BEAM PHOTOGRAPHY: A TECHNIQUE FOR IMAGING DARK CURRENTS

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Abstract

Dark currents are unwanted electron currents that stem from surface electrons emitted in rf cavities and accelerated in their electric field. This paper describes a novel technique to produce a 2D-image of dark currents and presents some results.

Ordinary black and white photographic paper was exposed to dark current electrons coming out of an 805 MHz cavity in the Lab G facility at Fermilab. This is a copper pillbox cavity in a 2.5 T solenoidal field parallel to the electric field. Thin rf and vacuum windows allow the electrons to exit the cavity. Due to the focusing effect of the magnetic field, a sharp picture of the dark currents sources is obtained. Single emitters, surrounded by regions of virtually no dark current, can be clearly identified.

INTRODUCTION

Dark currents are formed by electrons which are released from a cavity surface through field emission and which are subsequently accelerated in the cavity's electric field.

Dark currents have been studied in the context of the international Muon Ionization Cooling Experiment (MICE)[1], which is an accelerator R&D experiment for ionization cooling at a future neutrino factory[2]. Ionization cooling is a two step process in which muons are first sent through an absorber (mostly liquid hydrogen) in order to reduce both the transverse and the longitudinal momentum. In the second step, the particles are re-accelerated in an electric field parallel to the beam axis and the longitudinal momentum is restored. The net effect is a reduction of the beam divergence and – as the focusing is kept constant – a reduction of the normalized emittance.

MICE has three main components: an incoming spectrometer, the cooling apparatus with absorbers and cavities, and an outgoing spectrometer. The emittance before and after cooling is measured on a particle-by-particle basis in the spectrometers. The layout of MICE in Fig. 1 shows how close the sprectrometers are to the cavities. In fact, they are only separated by the 35 cm of liquid hydrogen absorber. This makes the measurement vulnerable to dark currents and to x-rays produced by dark current electrons and explains the interest of MICE in controlling dark current emissions.

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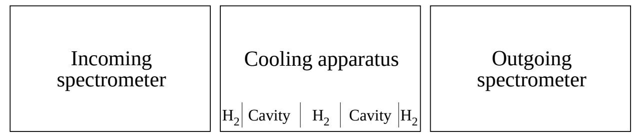

Figure 1: Layout of the MICE experiment. A differential measurement is performed between the two spectrometers. In the middle, there is the cooling apparatus with two cavities and three liquid hydrogen absorbers. The whole experiment is embedded in a fine-tuned set of solenoid magnets.

Frequency	805 MHz
Accelerating gradient	13 MV/m
Total accelerating voltage	1.04 MV
Magnetic field	2.5 T

Table 1: Operating parameters of the cavity and magnet.

EXPERIMENT SETUP

The MUCOOL collaboration operates an 805 MHz test cavity at the Fermilab Lab G[3]. This cavity has been specially designed to study dark currents and x-rays emitted from rf cavities. It features a pair of very thin windows, allowing the dark current electrons to exit the cavity. These windows can be changed. All measurements presented here have been performed with a 200 μm Cu rf window and a 200 μm Ti vacuum window.

The cavity is immersed in a superconducting solenoidal magnet with fields up to 5 T. All measurements except the one reported at the end were performed at a magnetic field of 2.5 T. The cavity operting parameters can be found in Tab. 1. To make the comparison easier, all measurements were performed at 13 MV/m field gradient.

METHODOLOGY AND MATERIAL

Ordinary photographic paper for black-and-white enlargements was used to detect the electrons. The paper was wrapped in contractor-grade black plastic foil to prevent exposure to ambient light. It was placed perpendicular to the beam axis at different distances to the cavity window, exposed for 30 s to 9 hrs and subsequently developed. The exposure time was adapted to the observed flux.

The advantages of photographic paper are its moderate speed (slower than polaroid paper, yet results are obtained in minutes), the low cost, its high grain and the large sizes available. The details of the material are outlined in Tab. 2.

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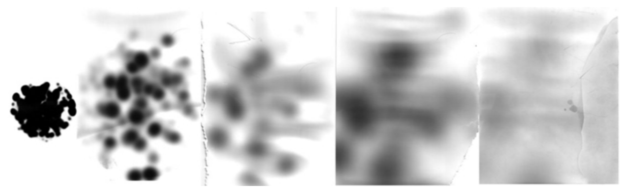

Figure 2: Distance series of photographic paper, taken at various distances of from the cavity window. The exposure time was 1 min for the first three pictures and 3 min for the latter two. All pictures are on the same scale.

Photographic paper	ILFORD® Multigrade IV, FB Fiber, MGF.5K [4] sizes 8x10 in and 11x14 in (20x25 cm and 27.5x35 cm)
Developer	Ilford Multigrade Paper developer, 1+9 diluted, 2 min
Fixer	Ilford Rapid fixer, 1+9 diluted, 2min

Table 2: Specifications of the photographic material used

After the development, the photographic paper was scanned using a Canon 20LIDE scanner with 300 dpi and 16 bits. To calibrate the scans, a sample white and black point was scanned with each picture. The levels of grey expressed at points of interest in percentage points were then extracted using a picture editing program. It was assumed that the level of grey is roughly proportional to the dose for levels of grey of up to 75%.

