A 2D semi-analytical electromagnetic model for cylindrical ICP sources with Faraday shield

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Introduction

Faraday shield(FS) is a metallic shield with slits through which electromagnetic energy is coupled into cylindrical ICP sources. Thus, the effect of FS on the RF power coupling is important to the RF ion sources for fusion[1].

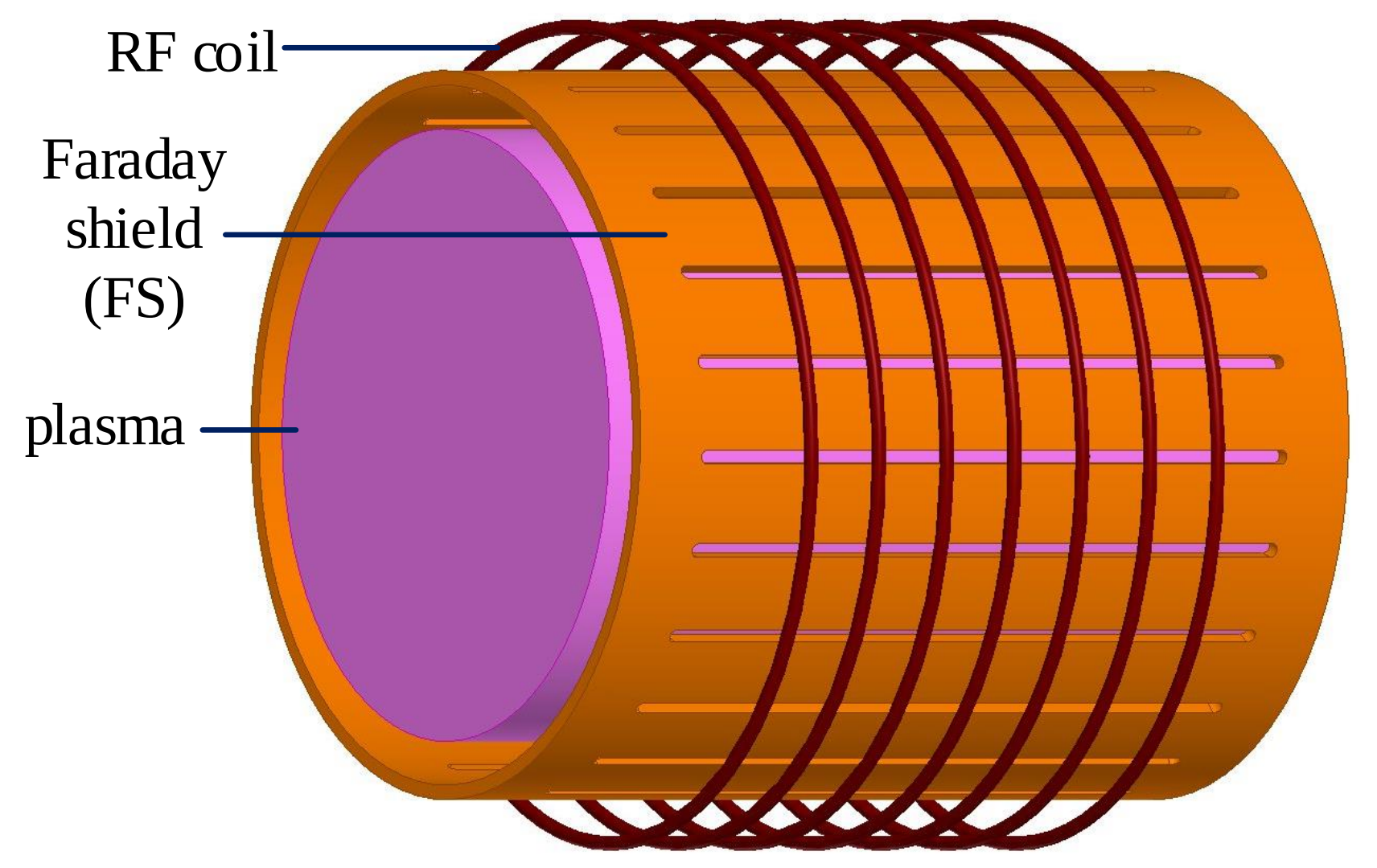


FIGURE 1. A 3D sketch of an ICP source.

