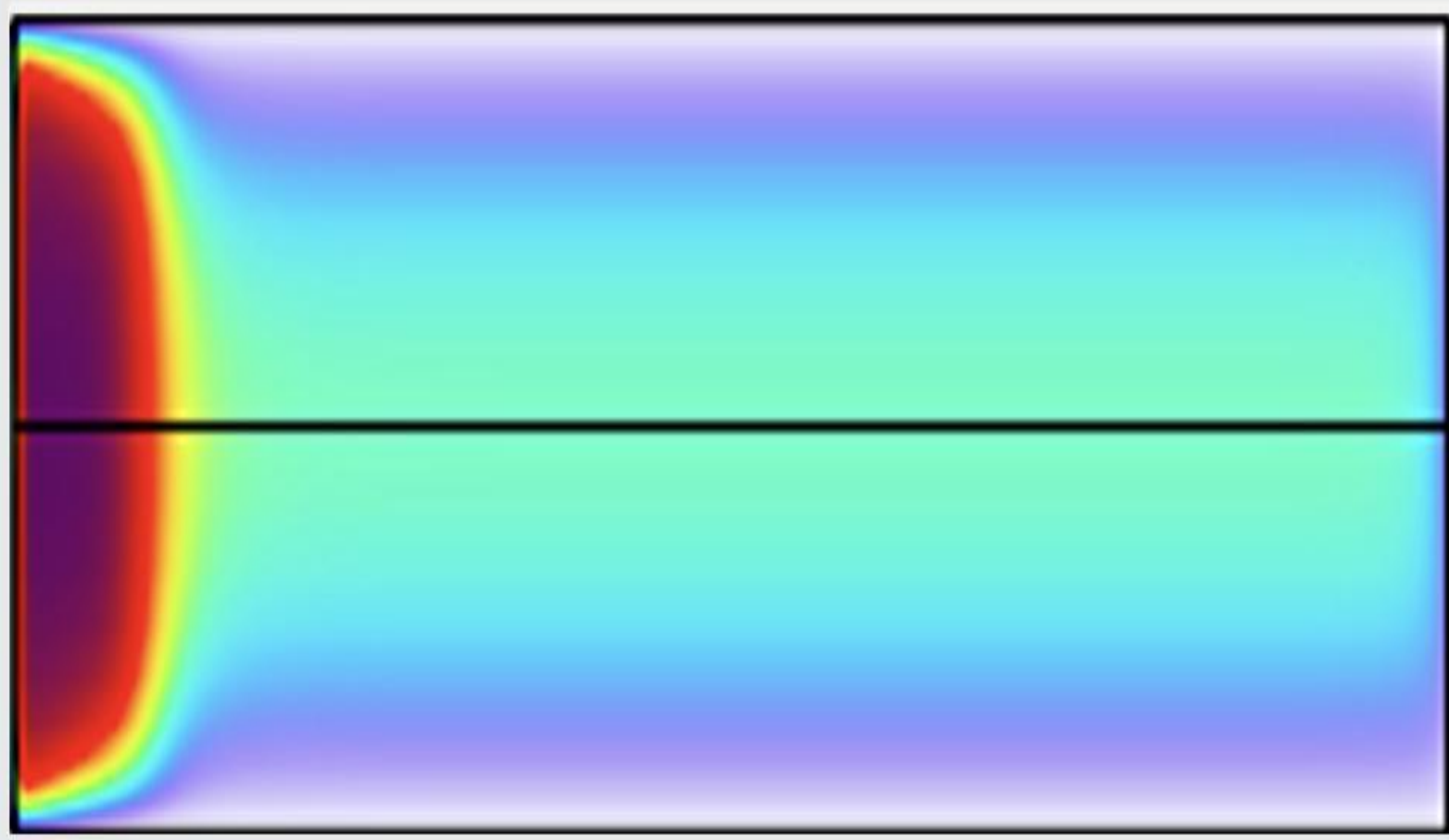




Predictive Modeling of Pulsed Capillary Discharges Using COMSOL

A self-consistent 2D model of a pulsed argon capillary discharge is developed using the COMSOL Plasma Module, coupled to a realistic external RLC circuit to characterize and optimize plasma sources for laser wakefield acceleration.

