RECENT STUDIES OF THE ELECTRON CLOUD INDUCED BEAM INSTABILITY AT THE LOS ALAMOS PSR*

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Abstract

Recent beam studies have demonstrated that a stable beam with the standard production bunch width of 290 ns and near the e-p instability threshold will become unstable when the bunch width is shortened significantly. This was not the case years earlier when the ring rf operated at the 72.000 integer subharmonic of the Linac bunch frequency. The present operating frequency is set at the 72.070 non-integer subharmonic and appears to be responsible for the recently observed "short pulse instability phenomenon". Experimental characteristics of the short pulse instability are presented along with comparisons to the instability under 72.000 subharmonic operating conditions.

INTRODUCTION

The electron cloud (EC) induced instability, also known as the two-stream e-p instability, has been observed ever since the PSR was commissioned in 1986 [1] and has been extensively studied since then. All the available evidence points to a two-stream instability from coupled motion of the proton beam and a "cloud" of low energy electrons. In our present picture of this instability, primary electrons arising mostly from beam losses are amplified by multipactor on the ~140 ns long trailing edge of the ~290 ns long beam pulse. Sufficient electrons survive the ~70 ns gap between bunch passages to be captured by the next bunch passage to drive the instability. The largest uncertainly in locating the main EC source is the distribution of primary electrons born at the chamber walls from grazing angle beam losses.

For the discussion to follow, it is helpful to understand the process for and signature of the instability threshold shown in Figure 1. During beam instability studies, we store a stable beam for typically 400 µs after the end of accumulation in order to allow the instability to develop at fixed beam intensity and in the absence of losses from H^0 excited states which field strip part way into the first dipole downstream of the injection stripper foil. The ring rf buncher voltage is lowered until a) exponentially growing coherent motion is seen on a beam position monitor (BPM) in the ring and b) a significant beam loss shows on the sum signal from 19 loss monitors and ~5% loss of beam current appears by the time the beam is extracted. Thresholds obtained by the above criteria are reproducible to ~5% of the buncher voltage. For buncher voltages ~5% above the threshold the beam is stable. At lower buncher voltages, the instability is more pronounced in that the losses are typically higher and the coherent motion and losses start earlier and may saturate.

The plot of instability threshold voltage as a function of beam intensity while all other beam parameters are held fixed is designated an **instability threshold curve**. These are typically linear in intensity (Q = charge stored/pulse) and have long been studied as a function of many beam setup parameters (e.g. emittance, bunch width, tune, multipole settings, buncher phase, etc) [2]. For instability threshold curves, the intensity is varied by beam jaws at the linac front end or by periodically chopping out a turn of injection. An example of threshold curves for 3 beam bunch lengths (PW, pattern width of one injected turn or mini-pulse) is shown in Figure 2 for data collected in 2001 when the PSR rf routinely operated at the exact 72.000 subharmonic of the linac frequency.

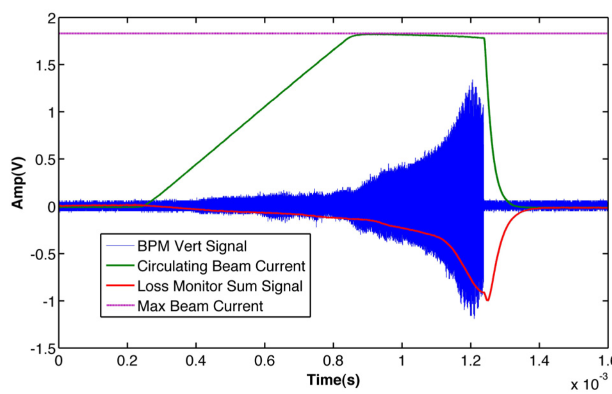

Figure 1: Experimental signature for the e-p threshold.