$$K_c = N_c I_c / l_c$$

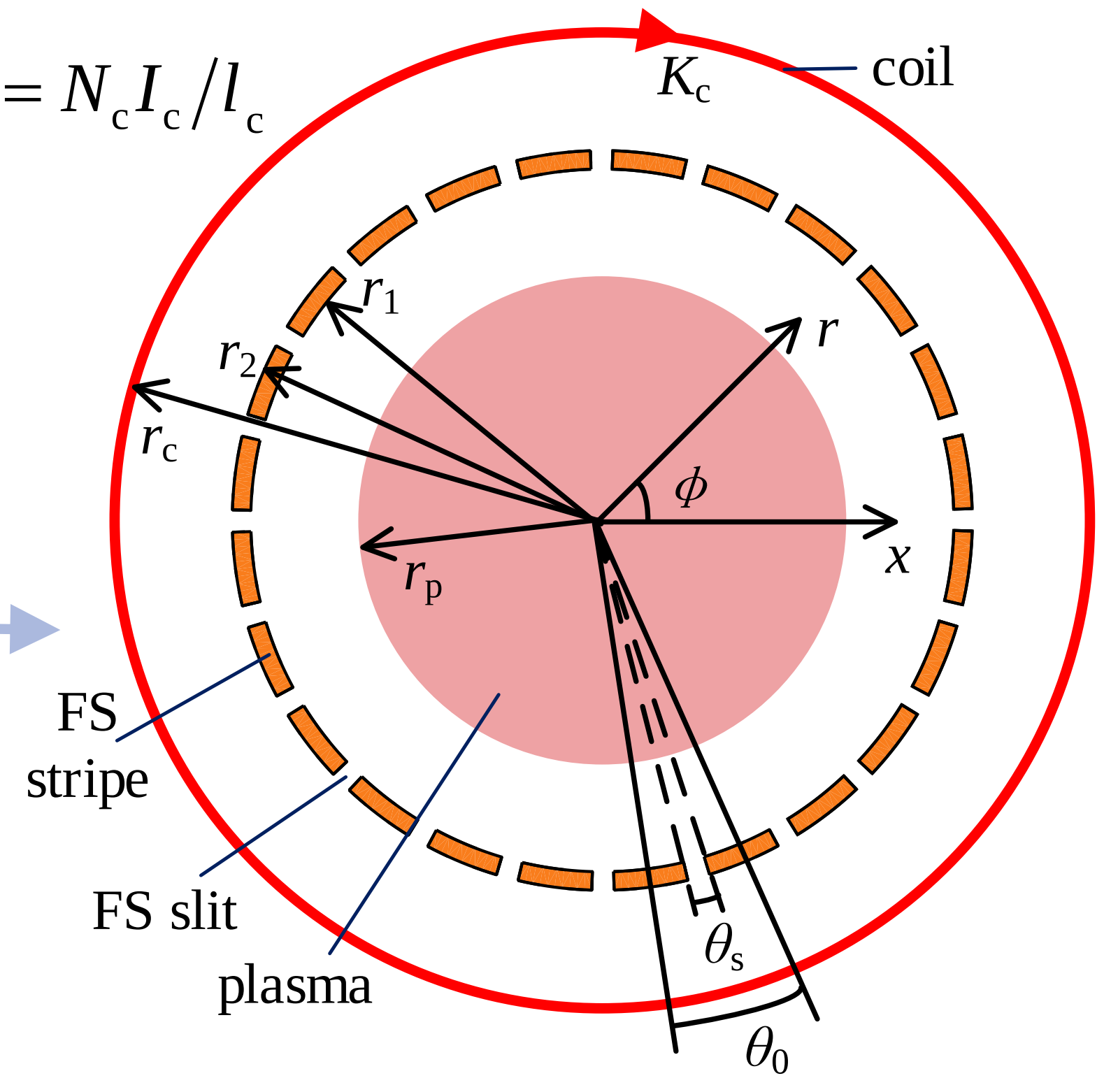


FIGURE 2. 2D model.