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Introduction & Goals

Pulsed capillary discharges are fundamental to generating high-density plasma waveguides for laser wakefield acceleration (LWFA) [1] and very high energy electron (VHEE) applications [2,3]. Their transient, non-equilibrium nature—spanning rapid electrical breakdown, quasi-steady current flow, and recombination decay—requires predictive modeling beyond simplified analytical approaches.

This work aims to develop and validate a numerical framework for

the argon-filled capillary configuration at the I-LUCE (INFN-Laser indUCEd Radiation Production) facility at INFN-LNS in Catania, Italy [4], incorporating the driving resistor-inductor-capacitor (RLC) circuit, capillary geometry, at 10 mbar gas pressure. The model is benchmarked against a reference current waveform from literature [5]. It aims to study and optimize plasma density profiles for stable electron beams, support VHEE radiotherapy (RT) research [6], and enable future studies on non-uniform density profiles and gas dynamics.

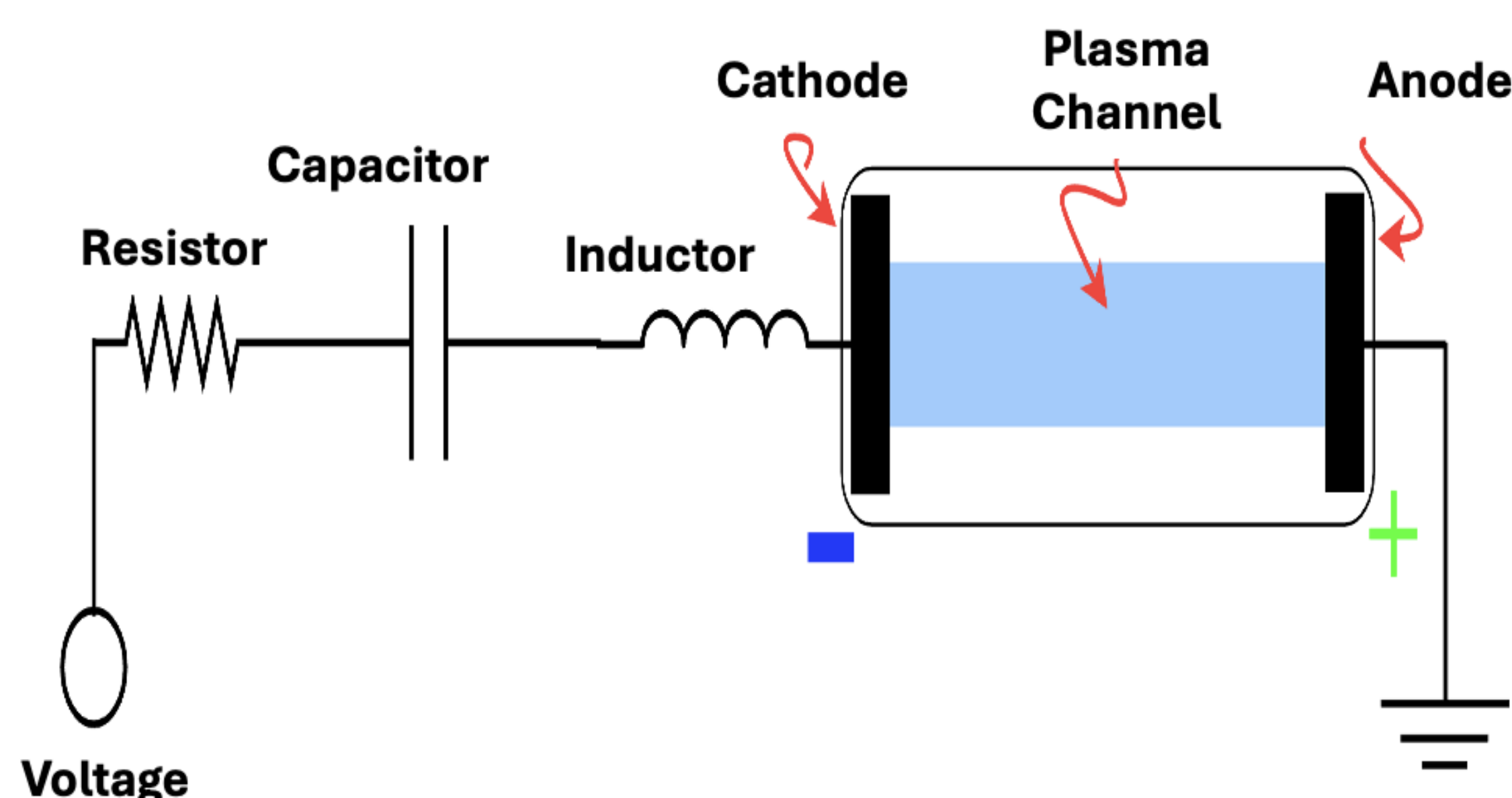


FIGURE 1. Schematic of the external pulsed resistor-inductor-capacitor (RLC) discharge circuit coupled in COMSOL model, with $R = 20 \Omega$, $L = 600 \text{ nH}$, $C = 5 \text{ nF}$.

Methodology

Model Physics

The fluid model solves coupled drift-diffusion equations for electron density (n_e) and mean electron energy density ($n_e \epsilon$), heavy species mass fractions using the Local Energy Approximation (LEA). Poisson's equation computes the electrostatic field and potential V , coupling the plasma to the circuit, with Townsend coefficients from LXCat cross-sections database as a function of reduced electric field (E/N).

