USE OF CR-39 PLASTIC DOSIMETERS FOR BEAM ION HALO MEASUREMENTS

I. Eliyahu, A. Cohen, E. Daniely, B. Kaizer, A. Kreisel, A. Perry, A. Shor and L. Weissman†,
Soreq Nuclear Research Center, Yavne 81800, Israel,
O. Girshevitz, BINA, Bar-Ilan University, Ramat-Gan 52900, Israel

Abstract

The first testing of CR-39 solid-state nuclear track dosimeters for beam halo measurement were performed at the SARAF phase I accelerator with ~ 2 MeV proton beams. Beam pulses of 90 nA peak intensity of the shortest possible duration (15 ns) available at SARAF were used for direct irradiation of standard CR-39 personal dosimetry tags. The lowest intensity and duration were used to minimize the beam core saturation on CR-39 tags. Other irradiations were done with beam pulses of 200 ns and 1 mA peak intensity. Specially prepared large area CR-39 plates with central hole for the beam core transport were used in the latter tests.

Weak beam structures were clearly observed in both types of irradiation. The tests showed feasibility of low energy beam halo measurements down to resolution level of a single proton. Different CR-39 etching conditions were studied. The advantages and drawback of the method are discussed.

INTRODUCTION

Beam halo phenomenon and growth of beam emittance are important issues for high-intensity linear accelerators as it directly translated to beam loss and accelerator activation. Special research programs were dedicated to the study of the beam halo formation [1] and appreciable progress was achieved [2]. Nevertheless, beam halo remains difficult to predict, measure and control. Even the definition of halo is a subject of some controversy [3,4]. From theoretical aspect the beam-dynamic predictions of weak beam tails are not always reliable due to complexity of the non-linear and time dependent effects leading to halo formation. From experimental point side the main difficulty is measurement of spatial distribution of weak beam tails at the presence of the many order of magnitude more intense beam core. Development of a simple and reliable tools and methods for beam halo diagnostics is highly desirable.

The first phase of the Soreq Applied Research Facility (SARAF) is operational since 2010 while the second phase is under design and planned to be commissioned starting at 2020. At phase I SARAF linac delivers CW and pulsed proton and deuteron beams at intensity up to 2 mA and at energy up to 4 MeV and 5.5 MeV for protons and deuterons respectively. At full specification SARAF will deliver 5 mA CW proton and deuteron beams at 40 MeV. The facility should satisfy hands-on maintenance requirement which in the case of intense beam require very low beam loss along the accelerator and the beam lines. In this respect understanding and control of the beam halo is a subject of great importance. The exact origin of the beam halo is not known but at least a significant contribution comes from the linac injector [5]. Hence, study of beam halo at the medium energy section is essential for halo tracking over the entire accelerator.

Importance of halo measurements was realized at the early stage of the SARAF project when significant efforts were spent in preparation for the beam halo measurements program [6]. Later on, however, this program was not vigorously pursued due to numerous challenges of the phase I accelerator commissioning and large number of physics experiments requested by the users. At the present, the SARAF team plans on launching only a limited halo research program, with limited beam time.

CR-39, allyl diglycol carbonate, is a plastic polymer commonly used for eyeglass lenses production. This material is also used since the 1970-s for nuclear track detection of cosmic rays, charge particles and fast neutrons [7]. The Soreq dosimetry department uses CR-39 radiation tags for personal radiation monitoring over the course of a few decades. For this halo investigation, we took advantage of significant experience accumulated at our research center with CR-39 and tested possibility of using of these detectors as simple means of beam halo diagnostics.

TESTS OF CR-39

Several issues should be taken in account when considering using CR-39 material for diagnostics of intense beams. Track detectors have very high sensitivity and thereby capability to detect each individual particle of the beam. On the other hand, the track detectors have a very low level of saturation. Thus, the beam fluence has to be reduced by many orders of magnitudes without changing the peak intensity to ensure successful use of the detectors. A fast beam chopping is an optimal technique for drastically reducing beam current while maintaining the beam profile of the intense beam. In the case of mA beam intensity even a single beam bunch may result in CR-39 saturation in the beam core. The possible way to overcome this problem is to use CR-detectors with a central hole for the beam core transport. Thus, only image of the beam periphery will be taken.

Additional question which should be considered is the conditions of CR-39 development after exposure. The

† weissman@soreq.gov.il

ISBN 978-3-95450-177-9

tracks produced by particles are revealed using chemical etching in potassium hydroxide (KOH) solution at constant temperature and different etching time. The number of the tracks and diameter of the tracks depends on these conditions [8]. The developing conditions have to be optimized on in order to obtain the image with best sensitivity to the region of interest.

As a first step we performed direct irradiation of standard personal CR-39 detectors. This irradiation coincided with the first test of a new fast chopper. The concept of the chopper includes fast sweep of the beam over a collimator in the low-energy sections [9] before entrance into the RFQ. In these tests the shortest pulses of 15 ns (~ 3 bunches) were obtained, more recent work with the fast chopper achieved single bunch per pulse of 0.3 ns, which will be helpful in future measurements.

