Development of Ion-Bombardment Surface Treatments for Suppression of Secondary Electron Emission in Accelerator Vacuum Chambers and Other Structures

Introduction

Particle accelerators have been essential tools for elementary particle physics research for many years. They are now becoming increasingly important for applied science, typically done at user facilities such as light sources and neutron sources. The performance of future high intensity positron and proton accelerators is likely to be limited by the development of electron plasma, typically referred to as an electron cloud (EC), in the accelerator vacuum chambers [1-5]. At the Cornell Electron-Positron Storage Ring (CESR), the CESR Test Accelerator (CESRTA) program has been underway for the last 3 years. The principal goals of the program are to develop and understand methods to mitigate EC production and to characterize the impact of EC on ultra-low-emittance positron beams [6]. One of the promising techniques for suppressing EC formation in regions with magnetic fields is the use of longitudinally grooved chamber surfaces, which help suppress the escape of secondary electrons from the walls into the central volume of the vacuum chamber. The use of macroscopic grooves increases the vacuum chamber impedance and can adversely impact high intensity beams, particularly if the beam motion has a significant component perpendicular to the direction of the grooves. A possible way to obtain the same "geometric" suppression of the electron cloud with less harmful effect on the beam is to use ion bombardment to produce vacuum chamber surfaces with micron or nanometer scale features. A research effort to prepare such surfaces on standard accelerator vacuum chamber materials is the topic of this proposal.

Electron clouds have been observed in a number of accelerators; EC can cause heating of cold vacuum chamber bores in designs with superconducting magnets, degradation in beam quality, and instabilities. Electron and positron rings in which EC has been observed include the Advanced Photon Source [7], the Beijing Electron-Positron Collider [8], CESR [9], the KEK B Factory [10], the PEP-II B Factory [11] and the ANKA light source [12]. Proton and ion rings in which EC has been observed include the CERN Proton Synchrotron [13] and Super Proton Synchrotron [14], the Fermilab Main Injector [15], the Relativistic Heavy Ion Collider [16], and the Spallation Neutron Source accumulator ring [17]. This has led to a significant investment of effort into the development of mitigation techniques [18,19]. Another accelerator application where secondary electron yield (SEY) mitigation is critical is for the performance of RF windows and RF couplers: in this case, electrons are accelerated by the electromagnetic field, impact the surface and produce secondary electrons; if SEY > 1, the density of the electron cloud increases exponentially ("multipacting"). Secondary emission in couplers and windows can be a problem for both normal conducting cavity systems [20] and superconducting cavity systems [21]. Thus we anticipate that the successful development of a new surface mitigation technology will have broader application than just to accelerator vacuum chambers.

Electron Cloud Mitigation: Macroscopic Techniques

Longitudinally grooved surfaces for SEY reduction have been extensively modeled for potential application in future accelerators, including the damping rings for the International Linear Collider (ILC) and the approved "Super B-factory" upgrades. For ILC-like damping ring parameters, sharp-angled triangular grooves can lower the SEY to values less than unity in regions with dipole magnetic fields [22-24]. The efficacy of these grooved surfaces has been studied experimentally at KEK [25] and CESRTA [26]. Figure 1 shows CESRTA results comparing a longitudinally grooved vacuum chamber with a bare Al chamber and a titanium nitride-coated chamber. A substantial reduction in the cloud density was observed using triangular grooves with an opening angle of approximately 20°.

Unfortunately, macroscopic grooves produce an increase in the chamber impedance presented to the beam, which may make this solution impractical for high beam intensities. Moreover, the fabrication of grooved vacuum chambers remains challenging. For typical vacuum chamber apertures, the typical groove height must be of order 2 mm or less and the radius of curvature of the groove tips and valleys should ideally be < 0.05 mm. These requirements are difficult to meet in an extruded chamber (the preferred fabrication technique for large rings). Hence, macroscopic grooves may prove to be impractical for large accelerator projects with limited budgets.

