ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-MOPCO13

SIMULATION AND FEASIBILITY ANALYSIS OF A NON-INVASIVE CAVITY BUNCH CHARGE MONITOR FOR LOW-ENERGY ANTIPROTON BEAMS

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Abstract

For high-precision experiments involving low-energy antiprotons, accurate non-invasive beam charge measurements are essential. This work presents a simulation study of a cavity-based Bunch Charge Monitor (BCM) as an alternative to invasive methods such as Faraday Cups and Microchannel Plate (MCP) detectors, which suffer from charge loss. The challenge is particularly significant for low-energy antimatter beams, where accounting for such losses is difficult. Motivated by the needs of antimatter experiments like AEḡIS at CERN, the study explore the feasibility of a compact re-entrant cavity design for non-relativistic beams. Preliminary simulations are presented along with identified limitations, highlighting the potential of this BCM and its prospects for further development.

INTRODUCTION

Non-invasive charge measurement of low-energy particle beams remains a challenge in precision physics experiments. As noted in [1], beams with long bunch lengths, low repetition rates, or non-relativistic energies are especially difficult to diagnose with conventional non-invasive techniques since detector sensitivity drops at long timescales and the induced image currents become weaker and broadened. Invasive devices such as Faraday Cups or MCPs can provide charge information, but they suffer from charge loss and cannot detect neutral secondaries (photons, pions, neutrons) generated during beam-matter interactions [2, 3]. This limitation is substantial for low-energy antimatter, where annihilation and complex interactions with matter make charge loss difficult to quantify. On the other hand, established non-invasive approaches such as current transformers or wall current monitors require integration over multiple bunches, which is not feasible in facilities with long bunch delivery intervals.

The Antimatter Experiment: Gravity, Interferometry, Spectroscopy (AEḡIS) at CERN [4] exemplifies these challenges. It produces antihydrogen from antiprotons delivered by the Extra Low ENergy Antiproton (ELENA) ring, where bunches arrive only once every two minutes [5]. Precise single-bunch charge measurements are essential for optimizing the experimental setup and accurately interpreting results, but remain difficult to achieve. AEḡIS currently employs invasive detectors alongside scintillator-based non-invasive diagnostics. However, the former cannot account for neutral secondaries [3], while the latter suffers from systematic uncertainties at the level of 50 % [6]. ELENA also operates a Cryogenic Current Comparator (CCC) [7], which provides excellent sensitivity but requires cryogenic cooling and magnetic shielding, limiting its applicability in environments such as AEḡIS, where strong magnetic fields and tight spatial constraints are present.

These limitations motivate the search for an alternative diagnostic method. A promising approach is a cavity-based Bunch Charge Monitor (BCM), which exploits the resonant response of an RF cavity to a passing beam. While cavity monitors are widely used for high-frequency, relativistic beams [8–11], their extension to the low-frequency, large-bunch-spread regime relevant to antimatter experiments has not yet been explored. This work presents a simulation-based feasibility study of a compact re-entrant cavity BCM designed to measure the charge of a single non-relativistic beam pulse of antiprotons. The study investigates how geometric modifications and material loading can reduce cavity size while maintaining sensitivity, and discusses the challenges involved. The results provide a first step toward future experimental implementation and highlight prospects for broader application in low-energy antimatter beam diagnostics.

CONCEPT OF A CAVITY BUNCH CHARGE MONITOR

The principle of a cavity BCM is well established; a closed metallic cavity supports discrete electromagnetic modes. A passing charged particle bunch excites modes whose frequencies overlap with its bunch spectrum components. This stored energy is extracted as a signal proportional to bunch charge [12]. Such devices have been successfully implemented at facilities including PSI, Switzerland and the TOP-IMPLART facility at INFN Frascati, Italy [8, 9].

Among the available modes, the TM_{010} mode is commonly used, as its longitudinal electric field couples efficiently to the beam. In most applications, the cavity frequency is chosen to match the bunch repetition frequency, enabling multi-bunch integration for high sensitivity. At very low repetition rates, like ELENA, matching frequency to repetition rate is impractical. Instead, it is more effective to tune the cavity to the bunch spectral width. In this study, a gaussian bunch of $\sigma_t \approx 75$ ns, corresponding to the ELENA beam, was chosen as the design target.

The fundamental frequency f_0 scales with cavity size. In the 1–100 MHz range, dimensions of a pillbox cavity span

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1–115 m, making standard cavity BCMs impractical for the megahertz regime of low-energy antiprotons. A cavity can be viewed as a lumped-element LC resonator, with f_0 given by Eq. (1),

$$f_0 = \frac{1}{2\pi\sqrt{LC}}. \tag{1}$$

Lowering frequency at fixed size requires increasing inductance, capacitance, or both. Re-entrant cavity designs achieve this compactly by adding nose cones, which enhance capacitance and inductance in the respective field regions as shown in Fig. 1.