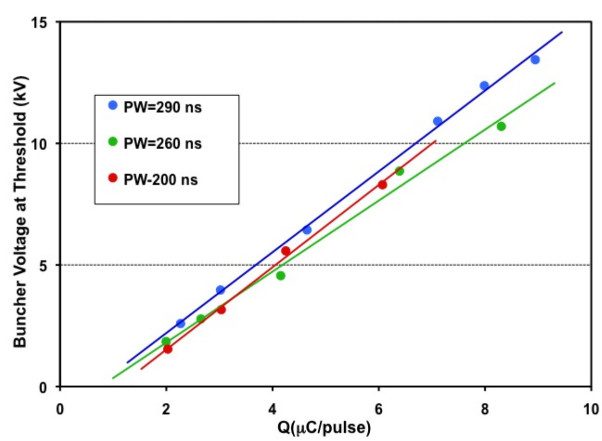

Figure 2: Instability threshold curves for various PW collected 5/26/2001 (72.000 subharmonic operation). Beam was accumulated for 1225 µs and stored for 400 µs after end of injection.

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RECENT EXPERIMENTAL RESULTS ON AMORPHOUS CARBON COATINGS FOR ELECTRON CLOUD MITIGATION

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Abstract

Amorphous carbon (a-C) thin films, produced in different coating configurations by using DC magnetron sputtering, have been investigated in laboratory for low secondary electron yield (SEY) applications. After the coatings had shown a reliable low initial SEY, the a-C thin films have been applied in the CERN Super Proton Synchrotron (SPS) and tested with Large Hadron Collider (LHC) type beams. Currently, we have used a-C thin film coated in so-called liner configuration for the electron cloud monitors. In addition the vacuum chambers of three dipole magnets have been coated and inserted into the machine.

After describing the different configurations used for the coatings, results of the tests in the machine and a summary of the analyses after extraction will be presented. Based on comparison between different coating configurations, a new series of coatings has been applied on three further dipole magnet vacuum chambers. They have been installed and will be tested in coming machine development runs.

MOTIVATION

In a proton or positron particle accelerator, an electron cloud can be generated by residual gas ionization, by photoemission when synchrotron-radiation photons hit the surface of the vacuum chamber and by subsequent secondary emission via a beam induced multipactoring process [1]. This process reduces the machine luminosity and beam quality. It leads to dynamic pressure rise, transverse emittance blow up, thermal load and beam losses. The goal of this work is to find a method to eliminate the e-cloud in the CERN Super Proton Synchrotron (SPS) in order to make the SPS able to deliver the ultimate beam to Large Hadron Collider (LHC) and reach maximum luminosity for the machine. Four important requirements are: the solution must be implementable in the existing SPS dipoles, does not require any bake out since the SPS has heating limitation, is robust against venting and also has a long life time. Simulations [2], [3] show that the threshold value for the SEY in order to avoid e-cloud in the SPS with nominal LHC beam is = 1.3.

In this work, carbon is chosen as coating material due to its few valence electrons and its non-reactivity. Carbon thin film coatings produced by DC magnetron sputtering in different coating set-ups have been tested for different applications.

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THIN FILM COATINGS

Four different coating configurations have so far been used due to the different geometries of the chambers to be coated, as listed in Table 1. Different discharge gases (Ne, Kr, Ar) and different coating parameters, such as temperature of substrate, discharge gas pressure, power applied during coatings have been tested. To maximize sputtering efficiency and reduce the risk of implantation of heavy discharge gas ions, such as Argon and Krypton, on the coating surfaces, we chose to use Neon as discharge gas after many tests.

In a perfectly cylindrical vacuum chamber, one graphite rod is used as cathode for the DC magnetron sputtering and this method was used for making most of the lab samples for SEY investigation as well as vacuum characterizations in the lab. In Fig. 1(a), the 7 meters long solenoid used to provide magnetic field parallel to the cathode in the cylindrical tube configuration is shown.

Since the shape of the vacuum chambers in the SPS is not perfectly round, we need to find other solutions to make a homogeneous coating. A configuration of a liner with rectangular cross section in a round tube with 4 graphite rods has been tested, as shown in Fig. 1(b). This configuration has been applied for both lab samples and liners for electron cloud monitors (ECM) used for electron cloud measurements in-situ the SPS, as shown in Fig. 1(c). The surface temperature can go up to 250 C during the coating.