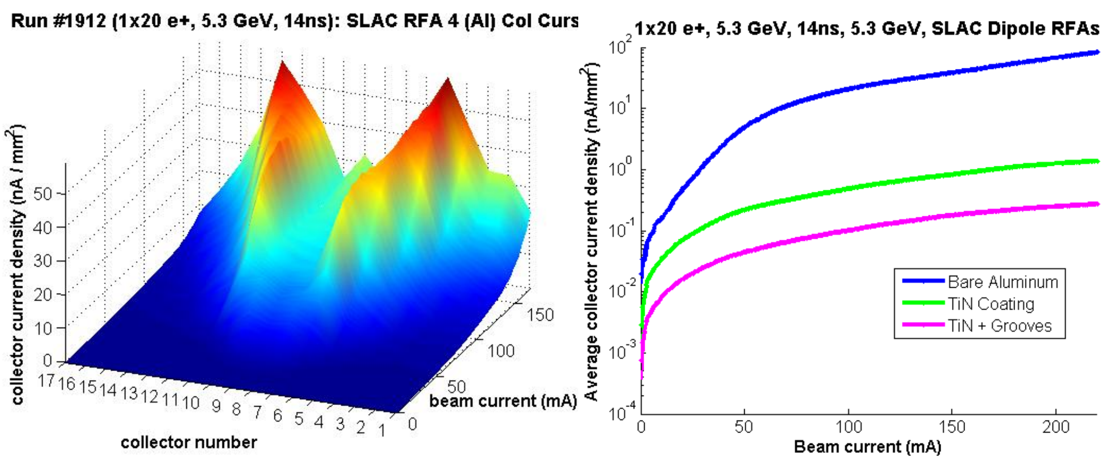

Figure 1: Left: measurement of the EC density as a function of transverse position and beam current using an RFA installed in a dipole vacuum chamber with an Al surface. Strong EC signals can be seen at high beam current. Right: measured RFA current in a dipole versus beam current with a 20 bunch positron train for a bare Al surface, a TiN-coated surface, and a grooved surface with TiN-coating. The efficacy of the grooved surface for suppressing the EC is clearly evident.

Electron Cloud Mitigation: Microstructural Techniques

An alternative technique to geometrically reduce the SEY is to make the surface features microscopic, rather than macroscopic. Measurements reported in the literature indicate that the SEY of copper surfaces can be reduced by ion treatment to produce surface roughening [27] or surface texturing [28]; two patents for such techniques have been filed [29,30]. Ion bombardment can produce textured surfaces with a dense, random array of needle-like spires perpendicular to the plane of the surface. The typical size scale of the spires is several microns. In addition, focused ion beams are now being used to produce periodic surface structures that may provide the same benefit. The use of micron or sub-micron scale surface structures has the potential to geometrically suppress the cloud with less adverse impact on the accelerator beam.

Proposed Microstructural Mitigation Research and Development Program

We propose a research program to develop surface texturing on copper and aluminum surfaces (typical materials for accelerator vacuum chambers). The research program would involve 3 major steps:

1. Development of an ion bombardment process to produce surfaces with reduced SEY, with the SEY characterization done locally in the laboratory;
2. Production of textured samples for installation in an accelerator, specifically in the CESR in-situ SEY station [31], to check the SEY under realistic accelerator conditions and evaluate the durability of the surface in this environment (including exposure to synchrotron radiation);
3. Preparation of a vacuum chamber with an ion-treated surface, equipped with a retarding field analyzer [32], for deployment in an experimental dipole chicane in CESR. This will allow us to measure the development of the EC with beams similar to those planned in future machines, and quantify the impact of the textured surface on the EC.

If the 3 phases of the research program are successfully accomplished, we would then be in a position to investigate methods for producing chambers in the quantities required for future accelerator facilities. The time scale to carry out the complete research program will span multiple years. Our timeline for the research effort is as follows:

Year 1

- o Develop techniques at EMSL to reproducibly create surfaces with microstructures that help suppress secondary electron emission
- o As suitable techniques are identified, prepare samples for in situ testing in CESR and begin the accelerator-based test program

Year 2

- o Continue to refine ion bombardment techniques for surface preparation at EMSL
- o Conduct tests on a range of samples in CESR
- o Assuming that the testing program is successful, begin fabrication of an accelerator test chamber, applying the most promising surface treatment to it

Year 3

- o Conduct tests on the prototype vacuum chamber to verify the degree to which the electron cloud is suppressed in a dipole field region
- o Evaluate the requirements for an industrialized process applicable to accelerator vacuum chambers and possibly other areas (eg, RF systems) where SEY mitigation is required

Project Objectives

This project will investigate the secondary electron yield from the patterned surfaces and correlate the yield to the chemical and structural properties of the microstructures and their interfaces. In particular, we will address the following scientific questions:

1. What are the detailed structural properties of the ion-beam-induced or patterned microstructures and their interfaces?
2. How are structural and morphological properties of the features correlated with the SEY?

Our overall aim is to optimize the microstructures for minimum SEY.