Typical intensity of SARAF phase I beam, 1-1.5 mA, is very intense for direct irradiation even with such short pulses. The beam intensity was reduced by more than four orders of magnitudes using an aperture and strong beam defocus using the solenoid magnets in the low-energy beam transport (LEBT) line. A 2.5 MeV 70 nA CW beam was measured by a Faraday cup behind the irradiation point. A quartz viewer was used for the tuning beam in the irradiation plane

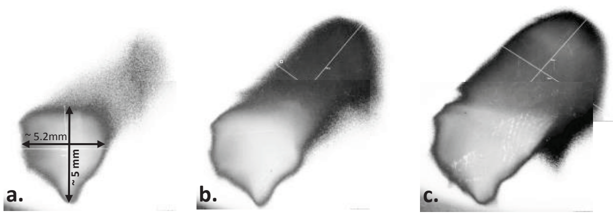

Figure 1: Images of on CR-39 tags taken with 1 (a), 1000 (b) and 100000 (c) fast chopper pulses

After beam tuning a CR-39 personal tag (30×42 mm^2) was introduced at the irradiation position and was irradiated by a few pulses produced by the fast chopper. To obtained broader range of CR-39 response we performed a series of irradiations of a few tags with 1, 10, 100, 1000, 10000 and 100000 fast chopper pulses. At each irradiation only one CR-39 was in the irradiation chamber to avoid background signal from beam scattering.

After irradiation the CR-39s were developed in KOH solution (400 gr KOH per a litter) at temperature of 80 ^oC for five hours. The developed CR-39s were examined by a microscope. Images of the tags irradiated by 10, 100 and 100000 fast chopper pulses are shown in Fig. 1. The zoom of the microscope did not allow for utilizing the whole area of interest, so each image is "stitched" from two pictures. Each image exhibits an intense core and weak tail. Even for a single pulse, the beam core is saturated. This contradicts our estimation of the fluence expected from a signal fast chopper pulse (~10^4 protons). It is possible that that the problem was in performance of the fast chopper for non-conventional LEBT beam optics used in this test. With increase of the fluence the saturation region expands but the main features of the image are consistent. Individual pits are clearly observed in the weak tail region (Fig. 2). Typical pit diameter is 6-7 µm. The individual pits can be readily counted using MATLAB software.

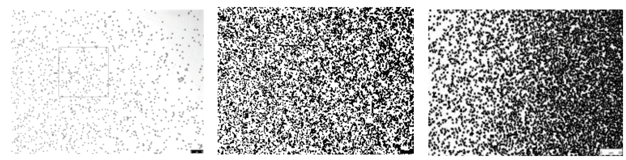

Fig. 2. Examples of magnified tail regions.

Furthermore digitization of images allows one to perform analysis of the pits distributions. An example of digitize image is shown in Fig. 3. The density of pits distribution was converted to a grey-scale intensity distribution using the ROOT software package [10]. Two dimensional distributions can be analysed and one dimensional projection can be taken using the ROOT package (Fig. 3). The grayscale intensity can be calibrated by direct integration of the pits density in the original image.

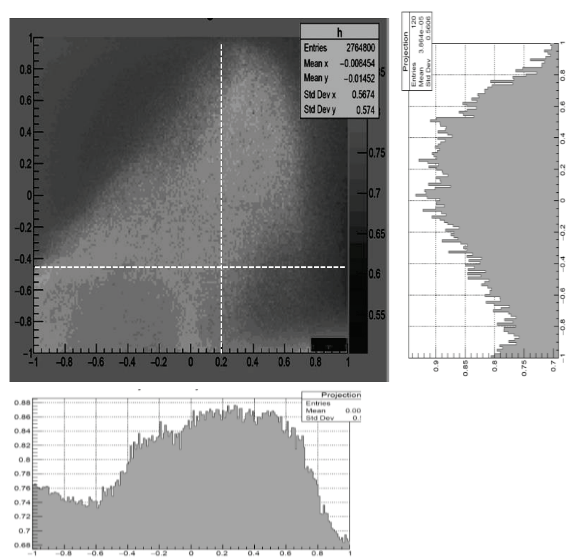

Fig. 3. Digitized image of an irradiated CR-39 with horizontal and vertical projections of the grey scale intensity.

Special efforts were taken to establish the optimum etching time. Several CR-39 tags were irradiated by 80 nA 2.5MeV protons using a single fast chopper pulse. Each of the irradiated detectors was developed at the same conditions (concentration of KOH solution and temperature) for periods of 1, 2 and 3 hours. After each developing period the tags were examined using the microscope and images were taken. Images of an irradiated CR-39 detector taken after 1, 2 and 3 hours development are shown in Fig. 4. It is evident from the figure that developing time of an hour results only in weak appearance of the core and no sign of the tail. Individual pits in the

ISBN 978-3-95450-177-9

weak tail start to appear after two hours of development and three hours corresponds to good image of the tail. Five hours etching time seemed to result in overdeveloping of pits (not shown here). The shape of the core is different comparing to Fig. 1. This is due to the different settings of the quadruple lenses upstream from the irradiation station. The orientation of the tail in the two irradiations is not affected by different quads settings. It appears that 2 hours is the minimum time required for developing CR-39 at these conditions.

