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In-situ measurements of the secondary electron yield in an accelerator environment: Instrumentation and methods

W.H. Hartung*, D.M. Asner[1], J.V. Conway, C.A. Dennett[2], S. Greenwald, J.-S. Kim[3], Y. Li, T.P. Moore, V. Omanovic, M.A. Palmer[4], C.R. Strohman

Cornell Laboratory for Accelerator-Based Sciences and Education, Cornell University, Ithaca, NY, USA

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ABSTRACT

The performance of a particle accelerator can be limited by the build-up of an electron cloud (EC) in the vacuum chamber. Secondary electron emission from the chamber walls can contribute to EC growth. An apparatus for in-situ measurements of the secondary electron yield (SEY) in the Cornell Electron Storage Ring (CESR) was developed in connection with EC studies for the CESR Test Accelerator program. The CESR in-situ system, in operation since 2010, allows for SEY measurements as a function of incident electron energy and angle on samples that are exposed to the accelerator environment, typically 5.3 GeV counter-rotating beams of electrons and positrons. The system was designed for periodic measurements to observe beam conditioning of the SEY with discrimination between exposure to direct photons from synchrotron radiation versus scattered photons and cloud electrons. The samples can be exchanged without venting the CESR vacuum chamber. Measurements have been done on metal surfaces and EC-mitigation coatings. The in-situ SEY apparatus and improvements to the measurement tools and techniques are described.

1. Introduction

Ideally, the beams in a particle accelerator propagate through a perfectly evacuated chamber. In reality, the vacuum chamber contains residual gas, ions, and low-energy electrons. Low-energy electrons can be produced by photo-emission when synchrotron radiation photons strike the wall of the chamber; by bombardment of the wall by the beam halo; or by ionization of residual gas by the beam. If the electrons hit the wall and produce secondary electrons with a probability greater than unity, the electron population grows, producing a so-called "electron cloud" (EC). In extreme cases, a large density of electrons can build up, causing disruption of the beam, heating of the chamber walls, and degradation of the vacuum.

Electron cloud effects were first observed in the 1960s [1]. A number of adverse effects from EC have been observed in recent years [2–11]. Several accelerators were modified to reduce the cloud density [5,7,11]. EC concerns led to EC mitigation features in the design of recent accelerators [10,12] and proposed future accelerators [13–15]. Additional information on EC issues can be found in review papers such as [1,12,16].

The Cornell Electron Storage Ring (CESR) provides X-ray beams for users of the Cornell High Energy Synchrotron Source (CHESS) and serves as a test bed for future accelerators through the CESR Test Accelerator program (CESRTA) [17–19]. A major goal of the CESRTA program is to better understand EC effects and their mitigation. The EC density is measured with multiple techniques [20–22]. The effectiveness of several types of coatings for EC mitigation has been measured on coated and instrumented chambers [20].

For a beam emitting synchrotron radiation (SR), three surface phenomena are important to the build-up of the electron cloud: photo-emission of electrons; secondary emission of electrons; and scattering of photons. Since it is possible for a surface to release more electrons than are incident, secondary emission can be the dominant EC growth mechanism.

Surface properties are known to change with time in an accelerator vacuum chamber: this is referred to as "conditioning" or "beam scrubbing." Beam scrubbing is thought to be due to the removal of surface contaminants by bombardment from SR photons, scattered photons, cloud electrons, ions, beam halo, or some combination thereof.

During the CESRTA program, a system was developed for in-situ measurements of the secondary electron yield (SEY) as a function of the energy and angle of the incident primary electrons. The goals of the in-situ SEY studies included (i) measuring the SEY of

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* Corresponding author.
E-mail address: wh29@cornell.edu (W.H. Hartung).

[1] Pacific Northwest National Laboratory, Richland, WA, USA.

[2] Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA.

[3] Department of Electrical Engineering, Princeton University, Princeton, NJ, USA.

[4] Fermi National Accelerator Laboratory, Batavia, IL, USA.

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surfaces that are commonly used for beam chambers; (ii) measuring the effect of beam conditioning; and (iii) comparing different mitigation coatings. Samples were made from the same materials as one would find in an accelerator vacuum chamber, with similar surface preparation (sometimes called “technical surfaces” in the literature).

The effect of exposure to an accelerator environment on the SEY has been studied by several groups [23–31]. Systematic errors in SEY measurements and countermeasures have been studied at SLAC [32,33]. In some of these studies, the samples were installed into the beam pipe for an extended period and then moved to a laboratory apparatus for SEY measurements. At Argonne, the removal of the samples required a brief exposure to air [23]. At PEP-II, samples were moved under vacuum using a load-lock system [31]. Studies at CERN and KEK, on the other hand, used in-situ systems, so that samples did not have to be removed for the SEY measurements [25–28]. The in-situ systems allow for more frequent measurements with fewer concerns about recontamination before the measurements, but require a more elaborate system in the accelerator tunnel.