To detect electron cloud we used the same type of monitors as in previous tests [1], [4], [5]. The schematic drawing of the device is shown in Fig. 1(c). The Electron Cloud Monitor (ECM) equipped with stainless steel (SS) liners with or without coating is then installed in a special dipole C magnet which provides a magnetic field perpendicular to the beam direction. Unless otherwise specified, during all the experiments the field was kept at 1.2 kG (the SPS injection value). On one side of the liner, small holes with a transparency of 7% are drilled to pass the electrons generated by e-cloud through the liner. Under those holes there is a multi strip detector to collect the escaped electrons, if any.

After the lab results showed a SEY lower than 1.3, the threshold value calculated by simulations [2] [3], three of the SPS dipole magnets were coated and tested with the LHC type of beams. In Fig. 1(d), an SPS MBB dipole and the vacuum equipment used for coating can be seen. Inside the dipole, the magnetic field during coating was provided by the dipole itself and was perpendicular to the cathodes. The power used during coating was also kept limited not to damage the coil. Three MBB dipoles have been coated in

Can electron multipacting explain the pressure rise in the ANKA cold bore superconducting undulator?

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Abstract

Preliminary studies performed with the cold bore superconducting undulator installed in the ANKA (ANgstrom source KArlsruhe) storage ring suggest that the beam heat load is mainly due to the electron wall bombardment. Electron bombardment can both heat the cold vacuum chamber and induce an increase in the pressure because of gas desorption. In this contribution we compare the measurements of the pressure in a cold bore performed in the electron storage ring ANKA with the predictions obtained using the equations of gas dynamic balance in a cold vacuum chamber exposed to synchrotron radiation and electron bombardment. The balance results from two competing effects: the photon and electron stimulated desorption of the gas contained in the surface layer of the chamber wall and of the gas cryosorbed, and the cryopumping by the cold surface. We show that photodesorption alone cannot explain the experimental results and that electron multipacting is needed to reproduce the observed pressure rise. Electron bombardment can at the same time explain the observed beam heat load.

INTRODUCTION

In order to produce synchrotron radiation of highest brilliance, third generation synchrotron sources make use of insertion devices (IDs). The state of the art available today for IDs is the permanent magnet technology with magnet blocks placed inside the vacuum of the storage ring. Following an initial proposal at SPRING8 [1], the concept of Cryogenic Permanent Magnet Undulators (CPMU) is presently considered as a possible future evolution of in-vacuum undulators [2, 3, 4, 5]. Superconducting undulators can reach, for the same gap and period length, higher fields even with respect to CPMU devices, allowing to increase the spectral range and the brilliance. At ANKA we are running a research and development program on superconducting insertion devices (SCIDs). One of the key issues for the development of SCIDs is the understanding of the beam heat load to the cold vacuum chamber. The beam heat load is a fundamental input parameter for the design of SCIDs since it is needed to specify the cooling power.

Studies performed on the cold bore superconducting undulator installed at ANKA indicate that a simple model of electron bombardment could explain the beam heat load and observed pressure rise during normal user operation [6]. In this paper we go a step further solving the equations of gas dynamic balance in a cold vacuum chamber exposed to synchrotron radiation and electron bombardment. We show that the observed pressure rise can be explained by the occurence of electron multipacting and not by photodesorption alone. The paper is organized as follows. For completeness, in the next two sections we summarize respectively the experimental setup and the observations described in more detail in Ref. [6]. Afterwards we present the equations of gas dynamic balance and the input parameters derived from the literature and used to solve the model, and we derive an approximate analytical solution to those equations and discuss its properties. We discuss then the main results of the comparison between observations and simulations, and finally we give some conclusions and outlook.

EXPERIMENTAL SETUP

ANKA is an electron storage ring used as a synchrotron facility [7]. A cold bore superconducting undulator built by ACCEL Instr. GmbH, Bergisch Gladbach, Germany [8], is installed in one of the four straight sections of the ring; the rest of the ring is at room temperature. The vacuum chambers of the warm part of ANKA have been baked before installation at 200°C for 48 hours and vented with nitrogen.