Summary on 2D electromagnetic models

Table 1. 2D EM models of ICP sources.

Type	Plasma	Faraday shield	
Anlytical	as lossy dielectric	absence	[2]
Semi-anlytical	absence	close to real structure	[3]
Numerical	as good conductor	real structure	[1], this work
Anlytical	absence	Infinitely thin	[4]
Semi-anlytical	as lossy dielectric	close to real structure	this work

Preconditions:

1. In [1-4] and this work, FS and/or plasma are assumed to be infinitely long straight, and the coil is assumed to be axially symmetrical and uniformly distributed.
2. In [3-4] and this work, metallic structures like copper FS are approximated as ideal conductors.
3. The electromagnetic models with plasma are not self-consistent description of the RF power coupling. In [2] and this work, the plasma is assumed to be uniform and unmagnetized. However, the RF magnetic field may have significant influence on the power coupling[5-6].
4. In this work, the plasma is assumed to be axisymmetric though the field inside may be non-axisymmetric.

Model

General description of 2D model

Governing equation:

$$\nabla \times \boldsymbol{H} = (\sigma + \mathrm{j}\omega\varepsilon)\boldsymbol{E}$$
$$\nabla \times \boldsymbol{E} = -\mathrm{j}\omega\mu_0 \boldsymbol{H}$$

Materials:

FS, coil: ideal conductor

plasma: $\sigma_{\text{plasma}} = \varepsilon_0 \dfrac{\nu_c \omega_{\text{pe}}^2}{\omega^2 + \nu_c^2}$, $\varepsilon_{\text{plasma}} = \varepsilon_0 \left(1 - \dfrac{\omega_{\text{pe}}^2}{\omega^2 + \nu_c^2}\right)$

