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, Russi

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 have an advantage in high-induced signal strength and sensitivity. While for beams with low repetition rates, the size is overlarge.

The benefits of metamaterials:

- lowering the cavity's resonant frequency and reducing its size.
- reducing electromagnetic field losses along with increasing sensitivity.

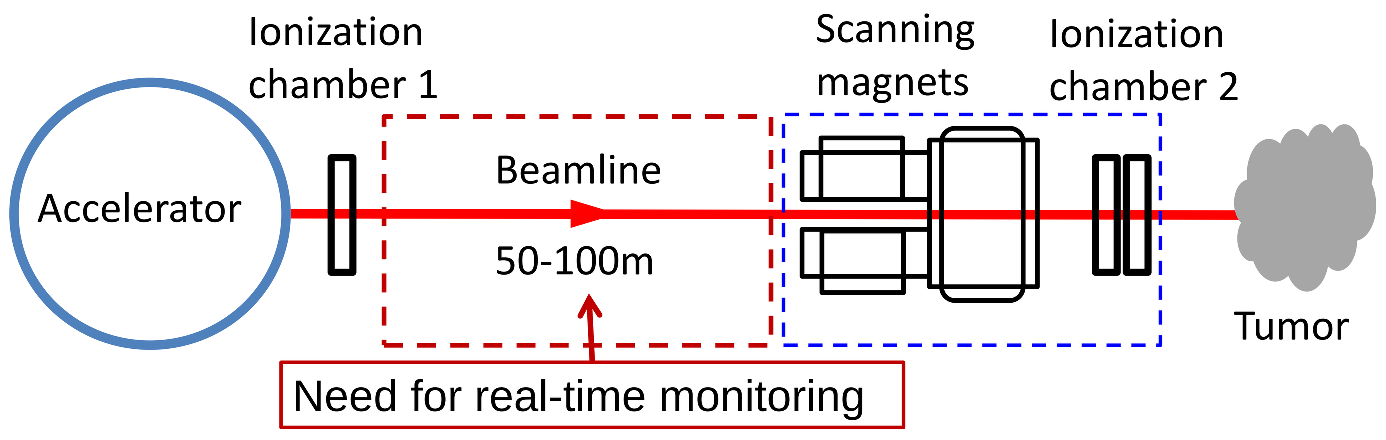

Figure 1: The necessity of beam current monitor for the application of proton therapy.

The frequency 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.

DESIGN AND MODEL

Incorporating a metamaterial unit cell allows the transmission of electromagnetic waves below the cutoff frequency of the resonant cavity.

- 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, its resonance frequency is reduced.

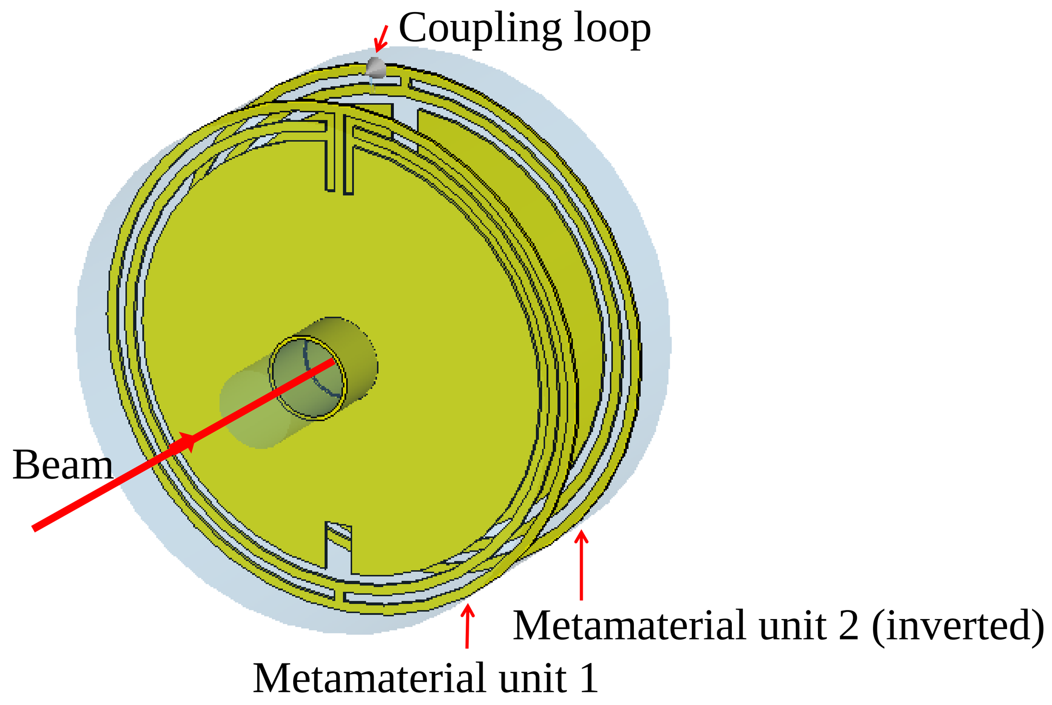

Figure 2: Model of the metamaterial-loaded cavity.