The storage ring compatible cryostat is shown in Fig. 1. The system is cryogen free and is cooled by three Sumitomo cryocoolers (RDK-408D @ 50 Hz) [9]: two of them cool the coils to about 4 K and one cools the UHV (Ultra High Vacuum) tank, which is at 10 K and protects the coils from the external thermal radiation. The cryostat consists of two separate vacuum systems for the cold mass: an UHV vacuum system for the beam and an insulation vacuum system for the coils and the rest of the cold mass. The pressure of the two vacua are monitored by pressure gauges at room temperature. A 300 μm stainless steel foil coated with 30 μm of copper is placed between the cold mass and the beam vacuum. A taper system connects the normal beam pipe with the cold mass and has two func-

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EMITTANCE GROWTH AND TUNE SPECTRA AT PETRA III

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Abstract

At DESY the PETRA ring has been converted into a synchrotron radiation facility, called PETRA III. 20 damping wigglers have been installed to achieve an emittance of 1 nm. The commissioning with beam started in April 2009 and user runs have been started in 2010. The design current is 100 mA and the bunch to bunch distance is 8 ns for one particular filling pattern with 960 bunches. At a current of about 50 mA a strong vertical emittance increase has been observed. During machine studies it was found that the emittance increase depends strongly on the bunch filling pattern. For the user operation a filling scheme has been found which mitigates the increase of the vertical emittance. In August 2010 PETRA III has been operated without damping wigglers for one week. The vertical emittance growth was not significantly smaller without wigglers. Furthermore tune spectra at PETRA III show characteristic lines which have been observed at other storage rings in the connection with electron clouds. Measurements at PETRA III are presented for different bunch filling patterns and with and without wiggler magnets.

INTRODUCTION

At DESY the PETRA ring has been converted into a synchrotron radiation facility, called PETRA III [1]. Originally, PETRA was built in 1976 as an electron and positron collider which was operated from 1978 to 1986 in the collider mode. From 1988 until 2007 PETRA was used as a preaccelerator for the HERA lepton hadron collider ring. Positron and electron currents of about 50 mA were injected at an energy of 7 GeV and accelerated to the HERA injection energy of 12 GeV. During the conversion to a synchrotron radiation facility from 2007 to 2008 one octant of the PETRA ring has been completely redesigned to provide space for 14 undulators. The new experimental hall is shown in Fig. 1. The commissioning with beam started in April 2009 and user runs have been started in 2010 [2]. PETRA III is presently running in a top up operation mode with *positrons* since PETRA III is sharing the same preacelrator chain with the synchrotron source DORIS, which is running with positrons to avoid problems with ionized dust particles.

The new facility aims for a very high brilliance of about 10^{21} photons/s/0.1%BW/mm^2/mrad^2 using a low emittance (1 nm rad) positron beam with an energy of 6 GeV. The very low emittance of 1 nm rad has been achieved with the help of 20 damping wigglers with a length of 4 m each

Figure 1: Aerial view of the new experimental hall of PETRA III which was build from 2007 to 2008.

and a peak magnetic field of 1.5 T and a period length of 0.2 m [3].

Beam parameters

A summary of the PETRA III design parameters can be found in Table 1 [1].

Table 1: PETRA III design parameters

Parameter	**PETRA III**	
Energy /GeV	6	
Circumference /m	2304.0	
Revolution frequency /kHz	130.1	
harmonic number	3840	
RF frequency /MHz	500	
Total current /mA	100	
Bunch Population $N_0/10^{10}$	0.5	12.0
Number of bunches	960	40
Total current /mA	100	100
Bunch separation Δt /ns	8	192
Emittance		
ϵ_x/nm	1	
ϵ_y/nm	0.01	
Bunch length /mm	12	
Tune Q_x	36.13	
Q_y	30.29	
Q_s	0.049	
Momentum compaction $/10^{-3}$	1.2	

The design current of 100 mA has been achieved but with a different filling scheme than originally foreseen