Decomposition of the magnetic field

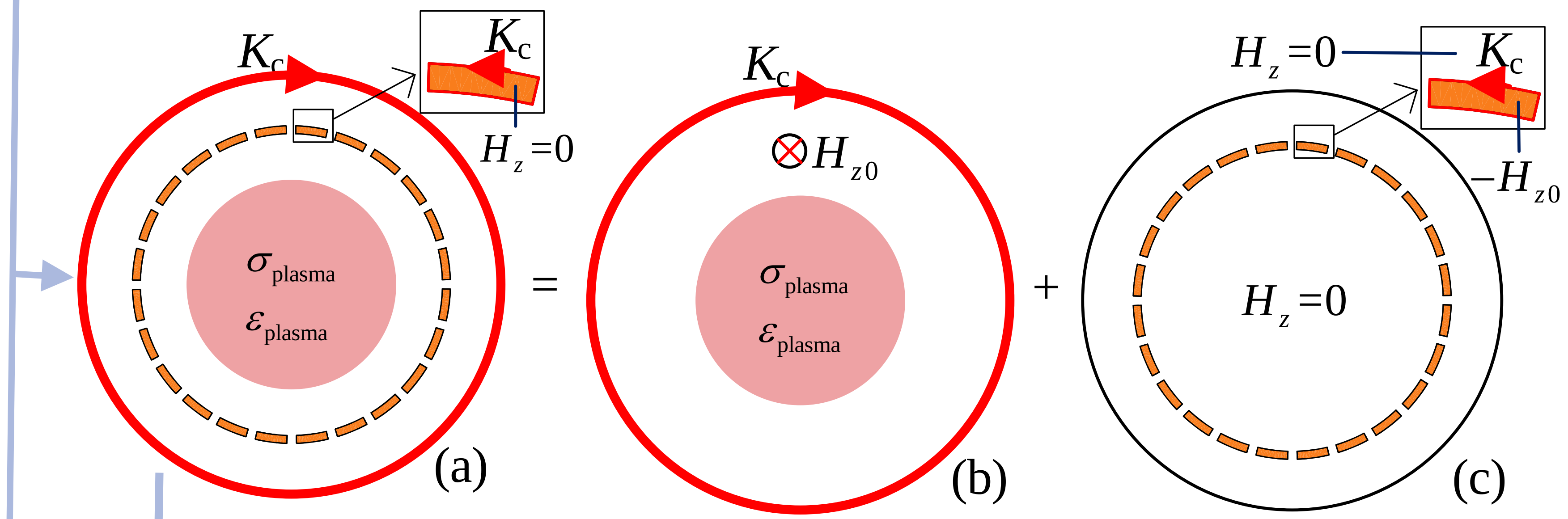


FIGURE 3. Decomposition of magnetic field. (a) *H* subjects to the overall BVP. (b) *H* in an ICP source without FS. (c) *H* due to the surface currents on S_{FS}.

$$H(r) = \begin{cases} H_{z0} J_0(k_c r) / J_0(k_c r_p), & \text{inside plasma} \\ H_{z0}, & \text{inside vacuum} \\ 0, & \text{inside FS stripe} \end{cases} \qquad H_{z0} = K_c \qquad k_c = \omega\sqrt{\mu_0(\varepsilon - \mathrm{j}\sigma/\omega)}$$

Decomposition of the electric field

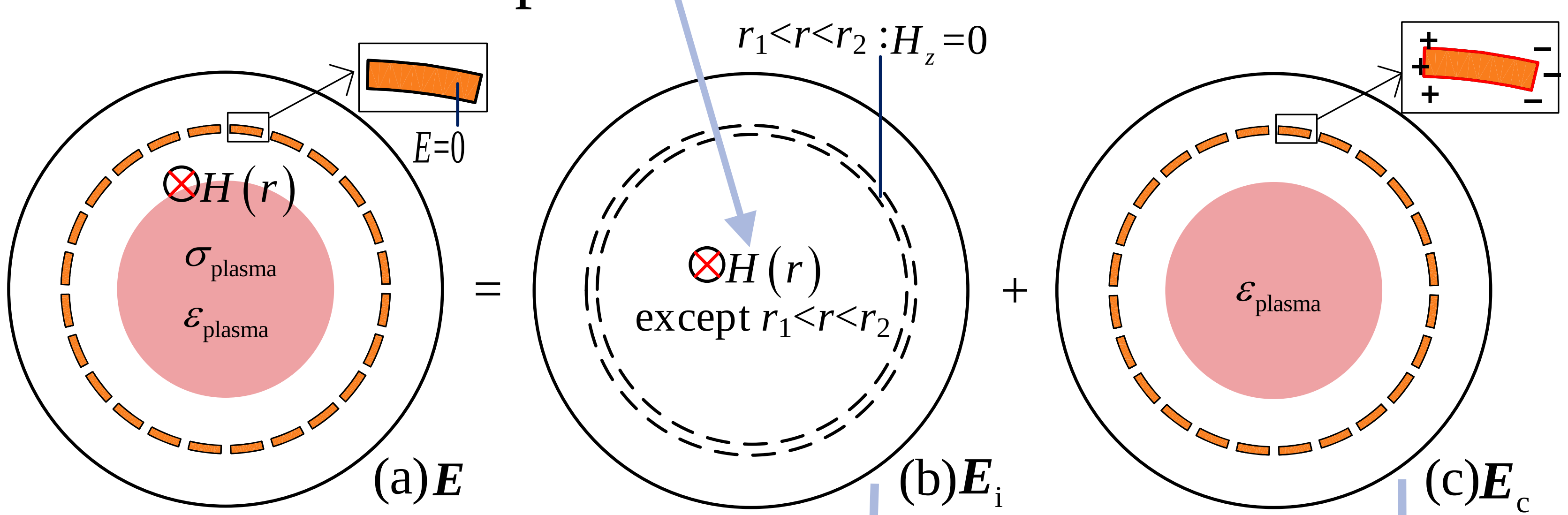


FIGURE 4. Decomposition of electric field. (a) *E* subjects to the overall BVP. (b) The vortex field induced by *H*. (c) The rest *E* field.

