

# NUMERICAL MODELING TO PREDICT IGNITION THRESHOLDS FOR PLASMA PROCESSING OF SUPERCONDUCTING RADIO-FREQUENCY CAVITIES\*

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## ABSTRACT

Laboratories such as Oak Ridge, Fermilab, and Jefferson Laboratory have been developing plasma cleaning techniques for superconducting radio-frequency (SRF) cavities. These techniques show promise as an in-situ method of mitigating degradation in cavity performance via removal of surface contamination. Plasma cleaning studies for SRF cavities in the driver linac at the Facility for Rare Isotope Beams (FRIB) began in 2020. Both neon-oxygen and argon-oxygen plasmas have been found to be effective in improving FRIB accelerating cavities. Models have been developed to predict the threshold RF electric field for ignition of a diffusion-dominated plasma using the solution to the diffusion equation for a given cavity shape; a numerical solution is needed for realistic cavity shapes. Predictions for several cavity shapes using numerical techniques will be compared to analytic approximations and ignition and extinction threshold measurements.

## INTRODUCTION

Careful surface preparation is needed for superconducting radio-frequency (SRF) cavities to ensure high performance in particle accelerators. Though SRF cavity assembly is done in a clean room, some particulate contamination may still be introduced. When a cavity is installed in a cryomodule and used for acceleration, there is a risk of further contamination.

Hydrocarbons on the cavity inner surface may lower the work function and worsen field emission [1]. Field emission can produce Bremsstrahlung X-rays, and, in severe cases, can reduce the cavity quality factor, such that the accelerating gradient of the accelerator must be reduced.

In-situ cavity cleaning techniques are highly desirable for reduction of contamination and improvement of performance without the need to remove and disassemble cryomodules, which is time- and labor-intensive.

Plasma processing has been developed as a method to remove contamination from SRF cavities via a weakly-ionized cold plasma. This is done by flowing a noble gas such as neon or argon through the cavity and ionizing the gas via a standing-wave RF electric field driven through an RF coupler. Oxygen is added to the noble gas to react with contaminants on the cavity surface. Byproducts from the chemical reaction of oxygen radicals with surface contaminants may be

volatile (CO, CO<sub>2</sub>, H<sub>2</sub>O), such that they can be pumped out of the cavity. Though developed to target hydrocarbon contamination, plasma processing may be beneficial for other contaminants as well.

The Facility for Rare Isotope Beams (FRIB) uses 324 SRF cavities to accelerate ions [2]. Plasma processing is being developed for FRIB quarter-wave resonators (QWRs) and half-wave resonators (HWRs) in support of long-term operation of the FRIB superconducting linac [3].

Simplified models may be used to predict the RF electric field needed to ignite a given gas mixture. Inputs to the models may be obtained from analytic approximations or numerical calculations. In this paper, predictions based on analytic and numerical approaches will be compared to plasma measurements on FRIB SRF cavities.

## DIFFUSION-DOMINATED MODEL

Plasmas within certain parameter ranges can be described approximately by a diffusion-dominated model [4]. The diffusion-dominated model is applicable for plasma ignition in FRIB cavities, and has been used to predict ignition thresholds for FRIB QWRs. However, the model's assumptions are not met for the case of plasma ignition in the FRIB fundamental power coupler (FPC), as the electron mean free path is not small compared to the relevant FPC dimensions [5].

### *The Diffusion Equation*

In order to predict the plasma ignition threshold field  $E_t$  for a given cavity geometry, driving frequency, and gas mixture, it is necessary to properly describe the behavior of electrons as ionizing particles. The effective diffusion length  $\Lambda$  describes the average distance traveled by ionizing electrons before they are re-combined into neutral material [6]. A kinetics-based derivation of the effective diffusion length relies on the eigen-solution to a simplified Fick's Law diffusion equation [7]:

$$\nabla^2 n = -\frac{\nu}{D} n = -\frac{1}{\Lambda^2} n, \quad (1)$$

where  $n$  is free electron number density,  $D$  is the diffusion coefficient, and  $\nu$  is the collision frequency, with the latter two determined by the gas mixture and state variables. The free electron number density  $n$  is assumed to be zero on the walls of the container due to electron re-combination at the conducting walls. Previous work used an analytic approach to find  $\Lambda$  for a simplified coaxial geometry which approximates the FRIB QWR shape. A numerical approach

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will be taken to find a more exact solution to the diffusion equation and thus a more precise value of  $\Lambda$  for several cavities.

### Determining $E_t$ from the Diffusion Length $\Lambda$

Previous studies predicted the ignition threshold from the diffusion length [6]. For sufficiently low gas pressure ( $p < 0.1$  Torr),

$$E_t = \frac{\ell}{\Lambda} \sqrt{\frac{mu_i}{3e}} \sqrt{v_m^2 + \omega^2}, \quad (2)$$

where  $v_m$  is the momentum-changing collision frequency,  $\omega$  is the RF angular frequency,  $u_i$  is the ionization potential and  $\ell$  is the mean free path length for electrons;  $m$  and  $e$  are the electron mass and charge, respectively. The gas composition and pressure determine  $u_i$ ,  $\ell$ , and  $v_m$  [7], while  $\Lambda$  depends on the size and shape of the cavity.

