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PEEK-POLYMER AS A VACUUM-WINDOW IN HIGH POWER RF-COUPLERS

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Abstract

PEEK is an advanced polymer known for its exceptional mechanical strength, thermal stability and radiation resistance, making it a promising candidate for applications in extreme environments. This study explores the viability of PEEK as a vacuum-window material in high-power radio frequency (RF) couplers. Traditionally, materials such as ceramics are employed for this purpose; however, they are costly to manufacture and impose limitations during the design process. PEEK offers additional advantages, including the possibility of additive manufacturing, which enables the integration of cooling channels for efficient thermal management. The research evaluates PEEK's electrical, thermal, and mechanical properties under conditions typical of high-power RF couplers, such as vacuum stability, RF-induced heating, and electromagnetic transparency. At the Institute for Applied Physics (IAP) PEEK is tested as a vacuum-window material in high-power experiments up to 35 kW. Following these tests, the material is validated to assess its performance and suitability for RF applications.

INTRODUCTION

The primary function of a coupler is to transfer the high-power RF signal from the amplifier into the cavity. Ideally, this coupling should be achieved with minimal reflection. In the setup used at IAP, the RF power is transmitted via a coaxial line to an inductive loop, which then couples to the magnetic field of the resonator. In this case, the coupler includes a transition region from the coaxial geometry to the inductive loop.

Furthermore, a vacuum-window is required to separate the vacuum inside the cavity from the external power feed. Usually, ceramic materials with a high dielectric constant ϵ_r are used for this purpose. Despite their numerous advantages and decades of successful application, these materials exhibit certain weaknesses. For instance, ceramic-inlets are prone to fracture under mechanical or thermal stress, causing costly replacements (see Fig. 1). As a result, alternative materials are being explored. One promising candidate is PEEK, which exhibits favorable RF-properties for its use as a vacuum-window. At IAP, a new coupler design is tested: A vacuum-window originally made of alumina ceramic was replaced with a PEEK-based replica.

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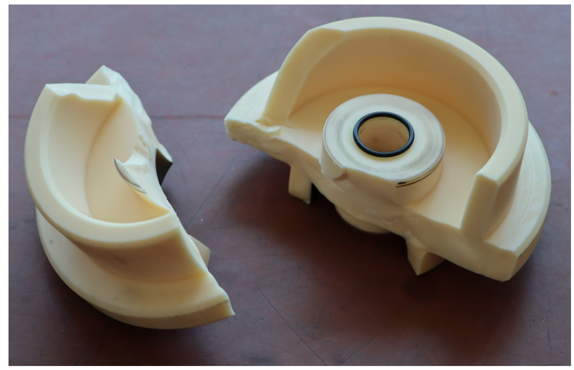

Figure 1: Two large fragments of a broken alumina vacuum-window [1].

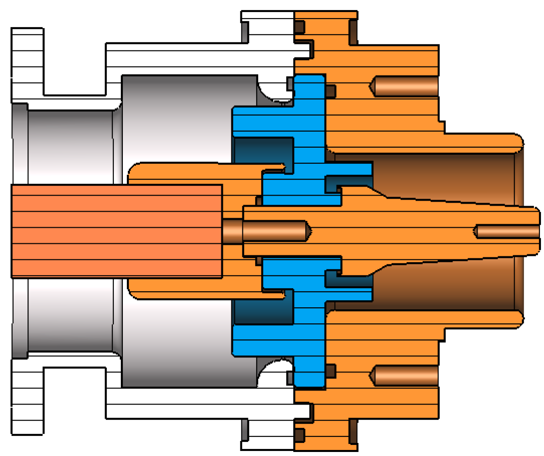

Figure 2: Cross-section of the CST model of the coupler. Shown are the vacuum-window (blue), the inner and outer conductor (orange) and a part of the outer conductor made of aluminum (grey).