$\boldsymbol{E}_i$ induced by the magnetic field in figure 4(b) has only azimuthal component

$$E_i(r) = \begin{cases} -\mathrm{j}\omega\mu_0 H_{z0} J_1(k_c r) / k_c J_0(k_c r_p) & (r \le r_p) \\ -\mathrm{j}\omega\mu_0 H_{z0} \left(r^2 - r_p^2\right) / 2r + r_p E_i(r_p) / r & (r_p < r \le r_1) \\ -\mathrm{j}\omega\mu_0 H_{z0} \left(r_1^2 - r_p^2\right) / 2r + r_p E_i(r_p) / r & (r_1 < r \le r_2) \\ -\mathrm{j}\omega\mu_0 H_{z0} \left[r^2 - \left(r_2^2 - r_1^2\right) - r_p^2\right] / 2r + r_p E_i(r_p) / r & (r_2 < r \le r_c) \end{cases}$$

$\boldsymbol{E}_c = \boldsymbol{E} - \boldsymbol{E}_i$, then it is approximated as a gradient field completely due to the electric charge accumulated on the surface.

$$\begin{cases} \nabla \times \boldsymbol{E}_c = 0 \\ \nabla \cdot \boldsymbol{E}_c = 0 \end{cases} \qquad \begin{matrix} \boldsymbol{E}_c = -\nabla\varphi \\ \nabla^2 \varphi = 0 \end{matrix}$$

$\varphi = 0$, at OM, ON and MN

$$\varphi = \left[\frac{-\mathrm{j}\omega\mu_0 H_{z0}\left(r_1^2 - r_p^2\right)}{2} + r_p E_i(r_p)\right](\phi \pm \theta_0/2),$$