Model Setup

- **Circuit Coupling:** Series RLC network ($R = 20 \Omega$, $L = 600 \text{ nH}$, $C = 5 \text{ nF}$) driving a time-varying plasma resistance $R_{\text{plasma}}(t)$.
- **Geometry & Conditions:** Capillary length = 30 mm, diameter = 1 mm, 10 mbar Ar, 5–20 kV pulses. Cathode with secondary emission ($\gamma = 0.25$, work function $\Phi = 5 \text{ eV}$), grounded anode, dielectric walls.
- **Plasma Chemistry:** A 4-species argon chemistry (Ar, Ar^+ , Ar^* , e^-) including elastic, excitation, ionization, and Penning ionization reactions. Townsend coefficients are used for reaction rates to better resolve cathode fall region.

Results

The RLC model accurately reproduces the current waveform (Fig. 2a) with a peak current of $\sim 668 \text{ A}$, matching the reference value of 670 A and validating our circuit modeling approach [5]. The simulation yields temporal profiles of current (Fig. 2a, 2d), electric potential (Fig. 2b), and reduced electric field (Fig. 2c). The electric potential (Fig. 2b) peaks around 1500 V , while the reduced electric field (Fig. 2c) peaks around 550 Td and decays to 200 Td over the discharge. Fig. 2d shows that electron density increases with applied voltage, reaching values on the order of 10^{17} cm^{-3} . The axial density profile (Fig. 2e) reveals a peak of $\sim 2.44 \times 10^{17} \text{ cm}^{-3}$. The axial temperature profile (Fig. 2f) shows temperatures of $\sim 0.5\text{--}6 \text{ eV}$ in the cathode fall and a uniform $\sim 2 \text{ eV}$ bulk plasma in the positive column.

Data presented in this work are from: S. Arjmand et al., 2D Modeling of Plasma Discharge in Gas-filled Capillary Using COMSOL Multiphysics, MDPI Appl. Sci., under revision, 2026.