## EFFECTIVE DIFFUSION LENGTH CALCULATIONS

The length  $\Lambda$  is solely determined by the geometry of the bounding surface and associated boundary conditions ( $n = 0$  on the surface of the cavity) as an eigenvalue solution to Eq. (1) [7]. For previous predictions [5], we obtained an approximate value of  $\Lambda$  by simplifying the QWR shape.

We can obtain a more precise value for  $\Lambda$  using COMSOL to solve the diffusion eigenvalue equation. A numerical solution to Eq. (1) can be calculated using COMSOL's mathematics eigenvalue solver [8], with the cavity geometry as a boundary condition. Table 1 compares the  $\Lambda$  values from COMSOL for several cavity shapes with the approximate values obtained for simplified cavities. The corresponding eigenfunctions from COMSOL are shown in Fig. 1. The QWR and HWR cases correspond to FRIB cavities; the  $\beta = 0.65$  case is an elliptical cavity developed for the FRIB energy upgrade [9]. For the latter shape, an integral approximation was used to obtain the analytic value of  $\Lambda$ , following an approach previously used for the CEBAF cavity [6].

Table 1: Analytic and numerical values of the effective diffusion length calculated using simplified geometries and COMSOL simulations, respectively.

Cavity Type	Cavity $\beta$	$\Lambda$ (mm)	
		Analytic	Numerical
QWR	0.086	26.7	35.0
HWR	0.29	22.8	26.7
HWR	0.53	33.7	44.1
Ellip.	0.65	31.0	34.4

## COMPARISON METHODS

When producing plasma in FRIB cavities, the forward, reverse, and transmitted power are measured in continuous wave mode. We can infer the stored energy  $U$  from these

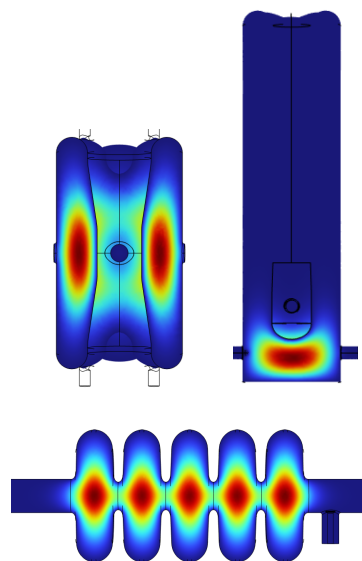


Figure 1: Heat maps of electron number density distributions obtained by solving the diffusion equation with COMSOL. Top left:  $\beta = 0.29$  HWR. Top right:  $\beta = 0.086$  QWR. Bottom:  $\beta = 0.65$  elliptical cavity.

measurements and the coupler strengths. The corresponding peak surface field  $E_p$  from an EM model of the cavity may then be inferred using CST Microwave Studio. We compare the predicted ignition field  $E_t$  to the measured  $E_p$  at plasma ignition, with  $E_p$  calculated from  $U$ . In previous comparisons for FRIB QWRs, this approach was considered as well as some alternative methods based on the integral of the electric field over different paths [5].

As shown in Fig. 2, when increasing the forward power  $P_f$  (green curve), a downward jump in the transmitted power  $P_t$  and cavity field  $E_p$  occurs when the plasma ignites. The cavity plasma zone is indicated by an orange background. If we reduce  $P_f$  (blue curve), the plasma persists until the extinction threshold is reached and the ionized gas returns to a neutral state. The horizontal lines indicate the corresponding ignition and extinction threshold field strengths.

## COMPARISON RESULTS

Predictions and measurements are compared in Fig. 3. The dashed lines are predictions based on analytic calculations of  $\Lambda$ ; the solid lines are predictions based on numerical calculations of  $\Lambda$  with COMSOL; the blue, red, and green circles are measured ignition thresholds for several resonant modes; and the black circles are measured extinction thresholds. The predictions are based on plasma parameters calculated from Table 2.1 in Ref. [10] for Ne at  $\sim 100$  mTorr:  $\ell = 12$  mm and  $v_m = 1.2 \cdot 10^8$  sec $^{-1}$  (not considering the contribution from  $O_2$ ). The agreement between the predictions and the measured extinction thresholds is reasonable in most cases. The measured ignition thresholds, on the other hand, are consistently higher than the predictions and measured extinction thresholds.