+ at AB/BC/CD, − at EF/FH/HG

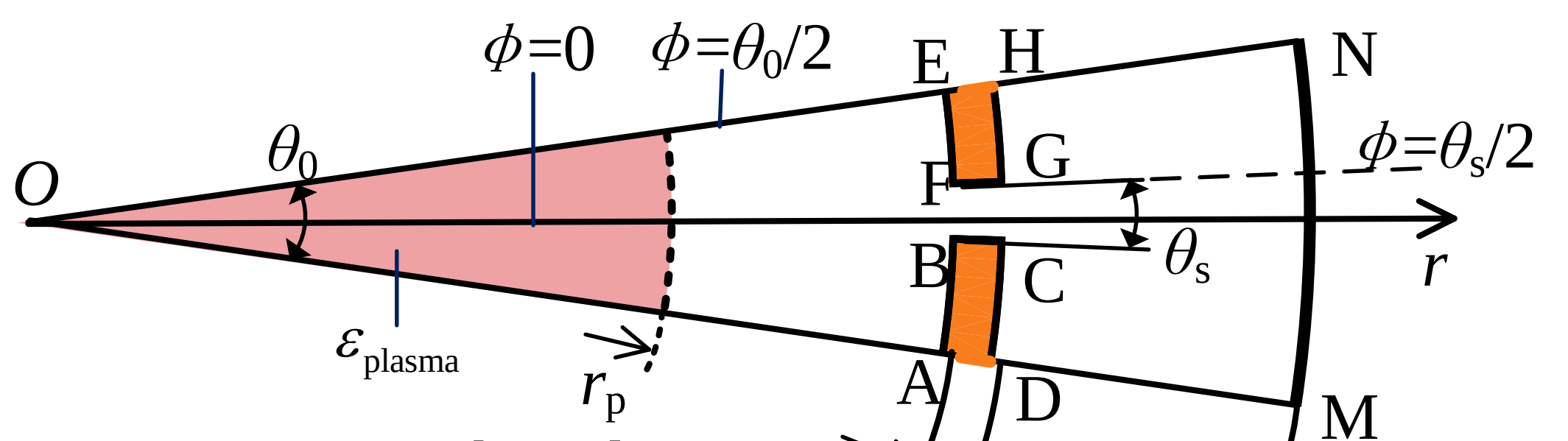


FIGURE 5. The solution domain of the gradient field.

All points are nearly in phase, so the quasi-static approach can be applied. Numerically solved.

Results

Sample case: r_c / r_2 / r_1 / r_p = 133 / 119 / 116 / 115 mm; 68 slits, each of width 2 mm;
a hydrogen discharge with f = 1MHz, p = 0.3 Pa, T_g = 630 K, n_e = 3.2e17 m^{-3}, T_e = 8.4 eV;
Thus, σ = 4.17e2 S/m, ε_r = -2.36e6.

PER per unit length $\quad P_{\text{plasma}} = \int_{\text{plasma}} \sigma_{\text{plasma}} \boldsymbol{E} \cdot \boldsymbol{E}^* \mathrm{d}S \qquad \text{PER} = P_{\text{plasma}} / I_c^2$