The SEY apparatus developed for CesrTA was based on the system used in PEP-II at SLAC [31]. In lieu of the PEP-II load-lock system, a more advanced vacuum system was designed, incorporating electron guns for in-situ SEY measurements. The measurements at CesrTA are similar to the in-situ measurements at CERN and KEK, but with several differences: (i) we have studied a wider variety of materials than measured at CERN; (ii) we have done more frequent measurements than done at KEK to get a more complete picture of SEY conditioning as a function of time and beam dose; and (iii) we have measured the dependence of SEY on position and angle of incidence. Systems similar to the CesrTA stations were recently sent to Fermilab for EC studies in the Main Injector [34].

The CesrTA in-situ samples are typically measured weekly during a 6-h tunnel access. The SEY chamber design allows for samples to be exchanged rapidly; this can be done during the weekly access if needed. There are 2 samples at different angles, one in the horizontal plane, the other 45° below the horizontal plane, as was the case at PEP-II. This allows us to compare conditioning by direct SR photons in the middle of the horizontal sample versus bombardment by scattered photons and EC electrons elsewhere. Because the accelerator has down periods twice a year, we are able to keep some samples under vacuum after conditioning to observe the changes in SEY over several weeks, without exposure to air.

Models have been developed to describe the SEY as a function of incident energy and angle (e.g. [35]). In the models, the secondary electrons are generally classified into 3 categories: “true secondaries,” which emerge with small kinetic energies; “rediffused secondaries,” with intermediate energies; and “elastic secondaries,” which emerge with the same energy as the incident primary. The models are used to predict the EC density and its effect on the beam. Our in-situ SEY measurement program is ultimately oriented toward finding more realistic SEY model parameters, for more accurate predictions of EC effects.

This paper describes the apparatus and techniques developed for the in-situ SEY measurements. For clarity, we divide the stages of the measurement program into three parts, Phase I, Phase IIa, and Phase IIb. We describe the in-situ apparatus and basic measurement method in Section 2. The Phase I measurement techniques are summarized in Section 3. In Phase II, improvements were made to the hardware and measurement techniques, as described in Section 4. The data analysis is discussed in Section 5, and examples of results are given in Section 6. Additional details on our SEY instrumentation and methods can be found in a separate report [36]. Preliminary SEY results for metals (aluminum, copper, and stainless steel) and EC mitigation films [titanium nitride, amorphous carbon (aC), diamond-like carbon (DLC)] can be found in other papers [19,37–39].

2. Apparatus and basic method

There are two SEY stations to allow exposure of two samples to the accelerator environment. The SEY measurements are done in the accelerator tunnel while the samples remain under vacuum. To keep the stations compact enough for deployment in the tunnel, we use an indirect method to measure the SEY. Our basic measurement method is the same as was used by SLAC [31,32,40] and other groups; the instrumentation is the same as was used at SLAC [40]. We measure the dependence of the SEY on the (i) incident kinetic energy K, (ii) incident angle θ, and (iii) impact position of the primary electrons (θ=angle from the surface normal). An additional station outside the tunnel is used for supplementary measurements.

2.1. Storage ring environment

In CESR, electrons and positrons travel in opposite directions through a common beam pipe. Beam scrubbing occurs mostly under CHESS conditions: a beam energy of 5.3 GeV, with beam currents of ~ 200 mA for both electrons and positrons. The SEY samples are installed into the wall of a stainless steel beam pipe with a circular cross-section of inner diameter 89 mm. The SEY samples are exposed predominantly to SR from the electron beam, the closest bending magnet being about 6 m away. The SEY beam pipe includes a retarding field analyzer for electron cloud characterization.

Cold cathode ionization gauges are used to monitor the beam pipe pressure; the closest gauge is about 1 m away. The base pressure is generally $\lesssim 1.3 \times 10^{-7}$ Pa. With CHESS beams, the pressure is typically $\lesssim 6 \times 10^{-7}$ Pa after beam conditioning.

2.2. In-Situ SEY stations

As shown in Fig. 1a, the samples have a curved surface to match the beam pipe cross-section. The samples are approximately flush with the inside beam pipe, with one sample positioned horizontally in the direct radiation stripe, and the other sample positioned at 45°, below the radiation stripe. Fig. 1b and c shows the SEY stations, including the equipment for moving the samples under vacuum and measuring the SEY.

More detailed drawings of one SEY station are shown in Fig. 2. A custom-designed vacuum “crotch” provides an off-axis port for an electron gun, a pumping port, and a side port for sample exchange. The sample is mounted on a linear positioner with a magnetically-coupled manual actuator.[5] The electron gun is at an angle of 25° from the axis of the sample positioner. The gun is mounted on a compact linear positioner[6] so it can move out of the sample positioner's path when the sample is inserted into the beam pipe (Fig. 2a).

When the sample is in the beam pipe (Fig. 2a), force is applied to the actuator to ensure that the sample is well seated. When the sample is in the SEY measuring position (Fig. 2b), the gun is moved forward to make the nominal gun-to-sample distance 32.9 mm. Moving the gun forward allows for a smaller beam spot size and a larger range of incident angles.

One or both of two gate valves are closed to isolate the CESR vacuum system from the SEY chambers during SEY measurements. The pressure inside the SEY chambers is typically $\lesssim 10^{-6}$ Pa with

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[5] Model DBLOM-26, Transfer Engineering, Fermont, CA.

[6] Model LMT-152, MDC Vacuum Products, LLC, Hayward, CA.