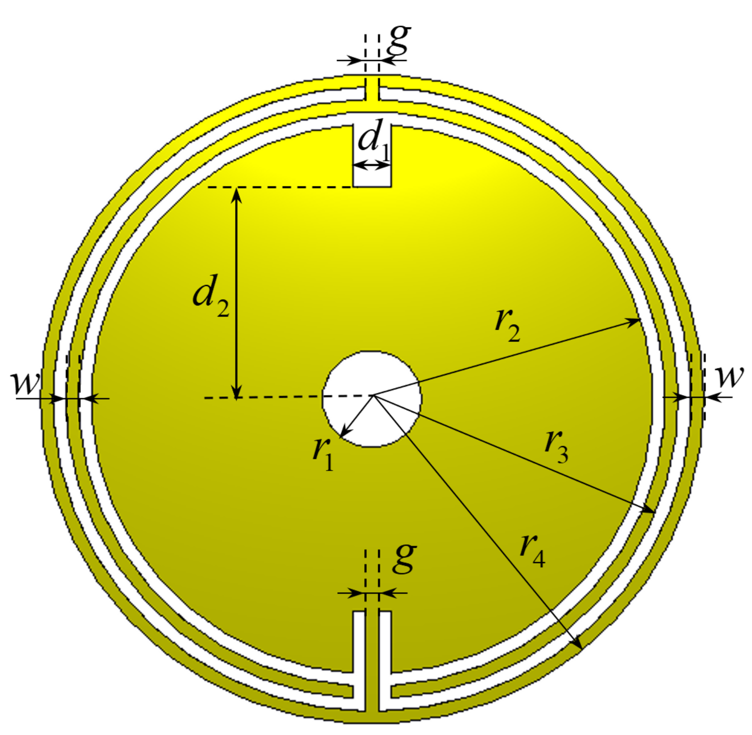

Figure 3: Schematic of a metamaterial unit.

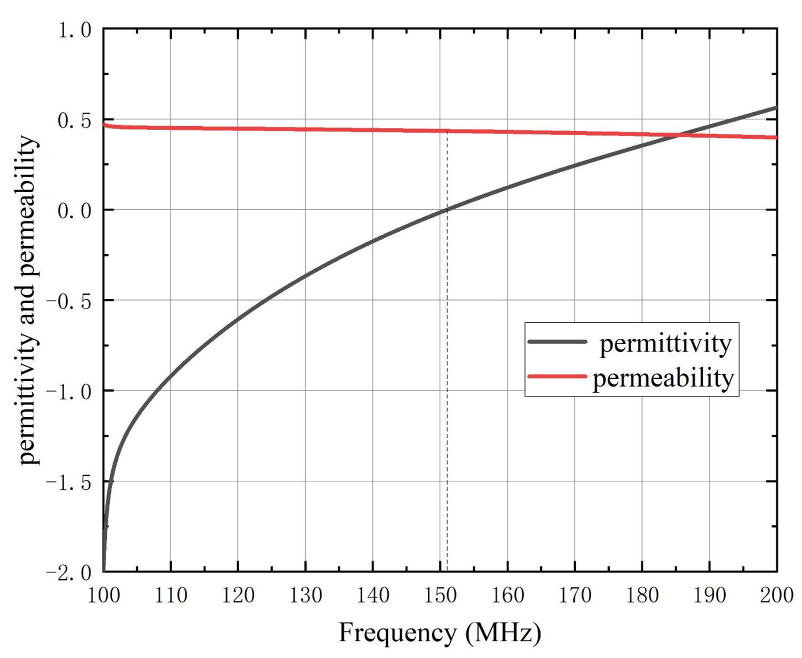

Figure 4: Retrieved permittivity and permeability of the metamaterial ; Below the frequency of 151.1 MHz, the effective permittivity drops below zero, implying that it provides a passband below 151.1 MHz when excited by a TM mode wave.

