PLASMA EDGE SIMULATIONS USING SPARSELIZARD C++ FINITE-ELEMENT LIBRARY

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1. Scrape-Off Layer

Integration of high fusion performance with sustainable power exhaust is one of the leading challenges of reactor-scale fusion devices. The current state-of-the-art simulation tools for scrape-off layer (SOL) plasma, such as SOLPS-ITER, employ a finite-volume plasma solver in 2D with either fluid or kinetic treatment of neutral transport [1]. However, with high-fidelity physics treatment, these are prone to relatively long computational times and convergence challenges. For computationally faster and dynamic simulations, 1D plasma solvers such as SD1D and DIV1D have been developed [2,3]. In this study, the applicability of the Sparselizard library [4] for the simulation of fusion plasma physics is investigated, starting with the 1D SOL fluid models. Sparselizard is an open-source C++ finite-element (FE) library for the numerical implementation of multiphysics systems utilizing the domain decomposition methods for high-performance computing [4].

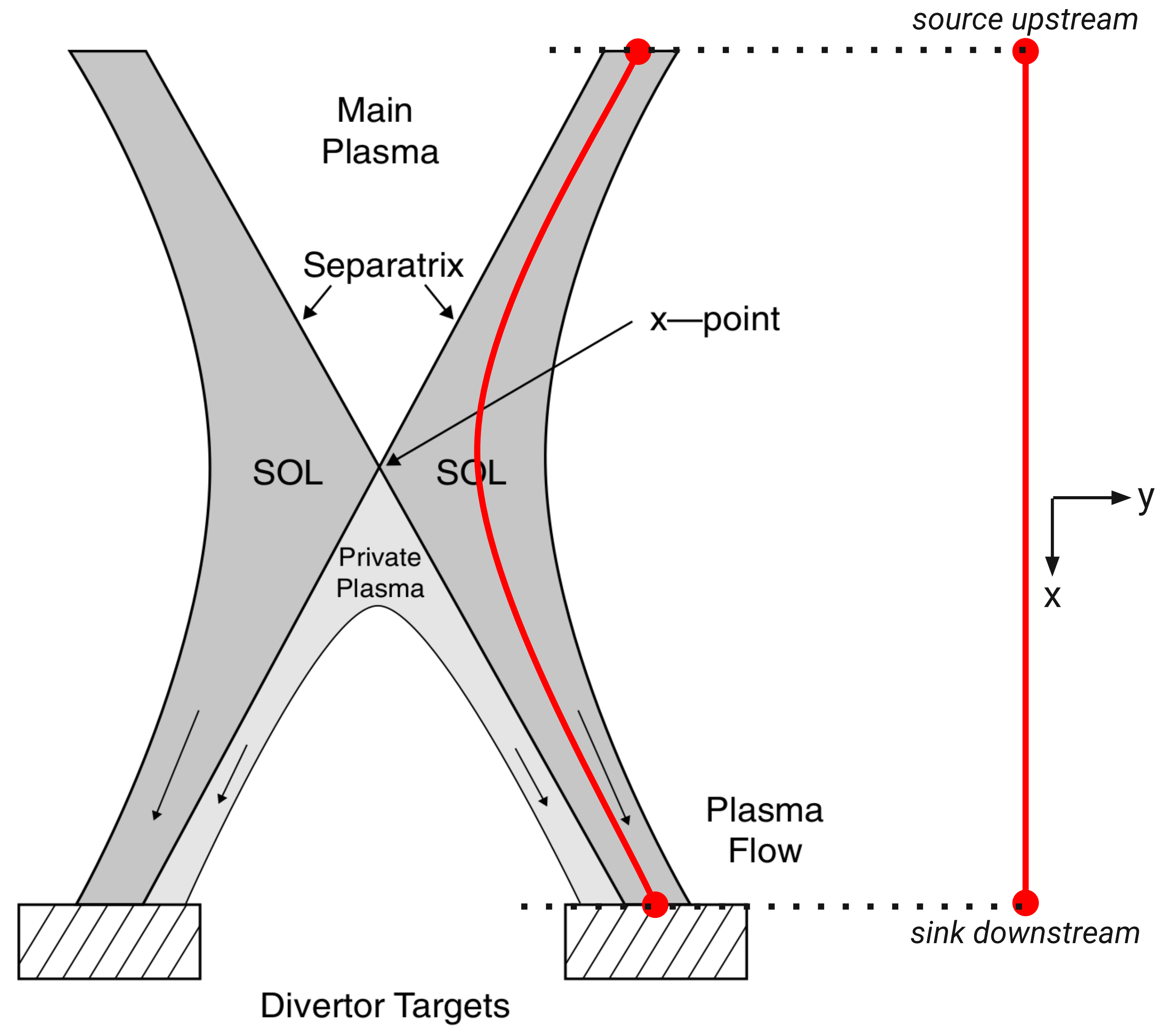

Fig. 1: 1D Scrape Off Layer [5].