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CESR-TA PROGRAM OVERVIEW*

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Abstract

The Cornell Electron/Positron Storage Ring has been configured as a damping ring test accelerator. The principle objective of the CesrTA program is to investigate electron cloud physics in the ultra-low emittance regime characteristic of a linear collider positron damping ring. The storage ring is equipped with 12 superferric damping wigglers to increase the radiation damping rate and decrease the emittance. At a beam energy of 2GeV, the 1.9T wigglers increase the damping rate by an order of magnitude and decrease the emittance by a factor of 5 to 2.6nm. Instrumentation to measure, and techniques to minimize sources of transverse coupling and vertical dispersion routinely yield sub 10pm vertical emittance. More than two dozen multi-channel retarding field analyzers have been installed throughout the magnetic guide field in order to characterize cloud buildup. Shielded button pickups have been deployed to measure cloud decay and energy spectra. Techniques to measure electron cloud induced tune shift, instability, and emittance dilution have been developed. We are building and extending simulations of electron cloud phenomena in order to interpret the measurements and to establish the predictive power of the models. We give an overview of the CesrTA ring parameters, the diagnostic instrumentation for low emittance tuning and electron cloud studies. Details will appear in the references to other articles in this proceedings.

CESRTA PROGRAM OBJECTIVES

The damping ring is the source of low emittance bunches of positrons for the international linear collider. The damping ring is required to store the full complement of bunches that will be delivered to the collision point in each linac cycle. The circumference of the damping ring is determined by the spacing of the bunches in the ring. And the spacing is limited by electron cloud effects. CesrTA aims to measure the development of the electron cloud and the dependence of that development on bunch spacing and bunch charge, on local magnetic field, and on the chemistry and geometry of vacuum chambers. Retarding field analyzers are used to measure the time averaged density of the electron cloud. Shielded button pickups yield a measure of the growth and then decay time of the cloud. In addition, we measure the effect of the electron cloud on the beam. We observe cloud induced tune shift, emittance growth, and head tail instability.

Measurements of the sensitivity of the beam-cloud dynamics to the beam size require that we achieve ultra-low vertical emittance, as near to that of the linear collider damping ring as possible. Beam based instrumentation and techniques for identifying and then compensation of sources of vertical dispersion and transverse coupling have been developed. An xray beam size monitor yields bunch by bunch and turn by turn measurement of vertical beam heights of order 10 microns with a few micron precision.

Vacuum chamber materials are characterized in terms of secondary (electron) emission yield (SEY). Knowledge of SEY is essential to predictions of electron cloud growth and equilibrium electron density. At CesrTA we have implemented an in situ SEY measuring device that provides a means of determining the secondary yield of sample materials at various stages of beam processing with no intermediate exposure to atmosphere.

CESRTA LAYOUT AND OPTICS

The Cornell Electron Storage Ring (CESR) layout is based on simple FODO optics. There are two diametrically opposed straights in which low beta insertions focused colliding beams of electrons and positrons. Superconducting damping wigglers, located in the machine arcs, served to reduce the radiation damping rate in low energy (2GeV/beam) operation from 500ms to 50ms, and to increase the horizontal emittance to order 100nm. The decreased damping time and increased emittance were necessary in order to maintain a high beam-beam current limit and to maximize luminosity. At the conclusion of the colliding beam program, the guide field optics were modified for low emittance operation as a damping ring test accelerator. The low beta optics were removed. Half of the damping wigglers were moved to one of the former low beta straights. The opposite straight was instrumented for measuring electron cloud effects.