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

SIMULATION

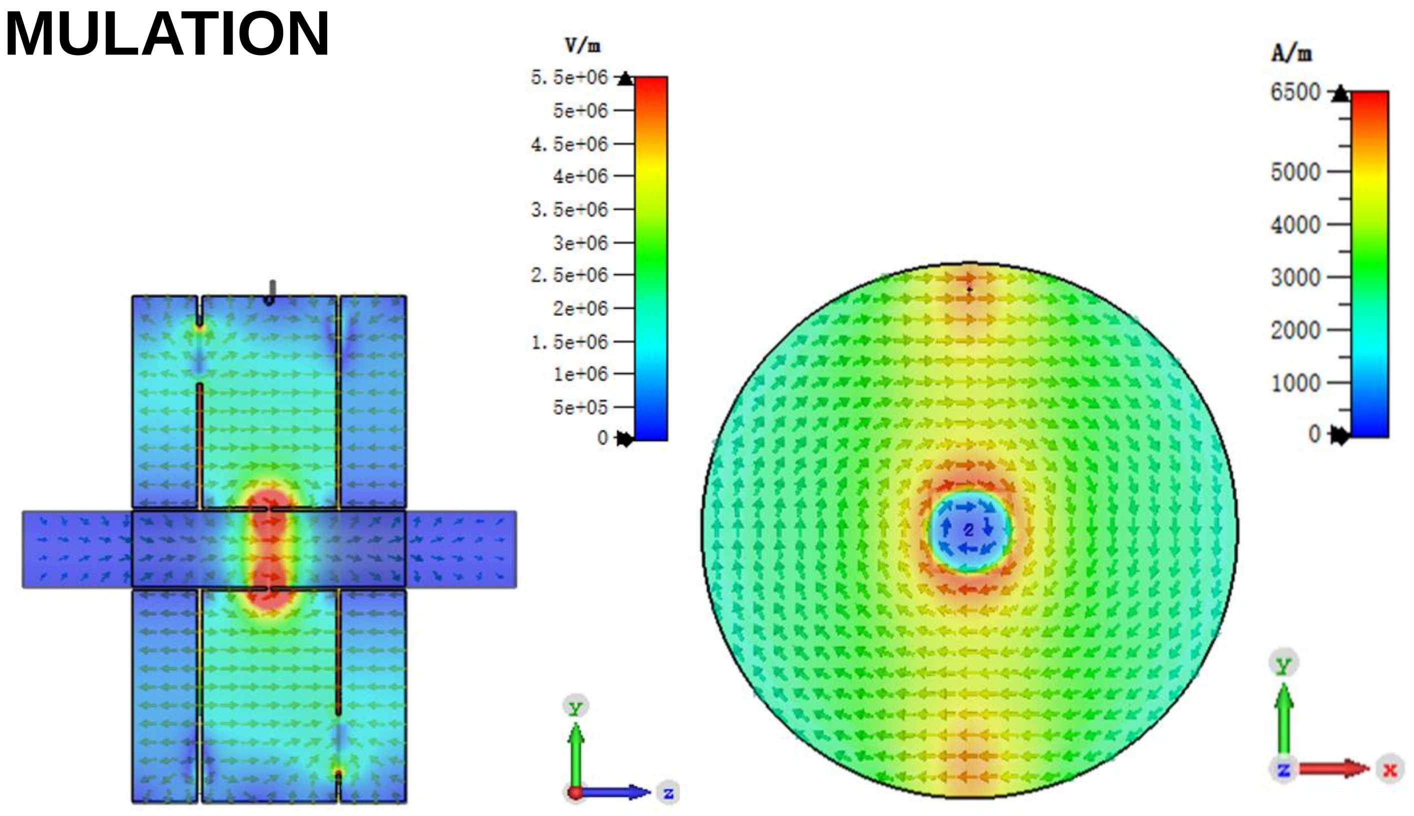

Figure 5: (left) The E field. (right) The H field. The metamaterial unit cell concentrates the electric field along the cavity axis, while the magnetic field is predominantly distributed in the transverse direction. This field distribution indicating that the cavity operates in a quasi-TM mode.

Table 2: key electromagnetic parameters

Parameters	Value	Unit
Frequency	146.00	MHz
Quality factor	6200	/
External quality factor	8035	/
Normalized shunt impedance	103.07	Ω

- The calculated output signal amplitude for a 70MeV (0.35nA) proton beam is 121.8nV. The beam intensity sensitivity reaches 348nV/nA.

ANALYSIS

Due to the non-circumferential symmetry of the metamaterial unit, the normalized shunt impedence slightly floats along with the change of offset in x and y direction perpectively.