PRE-CALCULATION

Of particular interest are the dielectric losses P and the reflection coefficient Γ. The inlet can be approximated as a smooth dielectric disk of thickness d, under the condition $d\sqrt{\epsilon_r} << \lambda_0$. In this case, the reflection coefficient is given by

$$\Gamma = \pi d f(\epsilon_r - 1)/c_0. \tag{1}$$

The dielectric losses can be estimated using

$$P = V_{\text{eff}}^2 \cdot \omega \cdot C \cdot \epsilon_r \cdot \tan(\delta). \tag{2}$$

From the dependencies $\Gamma \propto \epsilon_r$ and $P \propto \epsilon_r \tan(\delta)$ one can expect increased dielectric losses but a reduced reflec-

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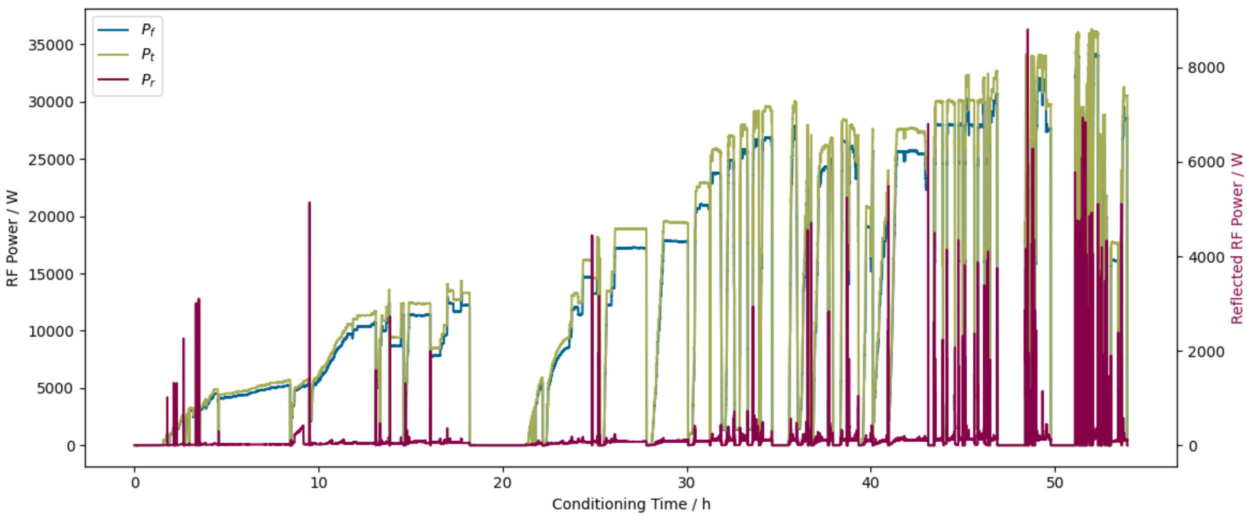

Figure 3: The diagram shows the progression of the power parameters during the conditioning process: Forward power (Pf, blue), reflected power (Pr, red) and transmitted power (Pt, green).

tion coefficient [2]. To further evaluate this hypothesis, both parameters were calculated at a forward power of 30 kW, using the frequency-domain solver in a CST simulation to provide preliminary reference values. The coupler design used in the simulation is shown in Fig. 2. The simulation results, summarized in Table 1, support the previous assumption and motivate the experimental validation of the PEEK-inlet in the following high-power conditioning.

Table 1: Dielectric Losses P_{cst} and Reflection Coefficient Γ_{cst} Determined by a CST-simulation of PEEK and Alumina

	PEEK	**Alumina**
ϵ_r	3.2	9.5
$\tan(\delta)$	2.5e−3	1e−4
P_{cst} / W	2.58	0.237
Γ_{cst}	2.4e−5	3.1e−3