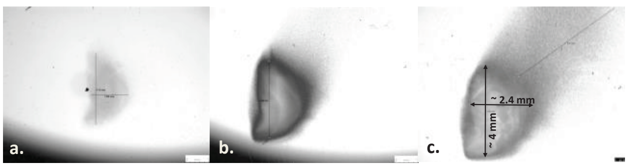

Fig. 4. Images of a single pulse with the fast chopper taken after developing the CR-39 during 1 hour (a), 2 hours (b), 3 hours (c). The area of integration is indicated.

It is clear that CR-39 detectors are not suitable for direct irradiation at high intensity linacs even for the shortest available beam pulses and greatly reduced beam intensity. The beam core has to be measured with other diagnostic tools. In the next series of test we have prepared a number of CR-39 detectors with a large hole in the middle in the area of the beam core. Large sheet of approximately 1 mm thick of allyl diglycol carbonate polymer were acquired [11]. A few of 40×40 mm^2 plates with a central hole of 14 mm diameter were cut from the sheet using a laser CNC cutter.

Protons beams of 2.2 MeV were used in this irradiation. In this test the nominal LEBT optics was used and the typical beam intensity of 1 mA was obtained at the exit of the accelerator. After tuning of the beam a CR-39 target was mounted and irradiated. In this experiment we used the SARAF slow chopper installed in the low-energy section [9]. A single 200 ns pulse, the shortest duration provided by the slow chopper, was applied on the CR-39 target.

An example of images, obtained by 2 hours developing, is shown in Fig. 5 A weak beam structure on periphery of the hole is clearly observed. The details of the observed weak tails are shown in the inserts.

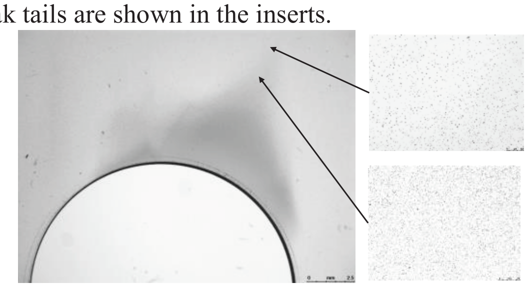

Fig. 5. Example of image taken with collimated CR-39 plate. An 1 mA 200 ns pulse has passed through the hole.

CONCLUSION AND FUTURE PLANS

First tests with irradiation of CR-39 detectors demonstrated feasibility of their use for high-quality quantitative measurements of the weakest beam tails structures. These measurements have to be combined with measurements of the beam core which have to be performed with conventional diagnostics tools. The advantages of CR-39 for beam halo measurements are low cost, simplicity and quantity of information obtained in a single exposure. The disadvantages are rather cumbersome off-line processing and low saturation threshold which lead to failure in a case of fluence miscalculation. Some additional efforts are needed for finding the optimum etching conditions for each specific beam species and energy.

As the next step we are planning detailed measurement of the beam distribution at the exit of the SARAF RFQ, which will be modernized in 2017. The core of distribution will be measured with a set of standard x-, y-profilers while the beam periphery will be studied with a set of CR-39 plates with holes of different diameters. This study will be essential for choosing the working range of the medium energy transport (MEBT) line beam scrappers and for overall commissioning of the SARAF phase II linac.

We would like to acknowledge Dr. D. Berkovits and Dr. I. Eisen for their comments to this report.

REFERENCES

[1] T.P. Wangler *et al*., *Nucl. Instr. And Meth*. A 519, 425. (2004).
[2] Theory and Design of Charged Particle Beam, M. Reiser, *Wiley-VCH* 2008, chapter 7 and references therein.
[3] P.A.P. Nghiem *et al*, HB2012, Benjin China (2012).
[4] A.S. Fisher, *IBIC15*, THBLA01, Melbourne, Australia (2015)
[5] A. Alexandrov and A. Shishlo, HB2016, THMY5Y01, Malmo, Sweden (2016).
[6] I. Mardor *et al*., *LINAC06*, TUP010, Knoxville, USA (2006)
[7] R.M. Cassou and E.V. Beton, Nucl. Track Detection, Vol. 2, p. 173-179, Pergamon Press 1978.
[8] M.J. Rosenberg *et al*., *Rev. Sci. Instr.* 85, 043302 (2014).
[9] A. Shor *et al*., JINST 7 C06003 (2012).
[10] http://www.root.cern.ch
[11] http:// www.homalite.com

ISBN 978-3-95450-177-9