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DEVELOPMENT OF A METAMATERIAL-BASED CAVITY BEAM CURRENT MONITOR AT HUST*

Yuexin Lu, Jiqin Li, Jian Wang, Zhengzheng Liu, Kuanjun Fan†
Huazhong University of Science and Technology, Wuhan, China
Jinfeng Yang, Osaka University, Osaka, Japan
Zhigao Fang, High Energy Accelerator Research Organization, Ibaraki, Japan
Oleg Meshkov, Budker Institute of Nuclear Physics, Novosibirsk, Russia

Abstract

The dimensions of a cavity beam diagnostic device are determined by its operating frequency, which is linked to the repetition frequency of the beam bunch. This relationship limits the effectiveness of such devices for measuring low repetition frequency bunches. In cyclotron-based proton therapy systems, where the bunch repetition frequency is relatively low, there is a need for real-time online monitoring during clinical procedures. To address this, we propose a metamaterial-loaded cavity beam diagnostic device with a fundamental mode resonant frequency that is double the bunch repetition frequency. Electromagnetic simulations demonstrate that this design significantly reduces the cavity size under low-frequency conditions and effectively mitigates the electromagnetic energy loss, resulting in improved sensitivity.

INTRODUCTION

Non-intrusive cavity diagnostic devices for beam current measurement offer significant advantages, such as high-induced signal strength and sensitivity. However, the size of a resonant cavity is inversely related to its operating frequency, leading to increased dimensions at lower frequencies, which can limit its applicability. To address the challenges in real-time monitoring of beams with low repetition rates and weak intensities, modifications to the cavity structure are needed to regulate its internal electromagnetic field distribution and reduce the operating frequency. PSI [1, 2] and HUST [3] have developed innovative cavity beam current diagnostic devices by filling the resonant cavity with dielectric materials, thereby enhancing their performance.

Metamaterials are a class of artificially engineered structures that can be designed to have negative effective permittivity and negative effective permeability [4], which can significantly alter the behavior of electromagnetic fields for various applications [5]. Previous research has shown that waveguides loaded with metamaterials can propagate quasi-TM mode waves at frequencies below the cutoff frequency of traditional metallic waveguides [6]. Building on this foundation, we designed a specially structured metamaterial and incorporated it into the resonant cavity, effectively lowering the cavity's resonant frequency and significantly reducing its size. This metal-based metamaterial overcomes the precision machining challenges associated with dielectric materials as cavity fillers while also reducing electromagnetic field losses within the cavity. The resonant frequency of this cavity-based Beam Current Monitor (BCM) is set at 146 MHz, aligning with the proton beam repetition frequency (73 MHz) of the HUST Proton Therapy Facility (HUST-PTF) at Huazhong University of Science and Technology. [7–9]

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† E-mail: kjfan@hust.edu.cn.

DESIGN

A cavity beam diagnostic device captures the electromagnetic field signal induced as the beam passes through the cavity, providing crucial information about the beam. In a cylindrical cavity resonator, the TM010 mode exhibits the strongest electric field at the center of the cavity. This electric field, directly proportional to the bunch charge, is concentrated almost entirely in the central region, making it highly suitable for current intensity detection.

The resonator, equipped with coupling loops, can generate a signal proportional to the beam charge q. For the TM mode, the amplitude sensitivity can be expressed as follows [10]:

$$V_{out} = \pi q f \sqrt{\frac{Z}{Q_{ext}}\left(\frac{R}{Q}\right)}. \quad (1)$$

In the equation, with given frequency f and line impedance Z, the voltage signal is related to the normalized shunt impedance R/Q and external quality factor Q_{ext}. The value of the external quality factor is determined by the antenna position.

To achieve a working frequency of around 146 MHz, a cylindrical cavity would typically require a radius of approximately 784 mm, which is impractically large for production and application. The use of metamaterials presents a viable solution to this issue. Specially designed metamaterials can exhibit negative effective permittivity or permeability depending on the frequency. Within a frequency range where the effective permittivity is negative, the TM mode can propagate. By incorporating a metamaterial unit cell, a negative refractive index passband is created, allowing the transmission of electromagnetic waves below the cutoff frequency of the resonant cavity. This feature can be utilized to significantly miniaturize the cavity.

Following the structure developed by Y. Wang et al. [11], the metamaterial unit was designed to meet the specific requirements. Metamaterial cells with a single slotted wire have smaller lateral dimensions and greater axial electric field intensity. By increasing the length of the slotted wire, the resonance frequency can be reduced. Figure 1

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illustrates the structure of the metamaterial unit. This unit exhibits a strong dispersive electrical response, resulting in a significantly strong electric field in the central area of the structure, which aligns well with the operating mode of the cavity monitor.