DISTANCE MEASUREMENT SERIES

A series of pictures were taken on the solenoid axis at varying distances from the cavity windows. The results are shown in Fig. 2. The first picture was taken at a distance of 1 cm from the cavity window, well inside the solenoid. The second picture was taken at the solenoid's end. The other three pictures were taken in the fringe field of the solenoid at distances of 20 cm apart.

The pictures show that the black spots seen on the first plane dilute and grow as the fringe field of the solenoid opens up. This picture makes it clear that the pattern of dark spots is really induced by electrons and not by x-rays, which are also emitted from the cavity.

The last two pictures illustrate very well how the electrons follow the magnetic field lines of the fringe field and how they get diluted in this process. This is important for the MICE experiment, because there is a flip in the field direction between cavity and spectrometers for most configurations. As seen in Fig. 2, the dark current electrons follow the field lines and virtually none will reach the spectrometer.

EXPOSURE TIME SERIES

At a fixed position at the end of the solenoid (this compares to the second position in Fig. 2) a time series of exposures was taken. The exposure times were: 30 s, 45 s, 1 min, 2 min and 5 min. The results, shown in Fig. 3, indicate a background rate that varies highly with the location. One can imagine dark current ”beamlets” that stem each from a single emitter.

Combining different exposure times makes it possible to extend the dynamic range of the photographic paper. If one looks at the 30 s picture, there is a spot that is completely black (marked with a dotted circle), while another area (marked with a dotted triangle) is still completely white. After 10 times the exposure time (300s), the region marked with a triangle is 10% grey. If one spot is only 10% grey after 10 times the exposure time, one can conclude that different beamlets vary at least $10 \cdot 10 = 100$ times in intensity.

PHOTOGRAPHIC RANGE TELESCOPE

A photographic range telescope was built with six layers of photographic paper separated by layers of 1.6 mm aluminum each. To be able to see high-energy particles with low rates and attenuated x-rays, the exposure time was extended to 9 hrs. It was thus expected that the first sheet of paper, which is not protected by the aluminum, would be completely black.

The image series is shown in Fig. 4. The light grey ring is due to a mounting device, that cast a shadow on the calorimeter. The active area of sheet no. 0 is completely black, as expected. The most energetic electrons penetrate the first layer of Al and can be identified on sheet no. 1. No electrons are seen after the second layer of Al on sheets no. 2 and beyond; only a uniform x-ray background can be identified.

This result is perfectly compatible with a MARS[5] simulation, that shows that for 1.2 MeV electrons, 20% survive one Al layer, and less than 10^{-4} survive two layers.

The x-ray background shows the expected attenuation pattern, with slightly lower intensities after each layer of Al.

MEASUREMENTS WITHOUT MAGNETIC FIELD

For comparison purposes, one exposure was carried out with no magnetic field. The photographic paper was located at the end of the solenoid. The exposure time was extended to 30 min.

No structure whatsoever could be detected. The photographic paper showed a uniform level of grey of 60%. This translates into an exposure time of 50 min for full black, a factor of 100 more than the darkest spots *with* magnetic field at the same location.

Figure 3: Time series of photographic paper, located at the end of the solenoid, exposed 30 s, 45 s, 1 min, 2 min and 5 min. The individual pictures have been taken during the course of a day. The image is remarkably stable in this time frame.

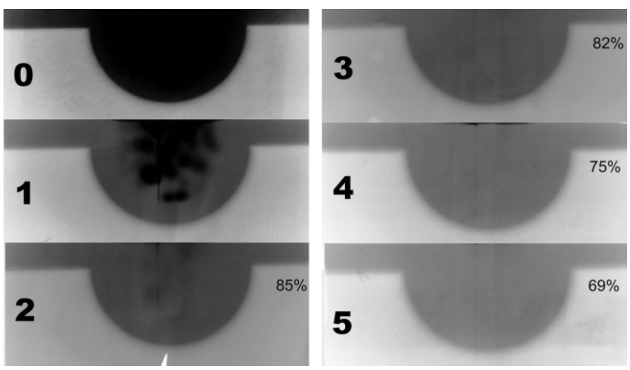

Figure 4: Image series of the photographic range telescope. The first image was directly exposed, then there was a shielding of 1.6 mm Al between each plate. The exposure time was 9 hrs.

CONCLUSIONS

For the **beam photography method** , one can conclude:

- Beam photography is capable of producing accurate 2D-images of dark currents.
- This method works only, if thin windows allow the dark current electrons to exit the cavity and if a magnetic field parallel to the beam axis guides the dark current filaments.
- X-rays are normally not detected, as they produce a signal that is a factor of 500 weaker than the electrons' signal.

Following facts about **dark currents** produced by the Lab G cavity have been revealed:

- About 50 different individual emitters have been identified.
- The pattern of these emitters does not change on the timescale of several days, even after breakdowns.
- The intensity of individual dark current filaments varies by a factor of more than 100,

leading to these conclusions for the **MICE experiment**:

- A field flip at the location of the absorber solves the problem of low-energy electrons, as these follow the field lines and are lost.
- Without field flip, the dark current filaments follow the field lines and reach the spectrometer. There, the local background rate varies by a factor of more than 100. When analyzing background effects in the spectrometers, it is not enough to consider the average background rate.

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