HIGH-POWER CONDITIONING

Conditioning can be understood as a type of surface treatment and represents a crucial step in the commissioning of RF cavities. It is a time-consuming process characterized by a dynamic interplay of outgassing, multipacting, and breakdown events, which complicate the procedure and often necessitate temporary setbacks. The process usually begins at low power levels, which are gradually increased over time. Conditioning is considered complete when the desired power level can be coupled into the cavity for a sufficiently long duration without causing a noticeable rise in internal pressure or reflected power [3]. The conditioning setup used in this study is identical to that of the MYRRHA CH-cavities at IAP [4] and operates the MAX-RFQ prototype at a frequency close to 176.1 MHz [5]. A solid-state amplifier delivers maximum power levels of up to 60 kW. The conditioning period extended from September to October 2024. During conditioning, maximum power levels exceeding 30 kW were sustained for at least 15 hours without any significant incidents. In total the coupler was used for over 50 h of conditioning. The timeline of the conditioning process is shown in Fig. 3. The vacuum is contained at previous levels at about 5×10^{-7} mbar.

RESULT

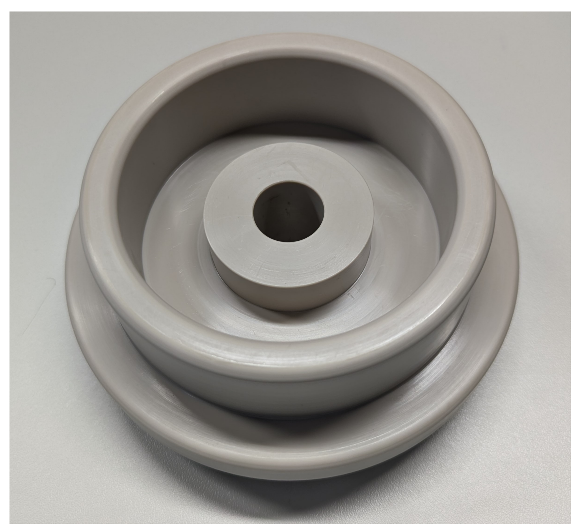

Figure 4: Physical condition of the PEEK-inlet after high-power conditioning in top view.

After high-power conditioning, the coupler was thoroughly inspected. No signs of damage were observed on the coupler and the PEEK-inlet remained intact. The edges of the inlet remained sharp, with no evidence of deformation. The condition of the vacuum-window is documented in Fig. 4 and shows no visible degradation.

The outcome of the high-power conditioning suggests that coupling powers exceeding 30 kW using a PEEK vacuum-window is fundamentally feasible. It was observed that

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reflection during operation did not increase, indicating effective coupling of the PEEK vacuum-window to the system, even when maintaining the conventional ceramic geometry and merely replacing the material. It can be assumed that the cooling is sufficient to dissipate the increased dielectric losses. These results support the assumption that PEEK is a promising and cost-effective alternative to conventional ceramics. They highlight the potential of PEEK for use in high-power couplers, as neither mechanical nor dielectric limitations were identified.

OUTLOOK

Future investigations into the performance limits of PEEK are recommended to evaluate the material's suitability for further applications. Therefore, tests at higher power levels over extended periods are necessary. This could also provide a foundation for the evaluation of additional high-performance materials, such as Teflon.

REFERENCES

[1] A. Rüffer, "High-Power-Test des 175 MHz RFQ Prototypen", Master's thesis, Inst. für Angewandte Physik, Goethe-Universität Frankfurt am Main, Frankfurt, Germany, 2022.

[2] H. H. Meinke *et al.*, "Taschenbuch der Hochfrequenztechnik, Band 1: Grundlagen", Springer, Berlin, Germany, 2013.

[3] K. P. Kümpel, "Untersuchungen am MYRRHA Injektor", Ph.D. thesis, Inst. für Angewandte Physik, Goethe-Universität Frankfurt am Main, Frankfurt, Germany, 2022. doi:10.21248/gups.68892

[4] P. Braun *et al.*, "Preparation for the conditioning of the MYRRHA CH-Cavities at IAP", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 3491–3493. doi:10.18429/JACoW-IPAC2024-THPR07

[5] M. Vossberg, H. C. Lenz, H. Podlech, A. Schempp, and A. Bechtold, "RF Measurement during CW Operation of an RFQ Prototype", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper WEPFI009, pp. 2720–2722.