The performance of cavities utilizing metamaterial units largely depends on their electromagnetic properties. Therefore, understanding the electromagnetic characteristics of the structure is fundamental to advancing the study of vacuum electronic devices integrated with metamaterials. In principle, an equivalent circuit model can be used to characterize the properties of a metamaterial structure if it is relatively simple. However, in our case, the structure is too complex to be accurately represented by an equivalent circuit. Therefore, we employed a trial-and-error approach to optimize the structure's parameters and achieve the design objectives.

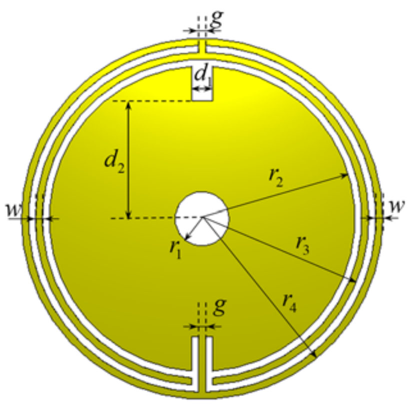

Figure 1: Schematic of a metamaterial unit.

CST SIMULATION

CST Studio is widely used in the simulation and design of microwave devices. In resonant cavity design, it allows us to determine the resonant frequency, quality factor, electromagnetic field distribution within the cavity, and other critical parameters.

Model Creation and Analysis Setup

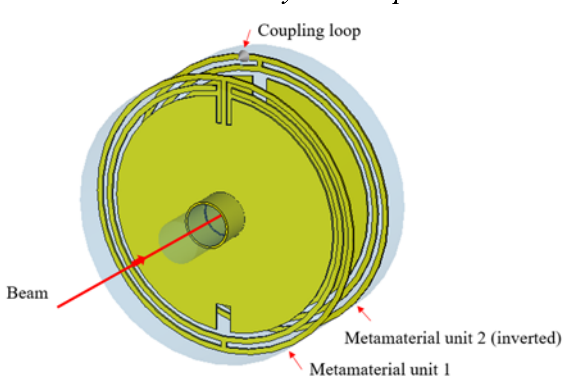

Figure 2: Model of the metamaterial-loaded cavity using CST 3D modeler.

In our design, the entire cavity is constructed from copper to minimize energy loss. As shown in Fig. 2, the cavity consists of two metamaterial unit cells, each loaded on one side of the cavity resonator, with the beam passing through the center. To address the issue of uneven electromagnetic fields caused by the asymmetric structure of a single slotted line, we used two single slotted line units placed in an inverted arrangement to reduce field non-uniformity. The coupling loop, which captures the voltage signal, is positioned accordingly.

Table 1 presents the optimized parameters of the metamaterial unit cell. The effective permittivity and permeability of the single metamaterial unit cell were determined through simulation and calculated using the S-parameter-based retrieval method, as shown in Fig. 3. The figure indicates that below the frequency of 151.1 MHz, the effective permittivity of the metamaterial drops below zero, implying that the metamaterial provides a passband below 151.1 MHz when excited by a TM mode wave. Consequently, it can be inferred that a cavity loaded with the metamaterial unit can achieve an operating frequency of 146 MHz.

Table 1: Designed Metamaterial Property

Property	r_1	r_2	r_3	r_4	g	w	d_1	d_2
Value (mm)	39	220	240	260	10	10	30	170

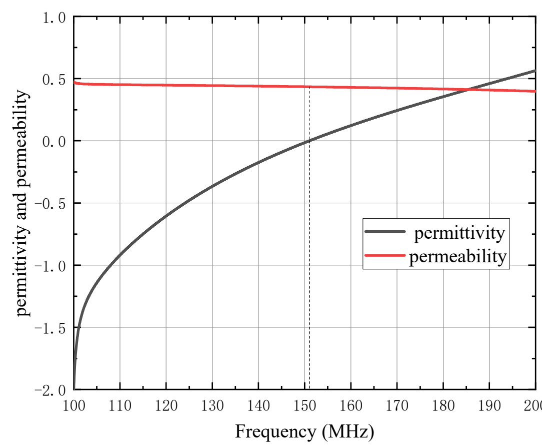

Figure 3: Retrieved permittivity and permeability of the metamaterial use the S parameter-based retrieval method.

Simulation Results

Figure 4 shows the field distribution within the cavity. Specifically, Fig. 4(a) illustrates the electric field distribution in the y-z cross-section, while Fig. 4(b) presents the magnetic field distribution in the x-y cross-section. The introduction of the metamaterial unit cell into the cavity concentrates the electric field along the axis, while the magnetic field is predominantly distributed in the transverse direction. This field distribution validates the working principle described earlier, indicating that the cavity operates in a quasi-TM mode. The key electromagnetic parameters derived from the simulation are listed in Table 2.