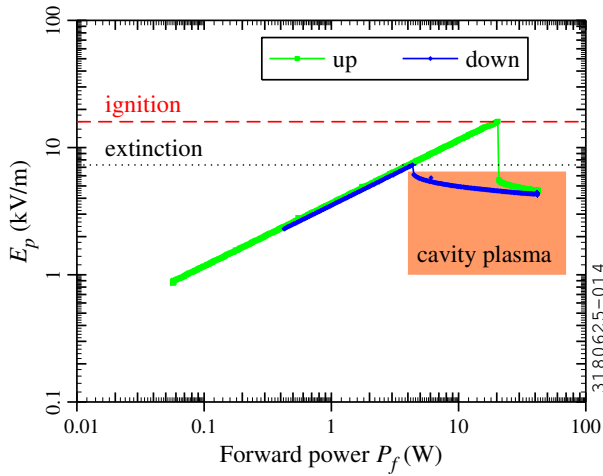


Figure 2: Power ramp-up to ignition and ramp-down to extinction for a FRIB  $\beta = 0.53$  HWR with Ne/O<sub>2</sub> plasma.

Predicted thresholds based on numerical calculations of  $\Lambda$  are consistently lower than those based on analytic calculations of  $\Lambda$ . The scatter in measured values makes it difficult to infer which method is a better match with experimental values. We note that the measured thresholds typically vary from one measurement to another, and appear to have some systematic trends dependent on the plasma history; only a sampling of measured values is included in Fig. 3.

### CONCLUSION

Plasma ignition threshold RF fields for several FRIB cavities have been predicted using a diffusion-dominated plasma model. Predictions based on numerical calculations of the effective diffusion length predict lower ignition thresholds than those based on analytic approximations. Comparisons with plasma measurements show that the predicted ignition thresholds are in reasonable agreement with measured extinction thresholds; the measured ignition thresholds are significantly higher than predicted. The simple diffusion-dominated model does not provide a quantitative explanation for this discrepancy.

The diffusion-dominated model could be used to predict ignition thresholds for other cavity shapes and could provide guidance for future plasma processing development work, though we can expect the measured ignition thresholds to be higher than predicted.

A more general model may be needed for accurate predictions of coupler ignition; for the case of FRIB fundamental power couplers, the diffusion-dominated model is inapplicable.

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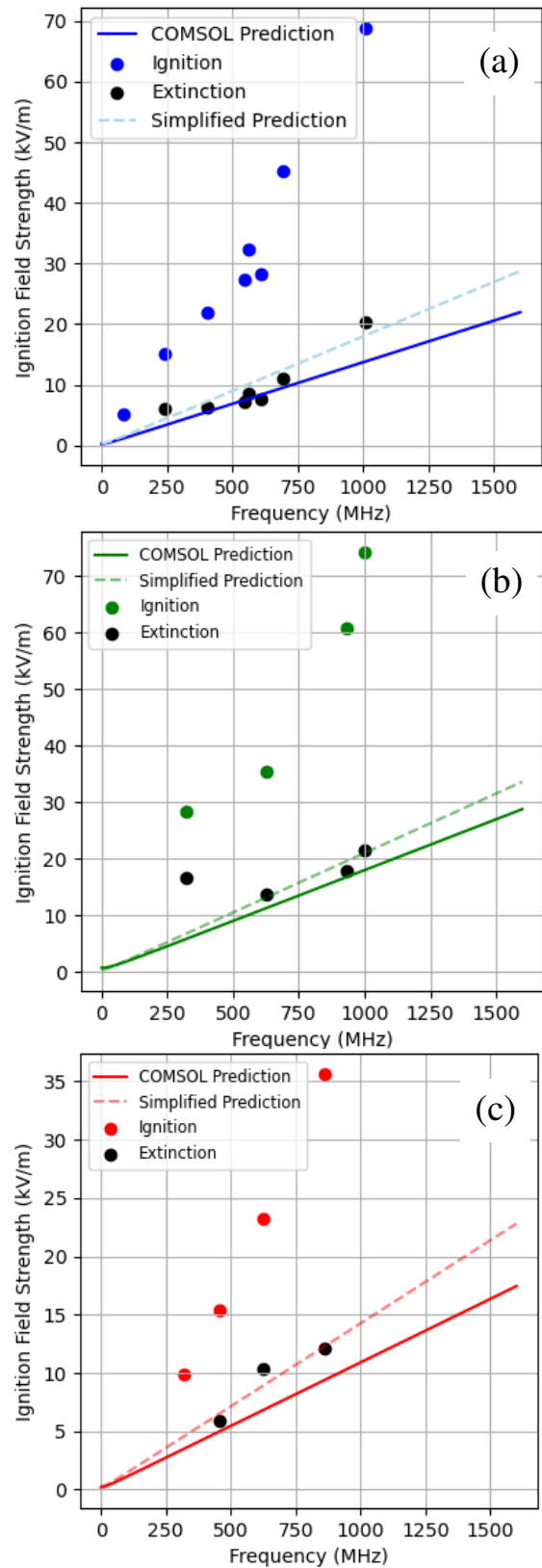


Figure 3: Comparison of predicted and measured plasma thresholds as a function of RF frequency for FRIB cavities: 95% Ne, 5% O<sub>2</sub>, pressure  $\sim 100$  mTorr. (a)  $\beta = 0.86$  QWR; (b)  $\beta = 0.29$  HWR; (c)  $\beta = 0.54$  HWR.

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