Technical Approach

I. Fabrication of Micron/Nanometer Scale Features Using Low and High Energy Ion Beams

In the first approach, we will produce grooves on Cu and Al substrates using low and high energy ion beams. Light ion and heavy ion species such as Ar+, Ni+ and Au2+ will be used for this purpose. The angle of incidence and energy of the ions beams will be varied to change the angle and morphology of the grooves. The energy of the Ar+ beams will be varied between 500 and 3000 eV, while the energy of heavy ions such as Ni+ and Au2+ will be varied between 1 and 4 MeV. Our collaborators at EMSL have already demonstrated that periodic structures can be generated and controlled on $SrTiO_3$ using 2 MeV Au ions with incidence angles of about 60°, as shown in Figure 2. These structures will be characterized using several state-of-the-art tools such as the scanning electron microscope (SEM), transmission electron microscope (TEM), helium ion microscope (HIM), and atom probe tomography (APT) to understand the microstructural evolution in these features and their interfaces. Initial characterization of the SEY will be conducted at EMSL and correlated to the microstructures. When structures with suitable SEY suppression have been achieved, samples suitable for study with the in-situ SEY measurement station in CESR will be prepared from standard Al and Cu alloys used in accelerator vacuum chamber construction. These samples will be shipped to Cornell for beam tests in CESR. The overall performance will be correlated to both the microstructures and the materials used in the accelerator tests.

II. Patterning Structures Using Focus Ion Beam

Another novel nanostructured design consists of ordered arrays of Cu and Al nanoscale pyramids and cubes, produced with a focused ion beam. One such structure is shown schematically in Figure 3. These structures will have well-oriented, polished surfaces with well-defined dimensions in comparison to the features generated by Approach I. In addition, the damage generated by the high and low energy beams will be significantly less in compassion to the beam damage on the samples generated using the first approach. Since the appropriate angle and dimension of the grooves are important for reducing the SEY, a comparison of these results with those of Approach I will help in developing a fundamental understanding of secondary emission behavior. As above, the structures will be characterized using SEM, TEM, HIM, and APT. Again, initial characterization of the SEY will be conducted at EMSL and correlated to the microstructures. Subsequently, samples for testing in CESR will be prepared from standard accelerator vacuum chamber materials and characterized with the CESR in-situ SEY system.

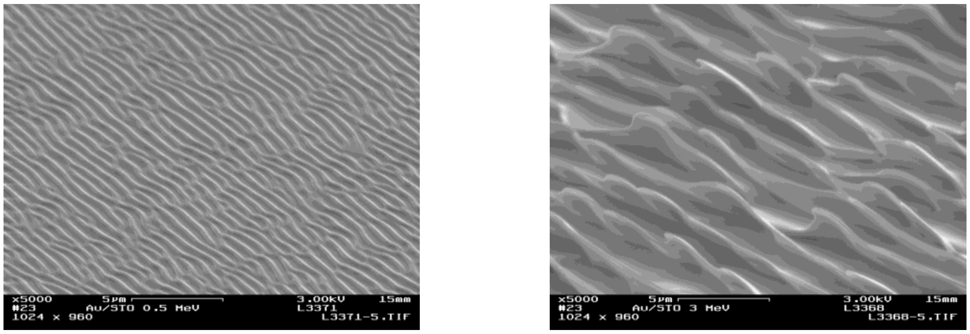

Figure 2: Periodic ripple structures formed by glancing-angle gold ion implantation. The height and wavelength of these periodic structures can be precisely controlled.

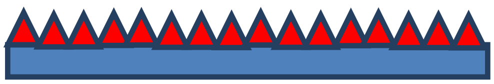

Figure 3. Side view of an ordered groove geometry on a Cu or Al substrate. The groove features can be controlled through the ion beam parameters.

Expected Results and Scientific Impact

Electron clouds are a critical issue for next generation accelerators. Next generation accelerators are important for the advancement of elementary particle physics and for the expansion of multi-user facilities where a number of researchers can advance basic and applied science in a collective and collaborative way. The goal of this project is the development of microstructures with reduced secondary electron yield that can be used to fabricate accelerator vacuum chambers with reduced generation of secondary electrons. The development of practical surfaces with low secondary electron yield could provide a significant benefit in performance for next generation accelerators.

Relation to EMSL

EMSL supports the mission of the Department of Energy, and building efficient accelerators for future user facilities is one of the primary activities of the DOE. This project will involve the science of interfacial phenomena, which is one of the science themes at EMSL. We also expect the project to be supported partly by the project in Cornell University and Chemical Imaging Initiative at PNNL. We consider this work to be highly relevant for EMSL, and we believe that it is a good match to the capabilities of EMSL; expertise at EMSL can be used to find answers to the scientific questions posed in this proposal.

EMSL Resources

Accelerator	120 hours
FIB/SEM	120 hours
TEM	80 hours
APT	120 hours
SEY	100 hours