Generally, it is desirable to use a cavity with a high unloaded quality factor (Q_0) as it results in a longer-duration output signal and more effective sampling points per beam

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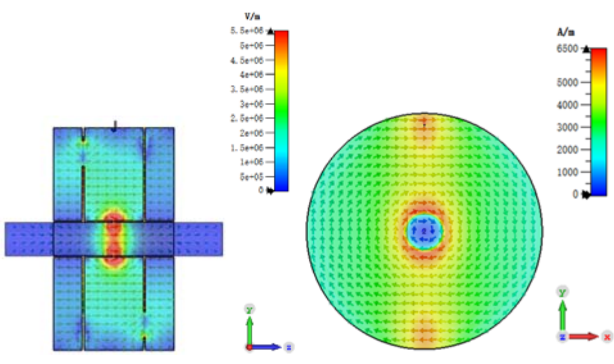
cluster signal, leading to a higher amplitude output signal. The results in the table show that the unloaded quality factor is quite high, and the normalized shunt impedance falls within the desired range.

Given that the design is an all-metal structure, there is no dielectric loss during operation, significantly improving the output signal amplitude compared to traditional dielectric-loaded cavity detectors. Moreover, we calculated the output signal amplitude of this cavity BCM. Based on the resonance frequency, external quality factor, and normalized tapped impedance obtained from the simulation, we determined that the output signal amplitude for a 70 MeV proton beam is 121.8 nV. Consequently, the beam intensity sensitivity reaches 348 nV/nA, which is 8.2 times greater than that of a dielectric-loaded cavity BCM [3].



(a) (b)

Figure 4: (a) The E field inside the resonator. (b) The H field inside the resonator.

Table 2: Resonator Property Results

Property	Value
Frequency-f	146.00 MHz
Quality factor-Q_0	6200
External quality factor-Q_{ext}	8035
Normalized shunt impedance-$\frac{R}{Q}$	103.07Ω

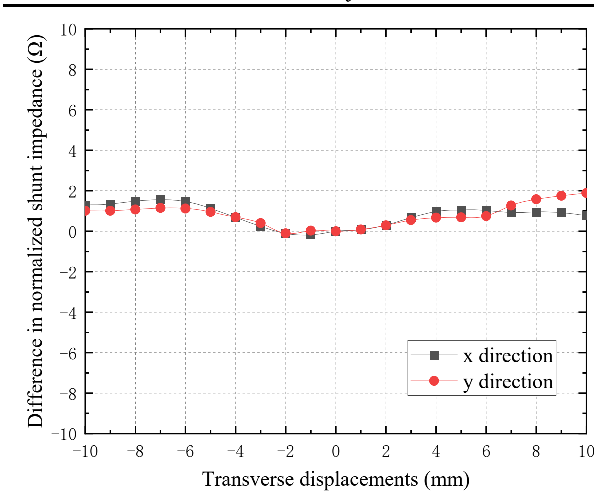


Figure 5: The difference in normalized shunt impedance with respect to the center in the beam pipe.

The normalized shunt impedance at various lateral positions was obtained from simulation results, allowing for the calculation of the output voltage signal amplitude of the metamaterial-loaded cavity BCM. The output signal amplitude is affected differently by beam offsets in the x-direction and y-direction due to the non-circumferential symmetry of the loaded metamaterial unit. Figure 5 illustrates the simulation results of the difference in normalized shunt impedance compared to that of the center, which exhibits minimal sensitivity to small displacements of the beam in both the x-direction and y-direction.

Furthermore, the voltage signal is simulated as a 73 MHz proton beam passing through the resonant cavity. The parameter coupling of the inductive pickup was calculated from the simulation, as shown in Fig. 6. The frequency corresponding to the peak of the curve aligns with the resonance frequency. Fig. 7 demonstrates the calculated voltage signal magnitude with the change of the beam intensity.

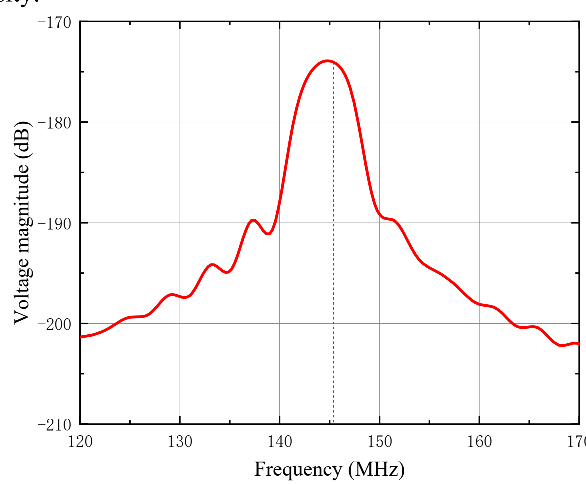


Figure 6: The parameter coupling of the cavity resonator model from the simulation.