The storage ring lattice is reconfigured with zero horizontal dispersion in all of the damping wiggler straights. The effect of the wigglers is to decrease the damping time as before, but to decrease horizontal emittance as well. At 2GeV, with the 12, 1.3m long damping wigglers operating at 1.9T, we achieve horizontal emittance of 2.6nm. Because the CESR quadrupoles and sextupoles are all independently powered, there is extraordinary flexibility of the lattice. As required by the experimental program we operate the storage ring over the energy range of 1.8-5.3GeV, with from zero to 12 damping wigglers, and with integer part of the betatron tune ranging from 10 to 14 with corresponding range of emittances, momentum compaction and bunch length. Parameters of a few of the many CesrTA

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E-CLOUD ACTIVITY OF DLC AND TIN COATED CHAMBERS AT KEKB POSITRON RING

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Abstract

A TiN coated copper chamber and diamond like carbon (DLC) coated aluminium chambers were installed to an arc section of the KEKB positron ring to make comparisons of electron cloud activity as well as total pressure and residual gas components during the beam operation under the same condition. For the DLC coating, two different types of surface roughness: smooth and rough were prepared. The chamber with large surface roughness that was obtained with cost-effective simple abrasive of the large grain before the coating was installed in the same arc section and exposed to the electron cloud until the KEKB shutdown. The measured electron cloud activity in the DLC coated chamber with smooth surface showed half and one-sixth of those in the TiN coated chamber and the copper chamber, respectively at the operation of around 1000 Ah. Much more reduction of the e-cloud activity owing to the DLC on the roughed chamber surface was found, that is a reduction of one-fifth and one-tenth, respectively, in comparison with the DLC on non-roughed chamber and the TiN coating on non-roughed chamber at around 1000 Ah.

INTRODUCTION

After we found reduction of secondary electron yield (SEY) due to electron beam induced graphitization at surfaces of many metals, alloys and compounds, we have been performing comparative investigation to show validity of carbon materials such as graphite, diamond, amorphous carbon, electron induced graphite layer and so on with other metals and compounds in order to reduce e-cloud activity in accelerators [1-6].

One can find a couple of advantages of carbon materials for mitigating e-cloud in the following: (a) low δmax and low SEYs at higher incident energies and at oblique incident angles of electrons are shown due to mainly the low mass density of carbon materials, (b) low outgassing is achievable, depending on the method to make the films, (c) carbon materials show less adsorption (low sticking coefficient) and quick desorption (low activation energy of desorption), (d) hard coating with good adhesion is possible, (e)carbon raw materials are inexpensive[1-3, 7-9].

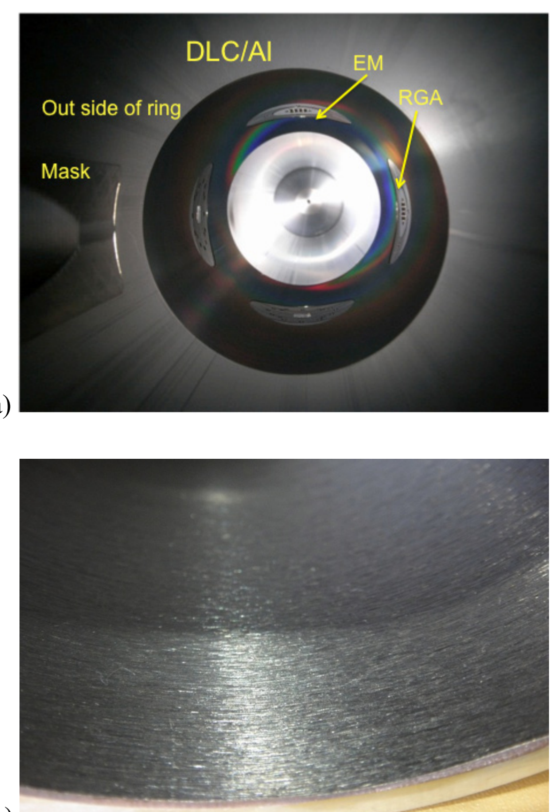
EXPERIMENTAL

Surface roughing was done before DLC coating on the inner surface of a 0.9 m-long Al beam chamber. For this purpose, cost-effective simple abrasive of the large grain with an average size of 30 microns was adopted with a process speed of 100 mm/min along with the chamber.

The DLC coating for the chamber shown in Fig. 1 was carried out mainly with acetylene gas of 1Pa in a pulsed DC plasma-CVD (chemical vapor deposition) chamber which allows us to coat DLC on a less than 3.5m-long chamber. The measured chamber temperature was not larger than 140 degrees C during the coating. Sample coupons were set inside of the envelopes that were connected to the Al chamber to confirm the film quality and the film thickness. The DLC deposition rate was measured to be 100 nm/min and the coating homogeneity was measured to be ±5%.