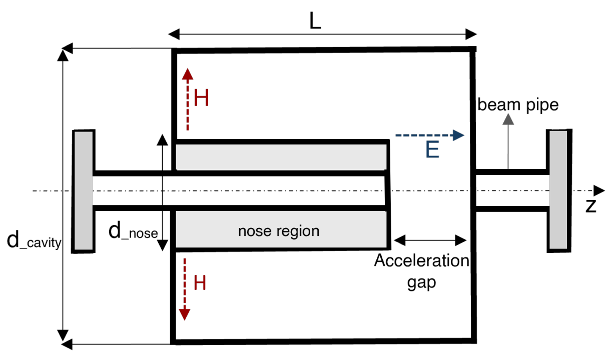

Figure 1: Cross section of a re-entrant cavity. The shaded nose cone increases capacitance, while cavity size sets frequency. Regions of strongest electric (E) and magnetic (H) fields are indicated.

Power Extraction and Material Loading

The signal obtainable from a cavity BCM depends on how efficiently the bunch excites the chosen mode and how effectively that energy is coupled out. The extracted power is given by the Eq. (2) [12],

$$P = R_s I^2 B^2 \frac{\beta}{(1+\beta)^2} \cos^2\phi, \tag{2}$$

where R_s is the shunt impedance of the cavity, I is the beam current, B is the bunch form factor, β is the coupling coefficient and ϕ accounts for any phase mismatch between the cavity resonance and the beam spectrum. The bunch form factor B depends on bunch shape. For a Gaussian bunch of length σ_t, $B = e^{-2\pi f_0^2 \sigma_t^2}$. Maximal P requires $B \approx 1$. For $\sigma_t = 75$ ns, this occurs at $f_0 = 1$ MHz.

Even re-entrant, a 1 MHz copper cavity would need multi-metre dimensions, far too large for AEḡIS with limited space. This can be reduced by adding high-permittivity dielectrics and high-permeability ferrites, which increase capacitance and inductance. However, these materials are lossy and reduce the shunt impedance, $R_s = V^2/2P_{loss}$, where V is the cavity voltage and P_{loss} is the power dissipated. To balance size and efficiency, materials are positioned with a small gap from the cavity wall, which reduces unnecessary field concentration in the lossy regions, and a combination of dielectric and ferrite materials can balance the losses. This enables compact design while maintaining sufficient shunt impedance. Thick dielectrics introduce higher-order modes and unwanted fields in the ferrite–wall gap. Practically, dielectric thickness must be moderate, since commercial piezoelectric dielectrics come as thin sheets. The ferrite thickness can be increased more flexibly. Based on these factors, a dielectric thickness of 10 mm was adopted.

SIMULATION SETUP

Copper Cavity

As a starting point, a re-entrant cavity was simulated in CST Studio Suite [13] using Oxygen-Free High Conductivity (OFHC) copper. Since the TM_{010} mode near 1 MHz would be impractically large, the TM_{020} mode at 2.29 MHz was considered, for which a 3 mm gap and 2 m nose gave a cavity of 4 m diameter and 2.4 m length. The longitudinal E field concentrates in the gap, while the H field is strongest around the nose walls. The E field distribution is shown in Fig. 2. Although the field is as expected, the resulting size is still too large for practical use.

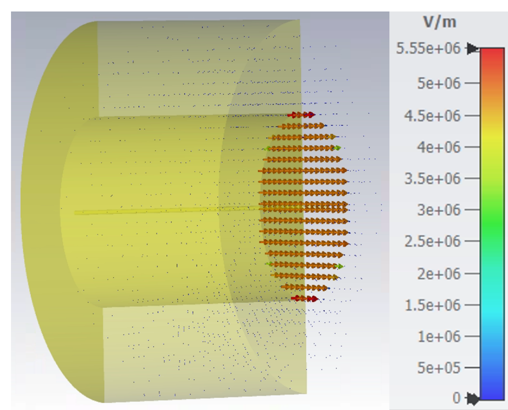

Figure 2: Electric field distribution of the copper re-entrant cavity (3 mm gap, TM_{020} mode).

Material Loaded Cavity

To reduce the physical size, a high-permittivity dielectric was added in the capacitive region and a ferrite in the inductive region as illustrated in Fig. 3.

Gaps were introduced between the inserts and cavity walls to limit dielectric and magnetic losses. The ferrite (Ni-Zn, μ_r = 1200) [14] and dielectric (Thorlabs THP44, ϵ_r= 1380) [15] properties are summarized in Table 1. This loading reduced cavity size from 4 m to 50 cm while maintaining acceptable RF performance. Table 2 lists the final cavity

Table 1: Material Properties used in Simulations

Material	ρ (kg/m^3)	ϵ_r	μ_r	tan δ
Ferrite	5000	-	1200	0.208
THP44	7750	1380	-	0.005

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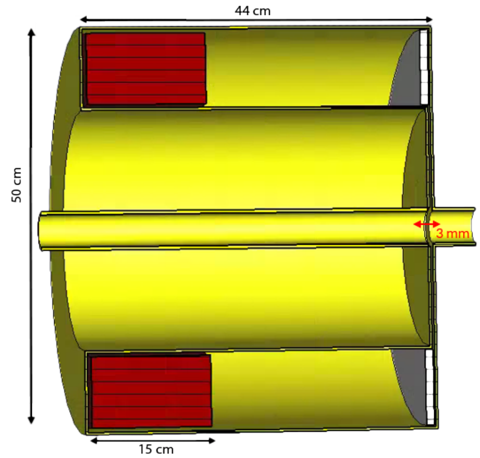

Figure 3: Re-entrant cavity with dielectric in the electric-field region and ferrite in the magnetic-field region. Gaps reduce material losses.