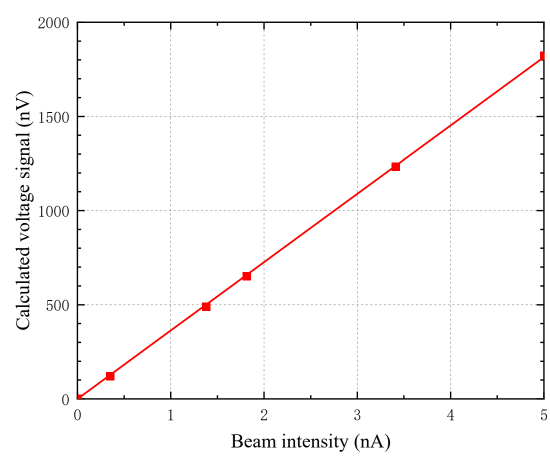


Figure 7: Calculated output signal magnitude.

CONCLUSION

This paper proposes an advanced cylindrical cavity loaded with metamaterials for real-time beam current measurement, specifically designed to monitor low-

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intensity proton beams. To match the second harmonic of the 146 MHz beam pulse repetition rate, a traditional resonant cavity would require a radius of 784 mm. However, by incorporating metamaterial unit cells, the cavity radius can be significantly reduced to 260 mm. This reduction not only decreases the overall size of the cavity but also simplifies machining and lowers fabrication costs. Additionally, since the design is entirely metallic, it eliminates dielectric losses during operation, resulting in a significantly improved output signal amplitude compared to conventional dielectric-loaded cavity detectors.

Future work will focus on optimizing the structural parameters of the metamaterials within the cavity monitor. We qualitatively analyzed the metamaterial unit parameters in this initial design and selected them tentatively without rigorous theoretical analysis. This approach leaves room for further optimization of the structural parameters, which will be thoroughly explored in subsequent studies.

REFERENCES

[1] Jansson, "Noninvasive Single-Bunch Matching and Emittance Monitor", *Phys. Rev. ST Accel. Beams*, vol. 5, p. 072803, 2002. doi:10.1103/PhysRevSTAB.5.072803

[2] S. Srinivasan *et al.*, "Beamline characterization of a dielectric-filled reentrant cavity resonator as beam current monitor for a medical cyclotron facility", *Phys. Med.*, vol. 78, pp. 101–108, 2020. doi:10.1016/j.ejmp.2020.09.006

[3] L. Jiqing *et al.*, "Design and performance study of a dielectric-filled cavity beam current monitor for HUST-PTF", *Nucl. Sci. Tech.*, vol. 34, no. 129, 2023. doi:10.1007/s41365-023-01278-0

[4] D. R. Smith *et al.*, "Composite medium with simultaneously negative permeability and permittivity", *Phys. Rev. Lett.*, vol. 84, p. 4184, 2000. doi:10.1103/PhysRevLett.84.4184

[5] T. Hand *et al.*, "The measured electric field spatial distribution within a metamaterial subwavelength cavity resonator", *IEEE Trans. Antennas Propag.*, vol. 55, no. 6, pp. 1781–1788, 2007. doi:10.1109/TAP.2007.89-8630

[6] R. Marques *et al.*, "Left-handed-media simulation and transmission of EM waves in subwavelength split-ring-resonator-loaded metallic waveguides", *Phys. Rev. Lett.* vol. 89, p. 183901, 2002. doi:10.1103/PhysRevLett.89.183901

[7] B. Qin *et al.*, "Design and development of the beamline for a proton therapy system", *Nucl. Sci. Tech.*, vol. 32, no. 138, 2021. doi:10.1007/s41365-021-00975-y

[8] P. Li *et al.*, "Design of HUST-PTF beamline control system for fast energy changing", *Nucl. Eng. Technol.*, vol. 54, pp. 2852–2858, 2022. doi:10.1016/j.net.2022.02.023

[9] Z. Mei *et al.*, "Optimization of a B4C/graphite composite energy degrader and its shielding for a proton therapy facility", *Nucl. Instrum. Methods Phys. Res. A*, vol. 995, p. 165127, 2021. doi:10.1016/j.nima.2021.165127

[10] S. Walston *et al.*, "Performance of a high resolution cavity beam position monitor system", *Nucl. Instrum. Methods Phys. Res. A*, vol. 578, pp. 1–22, 2007. doi:10.1016/j.nima.2007.04.162

[11] Y. Wang *et al.*, "All-metal metamaterial slow-wave structure for high-power sources with high efficiency", *Appl. Phys. Lett.*, vol. 107, no. 15, p. 153502, Oct. 2015. doi:10.1063/1.4933106