2. Simple SOL: 1D isothermal fluid model

One of the simplest approaches to modeling SOL plasma is a 1D fluid model consisting of equations for the conservation of mass and momentum with an assumption that the temperature is constant along the SOL. Considering the weak form of these conservation equations, a FE solver was implemented using the Sparselizard library. For certain types of particle source (S_p), it is possible to obtain an analytical solution from the strong form isothermal fluid model [5] - allowing the comparison of results from the FE implementation in Sparselizard.

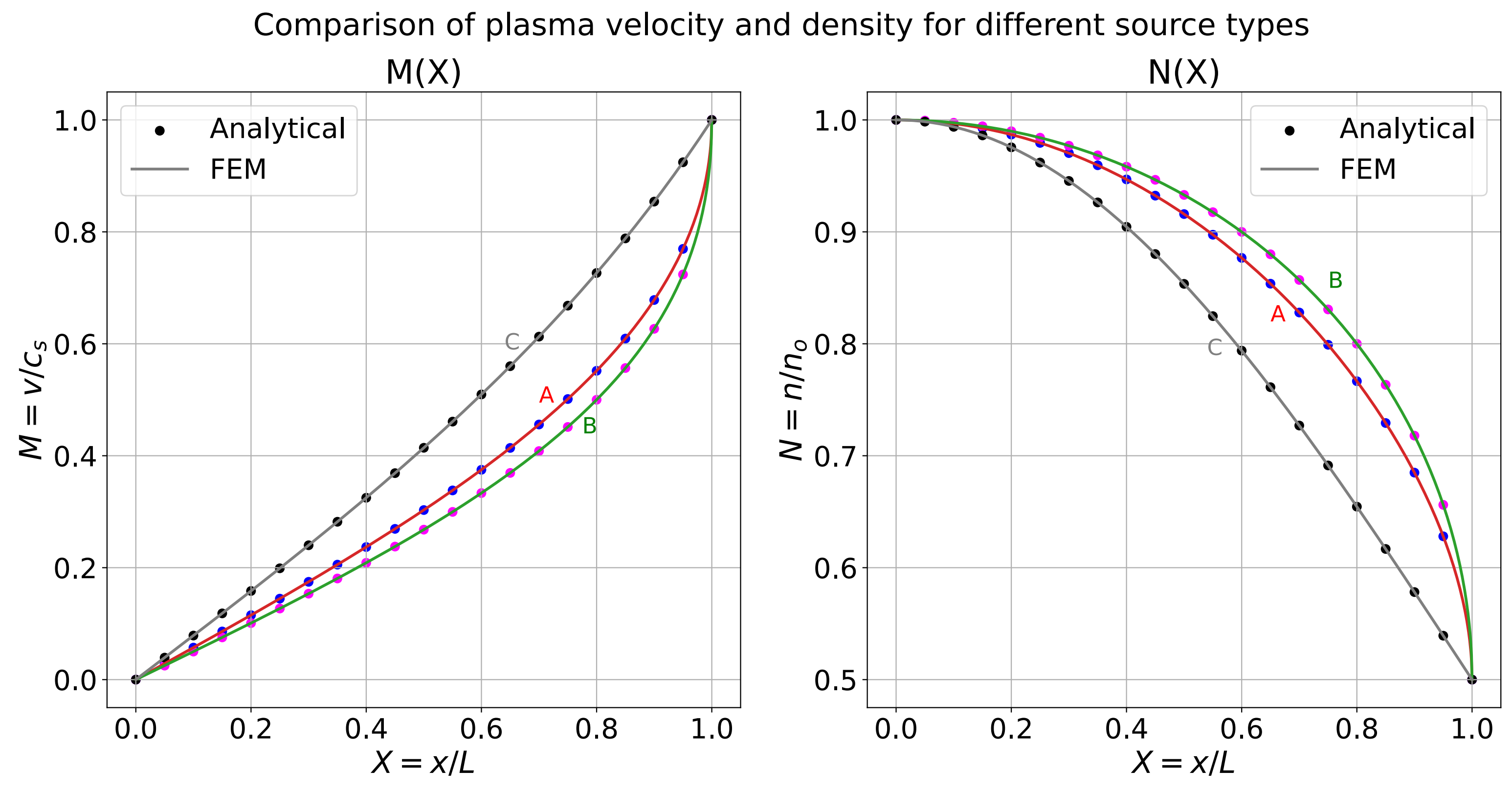

Fig. 2: Profile of normalized plasma velocity (M) and density (N) along SOL for different source (S_p) types:

$$\text{A) } S_p \propto N; \qquad \text{B) } S_p = \text{constant}; \qquad \text{C) } S_p \propto \frac{1 - M^2}{1 + M^2}.$$

3. Self-consistent source and temperature

A diffusive neutral model was introduced to self-consistently determine the neutral distribution and particle source. The self-consistency was extended to the plasma temperature through the energy equation, assuming electron heat conduction as the sole energy transport mechanism. Due to the strongly coupled and self-consistent interactions between various physical terms, a fully coupled solver is implemented. Thus, all the conservation equations are solved simultaneously. In the FE formulation, stabilization techniques and Newton linearizations are employed. The resulting system of equations is solved using Newton's iteration. For verification, the results from the FE simulation were compared with the two-point model.

