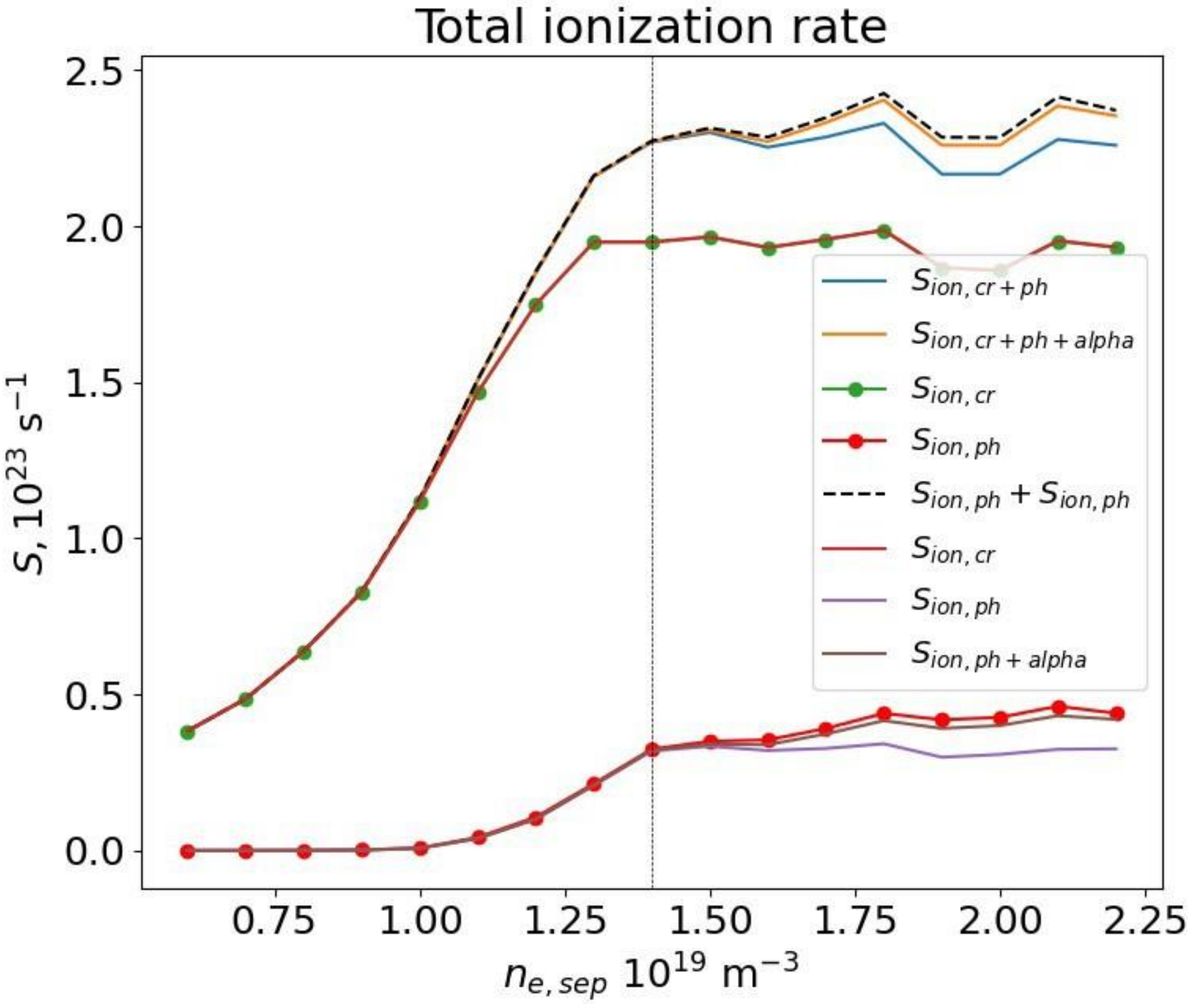
Opacity-reduced CRM using population escape factors from EIRENE