- The influence on small displacements from the center is little enough to be neglect.

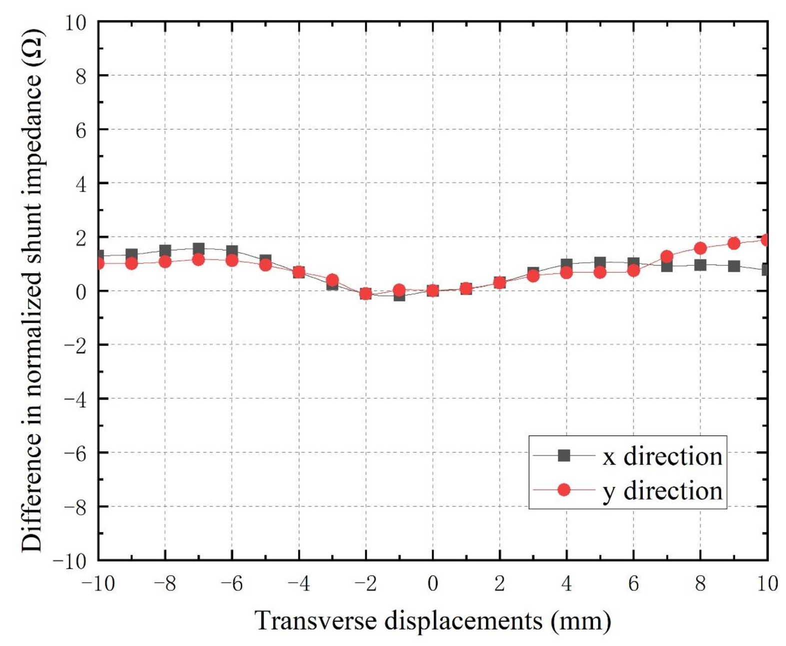

Figure 6: Difference in normalized shunt impedance compare to that of the center.

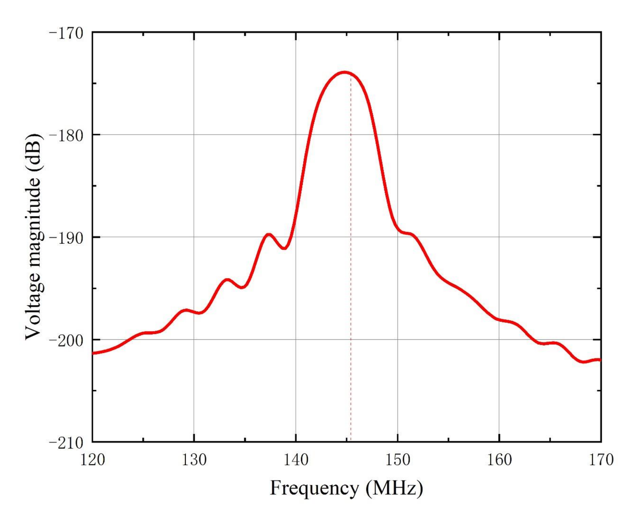

Figure 7: The voltage magnitude derived from the inductive pickup

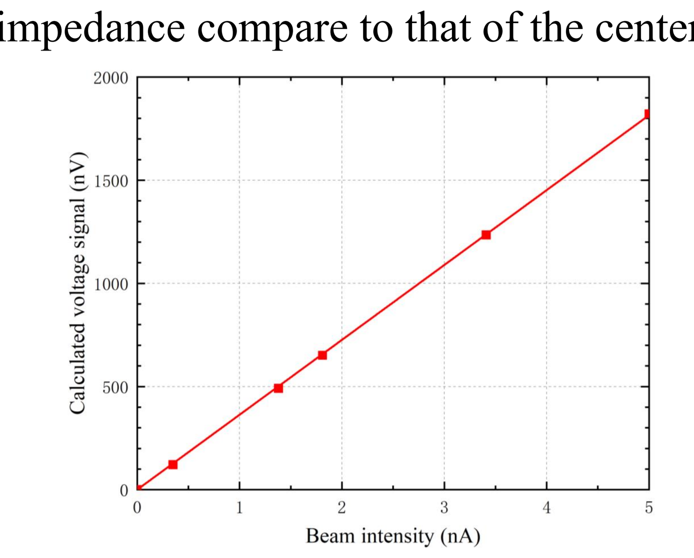

Figure 8: Calculated output signal magnitude

SUMMARY

An cylindrical cavity loaded with metamaterials for real-time beam current measurement is proposed. The overall reduced size of the cavity 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.