Figure 1: 0.9m long DLC coated Al Chamber after the surface roughing.

(a)



(b)

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ELECTRON CLOUD MITIGATION INVESTIGATIONS AT CESR-TA*

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Abstract

As part of an effort to understand and mitigate the electron cloud effect, the CESR storage ring at Cornell has been reconfigured into a damping ring-like setting, as well as instrumented with a large number of electron cloud diagnostic devices. In particular, more than 30 Retarding Field Analyzers (RFAs) have been installed. These devices, which measure the local electron cloud density and energy distribution, have been deployed in drift, dipole, quadrupole, and wiggler field regions, and have been used to evaluate the efficacy of cloud mitigation techniques in each element.

INTRODUCTION

The density, energy distribution, and transverse profile of the electron cloud can depend strongly on several parameters that can vary substantially throughout an accelerator. These include local photon flux, vacuum chamber shape and material, primary and secondary emission properties of the material, and magnetic field type and strength. Therefore it is useful to have a detector that can sample the electron cloud locally. At CesrTA we have primarily used Retarding Field Analyzers (RFAs) for this purpose [1]. RFAs can measure the energy distribution of the cloud by applying a retarding potential between two grids, rejecting any electrons below a certain energy[2]. In addition, most RFAs are segmented across the top of the beam pipe, effectively measuring the transverse distribution of the cloud.

We have used these devices to probe the local behavior of the cloud in the presence of different mitigation schemes. Several such schemes have been proposed, including beam pipe coatings (TiN, amorphous Carbon, NEG) [3, 4], grooved beam pipes [5], solenoids, and clearing electrodes [6].

Table 1 provides a list of the mitigation techniques that have been evaluated so far at CesrTA.

Table 1: Mitigation techniques at CesrTA

Field Type	Base Material	Mitigation
Drift	Aluminum, Copper	TiN, Carbon, NEG coatings, solenoids
Dipole	Aluminum	TiN coating, grooves
Quadrupole	Aluminum	TiN coating
Wiggler	Copper	TiN coating, grooves, clearing electrode

DRIFT MEASUREMENTS

Fig. 1 shows a typical retarding voltage scan in an TiN coated drift chamber for a 45 bunch train of positrons, at 1.25 mA/bunch (corresponding to a bunch population of 2×10^{10}), 14ns spacing, and beam energy 5.3 GeV. The plot shows the RFA response as a function of collector number and retarding voltage. The RFA signal is expressed in terms of current density in nA/mm^2, normalized to the transparency of the RFA beam pipe and grids. In principle, this gives the time averaged electron current density incident on the beam pipe wall. The signal is peaked at low energy and in the central collectors, though some current remains at high energy in the central collectors and at low energy in all collectors.

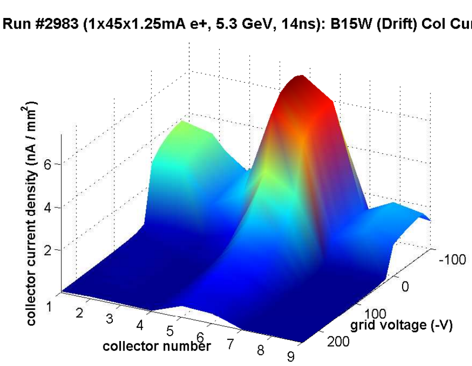

Figure 1: Example voltage scan: TiN coated drift RFA

We have taken RFA data in both TiN and amorphous Carbon coated drift chambers, as well as an uncoated Aluminum chamber. All three of these chambers have been installed at the same location in the ring at different times. This ensures that the comparison is done with the exact same beam conditions, including photon flux and beam size.