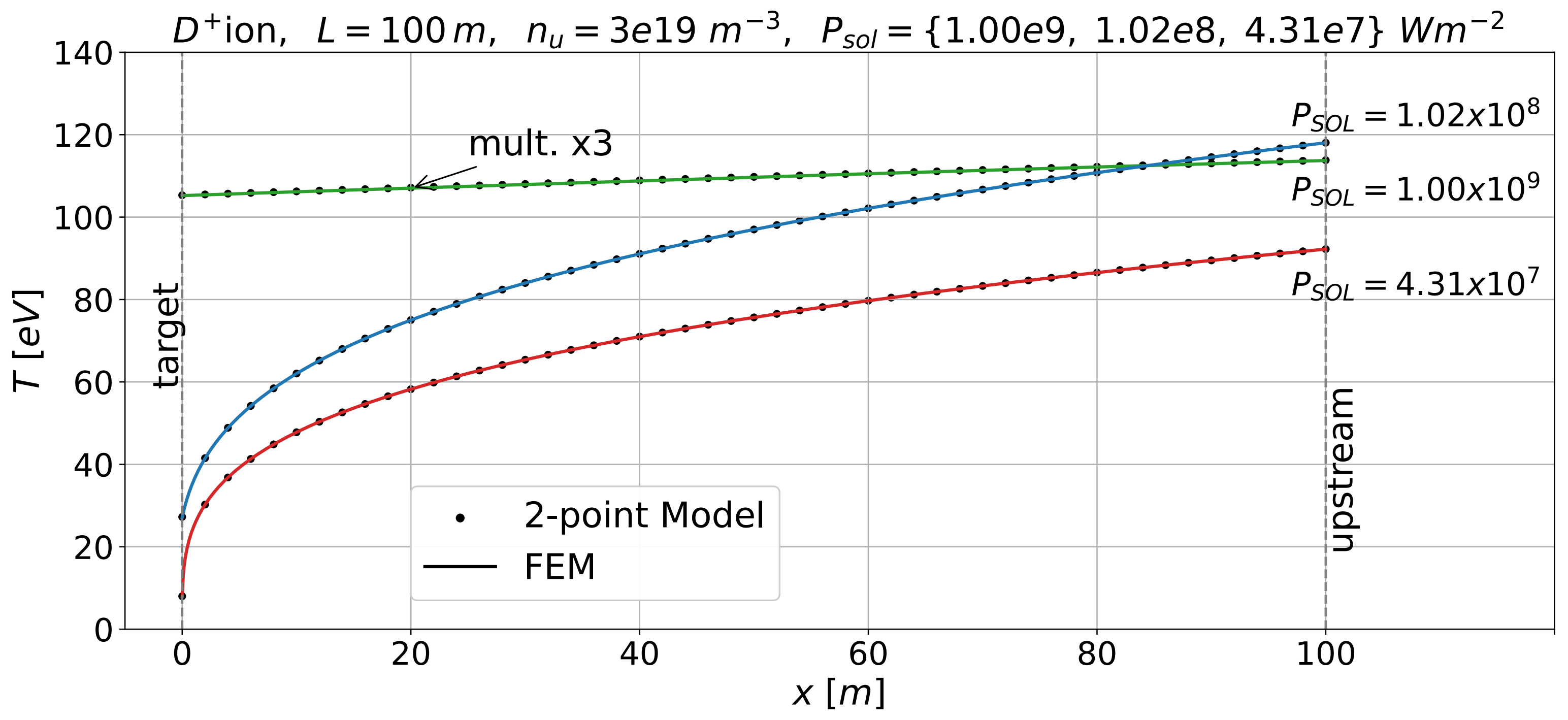

Fig. 3: Temperature profile along SOL for various input power P_{SOL}.

4. Further work: Benchmark with SD1D

Thus far in the implementation, no energy losses have been considered. Furthermore, only ionization and charge exchange processes were included in the mass, momentum, and neutral conservation equations. In the further steps, the plasma edge solver in Sparselizard will be extended to consider heat convection and losses in the energy transfer. Additional source and sink terms due to processes such as recombination, elastic scattering, and excitation will also be considered in flux and momentum conservation. For benchmarking, the results from Sparselizard would be compared with those obtained from the open-source SD1D simulation.

5. References

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