$$A_{eff} = \theta_p A$$

- Applied to SAWADA95 CRM
- Ionization rate matches ‘exactly’ to EIRENE values



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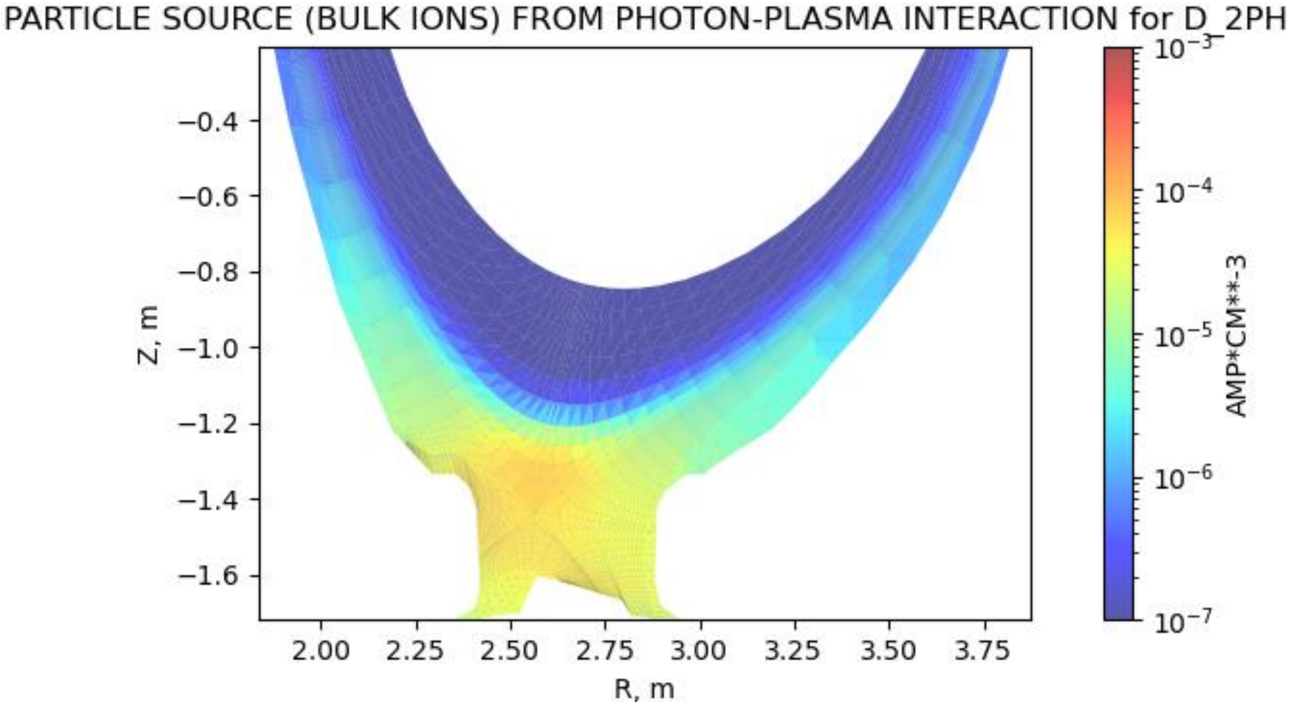
Radiation transport applied to static plasma solutions from JET81472 D SOLPS-ITER runs

- $n_{e,sep}$ = 0.6e19 – 2.2e19
- Ly-alpha and Ly-beta as test-particles

- Photon-gas implementation functional – tested for $n_{e,sep}$ = 9e18 - 12 iterations



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To-do lists:

- Comparison with EDGE2D-EIRENE photon solutions – JET81472 static plasma opacity study (paper)

- Opacity effect on electron cooling rate

- Expanding h_colrad for H2 and H2+ contribution to H*

- Full SOLPS-ITER simulation for new predictions of JET81472

- Grid parallelization for future large CRM calculations
  - For H Lyman lines, MC part still the dominant cpu time

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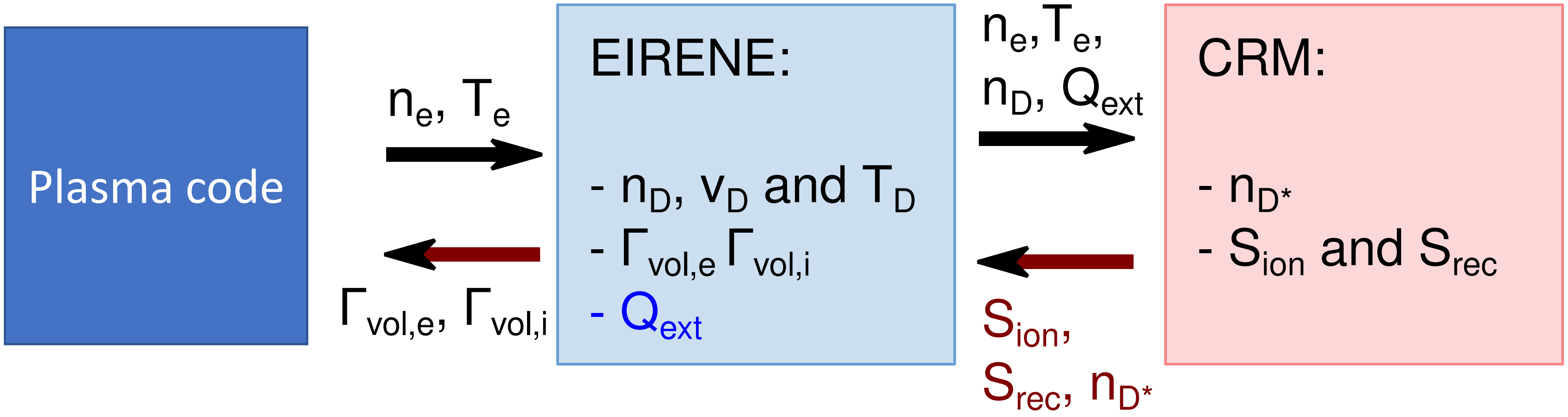
Next^2: Plasma-photon-gas coupling



- Self-consistent n_e,T_e → new high-recycling, detached dynamics (hopefully better I_{div} prediction)
- Connect with EIRENE input parallelization work (Yannick, next code camp?)