Compared to a 2D numerical model

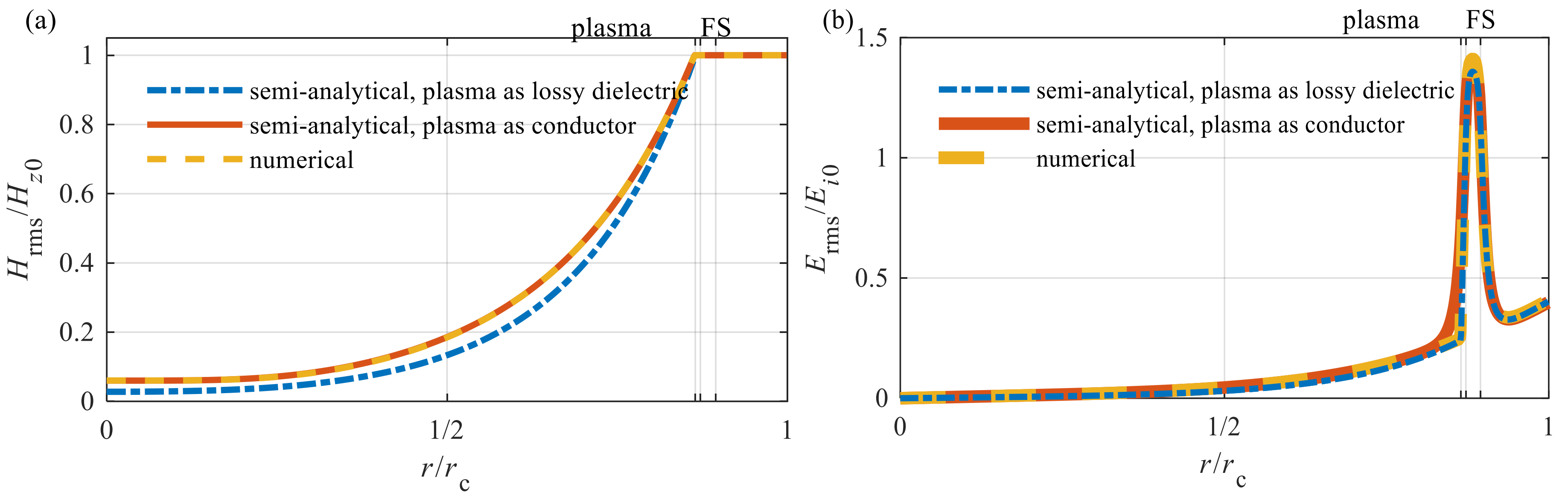


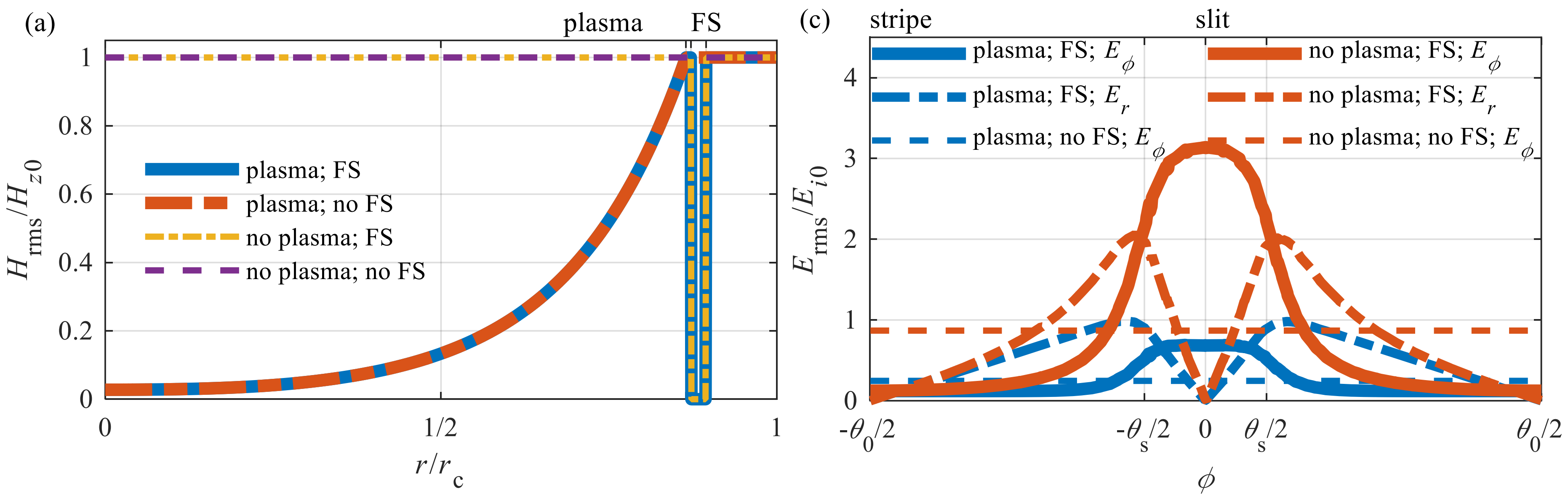
FIGURE 6. Field from different models. (a) *H*(*r*) at *Φ* = 0. (b) *E*(*r*) at *Φ* = 0.