Table 2: Final Geometry Parameters of the Optimized Cavity

Parameter	**Values (mm)**
Cavity diameter	500
Cavity length	440
Nose diameter	303
Accelerating gap	3
Ferrite thickness	150
Ferrite gap to wall	5
Dielectric thickness	10
Dielectric gap to wall	2
Beam pipe inner diameter	40
Beam pipe outer diameter	48.3
Cavity wall thickness	3

geometry.

The optimized cavity resonates at 2.29 MHz with an unloaded Q factor of 409 and a shunt impedance of 94 kΩ. Figure 4 and Fig. 5 show a comparison of the electric (E) and magnetic (H) field profiles of OFHC copper cavity and material loaded cavity.

CONCLUSIONS AND PROSPECTS

This study presents a feasibility analysis of a compact re-entrant cavity as a non-invasive BCM for low-frequency, non-relativistic antimatter beams. We analyzed how geometry and dielectric-ferrite placement can compact the cavity. The study confirms that this configuration can balance compactness with impedance. This approach is a promising alternative to invasive diagnostics, especially where charge preservation is important. For the given shunt impedance, a single bunch is expected to deposit power on the order of femtowatts into the cavity. Signal could be improved by increasing shunt impedance via material and design optimization. However, ferrite losses may cause heating, an effect not yet included in the present simulations. Dielectric and ferrite supports should use conductive fixtures, like copper, to minimize field disturbance.

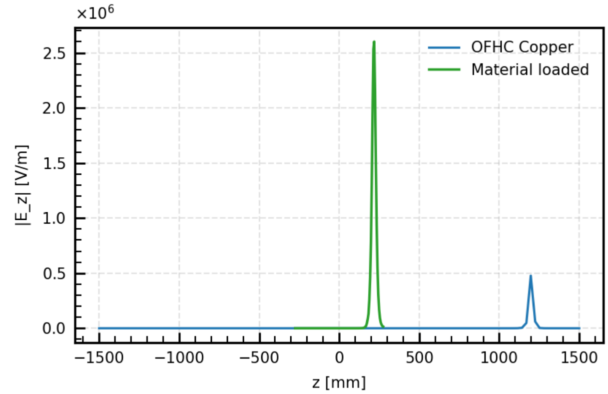

Figure 4: Electric field strength across the beam pipe for a 4 m copper cavity and a 50 cm material-loaded cavity, showing peaks in the 3 mm gap.

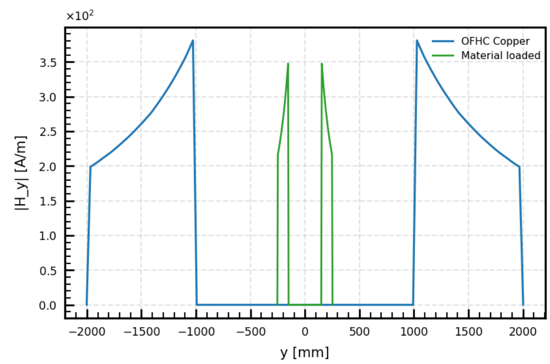

Figure 5: Magnetic field strength (H_y) for a 4 m copper cavity and a 50 cm material-loaded cavity, showing peaks around the nose cylinder.

Noise analysis shows the femtowatts signal is below system noise, requiring advanced extraction such as cryogenic amplification or double extraction. The latter is promising but requires further study. Although the cavity size of 50 cm is still relatively large, these results indicate that ferrite and dielectric loading can bring the resonance frequency into the required range while maintaining a reasonable shunt impedance. This provides a first step toward a practical compact BCM design. Further development would need to address material losses, thermal management, cost, and optimization of coupling and extraction. Upcoming simulations will focus on refining the cavity geometry, studying frequency tuning, evaluating cooling strategies, and improving sensitivity. A prototype could be considered once these steps have been addressed. With further development, such a device could serve AEḡIS and other exotic-atom or precision-physics facilities.

ACKNOWLEDGEMENTS

This project is funded by the Science and Technology Facilities Council (STFC) under the Doctoral Training Grant ST/Y509838/1, EPSRC under grant agreement-

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EP/XO14851/1 and the STFC Cockcroft Institute core grant No. ST/V001612/1.

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