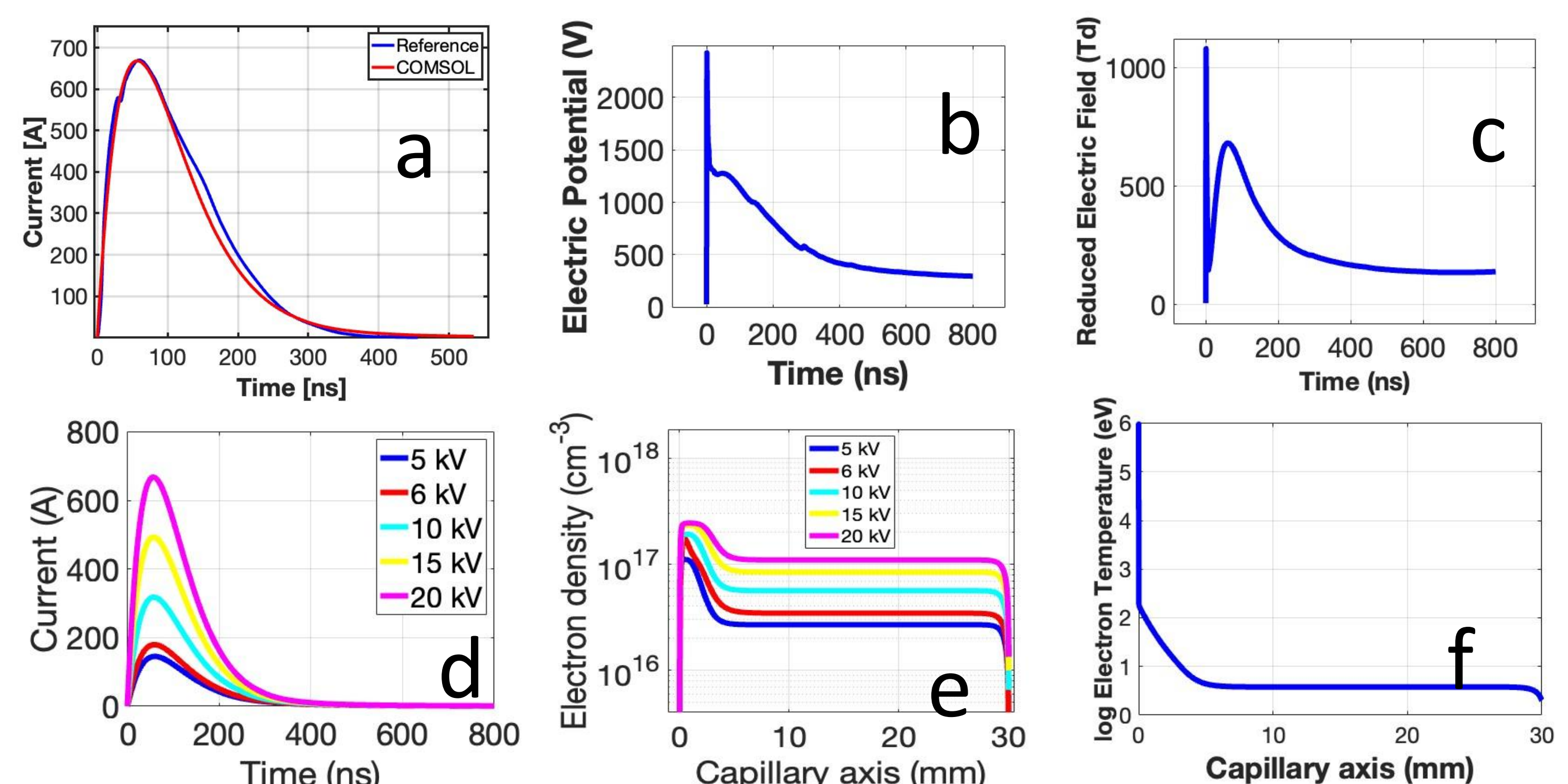


FIGURE 2. Comparison of discharge current from reference and COMSOL (a); electric potential (b); reduced electric field (c); temporal evolution of current vs applied voltage (2d); axial n_e (e); axial T_e (f).

REFERENCES

1. T. Tajima, Laser electron-accelerator, PhysRevLett, 43:267, 270 (1979).
2. L. Labate et al., Toward an effective use of laser-driven very high energy electrons for radiotherapy, 10: 17307, (2020).
3. S. Arjmand et al., Implementing capillary design for very high energy electron (VHEE) applications at I-LUCE facility, RAD Conf. Proc, 8, 96-102 (2024).
4. GAP, Cirrone et al., Laser-driven user facilities and status of I-LUCE at Laboratori Nazionali Del Sud of INFN (Italy), RAD Conf. Proc, 8, 103-109 (2024).
5. A. Curcio et al., Modeling and diagnostics for plasma discharge capillaries, Phys.Rev. E 100, 053202 (2019).
6. S. Arjmand et al., Preformed plasma waveguides for FLASH radiotherapy, Nucl. Instrum. Methods Phys. Res. A, 1081, 170891 (2026).