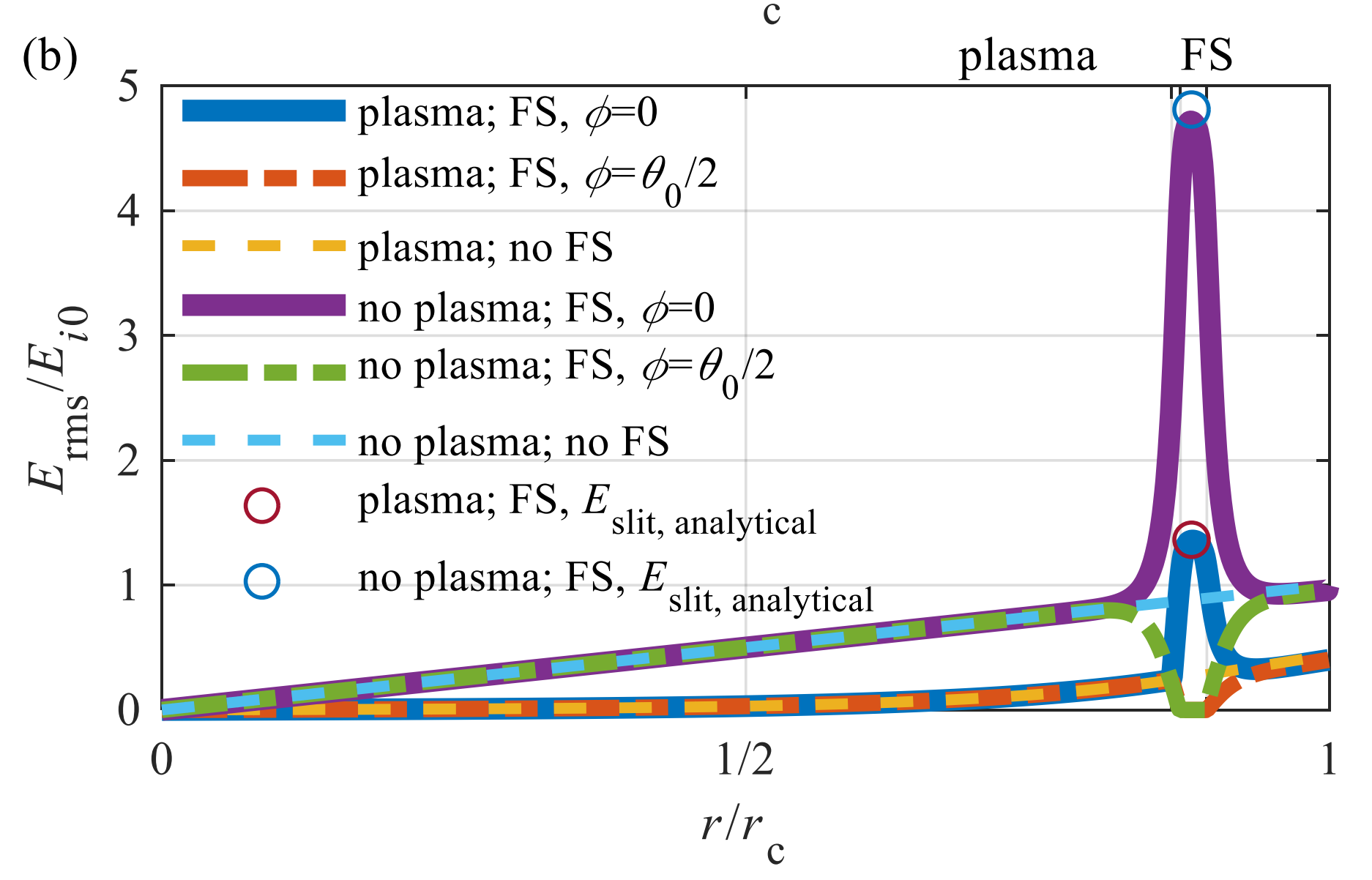
PER from semi-analytical model(conductor) : PER from numerical model ≈ 1.1 : 1

→ The semi-analytical model is ok in terms of EM field calculation.

PER from semi-analytical model(conductor) : PER of plasma as lossy dielectric ≈ 1.4 : 1

Influence of FS





In this model:

1. FS doesn't affect *H* outside FS stripes.
2. FS results in: *E* around the slits ↑, E around the middle of the stripes ↓
3. The effect of FS is mainly due to the gradient field, viz. the charge accumulated on FS surface.
4. The depth at which FS can affect the field in plasma < The depth at which FS can affect field in vacuum.

FIGURE 7. Field due to FS and plasma. (a) *H*(*r*) at *Φ* = θ_0/2. (b) *E*(*r*) at *Φ* = 0, θ_0/2. (c) *E*(*Φ*) at = *r* = (r_p+r_1)/2.

PER with FS : PER without FS= 1 : 1

→ In this model:

The depth at which FS can affect RF coupling in plasma << The skin depth of plasma.

References

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Acknowledges

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