A comparison of different beam pipe coatings in a drift region can be found in Fig. 2. It shows the average collector current density as a function of beam current (in this case

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EXPERIMENTAL EFFORTS AT LNF TO REDUCE SECONDARY ELECTRON YIELD IN PARTICLE ACCELERATORS

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Abstract

A common effort in most accelerator centres is to develop new technologies to produce and test beam pipe inner walls of particle accelerators with an as low as possible Secondary Electron Yield (SEY). This item, in fact, is crucial in controlling Electron Cloud formation and in reducing its effects that are well known to be a potential bottle-neck to the performances obtainable from present and future accelerators. Frascati has a longstanding experience in qualifying materials in terms of surface parameters of interest to e-cloud issues. We are routinely measuring SEY, its dependence from electron energy, temperature and scrubbing. We are about to be ready to study not only the Photo Electron Yield (PEY), but more importantly, to characterize in situ the surface chemical composition and eventual modifications occurring during electron or photon irradiation by using synchrotron radiation beamlines in construction at DAΦNE. Our experimental measurements of the relevant parameters can be also confidently compared to simulations, performed by running the EC codes, in order to elucidate the final consequences on machine performances. Such a combined characterization effort is also suggesting ways to produce low SEY materials coatings. This issue is particularly important in view of the possible construction in Italy of a Super-B high luminosity collider [1], where e-cloud issues are foreseen to be a potential bottleneck to operational machine performances.

INTRODUCTION

In accelerator rings beamlines with positively charged beams, an electron cloud [2] may be initially generated by photoelectrons or ionization of residual gas and increased by the surface secondary emission process. If an electron cloud (EC) forms, it may couple with the circulating beam and cause beam instabilities, tune shift, and vacuum pressure rise, ultimately affecting the machine performances. Electron cloud detrimental effects have been observed at many storage rings [3] and are expected to be a serious issue for future machines like ILC-DR and Super-B.

EC build-up and evolution depend strongly on the surface properties of the accelerator walls such as Secondary Electron Yield (SEY), defined as the number of emitted electrons per incident electron and commonly denoted by δ. Generally for metal surfaces used in accelerators, the value of SEY ranges from 1 to 3 in the 0-500 eV energy range, and reaches a maximum (δ_{max}) around 200 eV. The SEY of technical surface materials for accelerator vacuum chambers has been extensively measured in the past years at CERN [4, 5], KEK [6, 7], SLAC [8, 9, 10] and other laboratories [11].

A low SEY is essential for the operation of particle accelerators, since their design luminosity and performances relies on a SEY value of about 1.3 or less. Clearly, an industrial surface with such a low yield should be stable in time and during operation, and have the necessary requirements in terms of vacuum compatibility, impedance, surface resistance, etc.. Up to now, unfortunately the significant effort done by many laboratories to find suitable surface coatings or systems, has not yet given satisfactory and conclusive results. LHC, for instance, does not count on a specific low yield material coating but on the experimental evidence that the SEY of the chosen Cu surface is strongly reduced by surface conditioning during initial operations (or commissioning). In this framework, the understanding of the conditioning process is needed to predict the conditioning time and beam parameters required to reach accelerator design performances. To this scope we have measured SEY reduction (scrubbing) not only versus the dose (the number of impinging electrons per unit area on sample surfaces) of the impinging electrons, but also versus their energy, with special attention to low energy primary electrons (<50 eV) which have been recently shown to have peculiar behavior in terms of reflectivity [4]. Such studies, performed on Cu prototype of the beam screen adopted for the Large Hadron Collider (LHC), have shown that scrubbing efficiency depends not only on the dose but also on the energy of incident electron beams [12,13].

So, while it is clear that scrubbing is one possible solution to obtain low SEY beam pipe accelerators, it seems very useful to study the actual chemical phenomena occurring at the real surfaces and causing the observed SEY reduction. Such careful surface analysis can not only clarify some important functional aspects related to the scrubbing process, but also can individuate new strategies in producing stable low SEY materials.

In this context Surface science techniques and synchrotron radiation spectroscopies are ideal tools to perform “in situ” characterization of the chemical composition of a relevant surface material and its eventual modifications occurring during electron or photon irradiation. To convince ourselves that such research line could indeed give significant insight to the scrubbing

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Feedback Control of SPS E-clouds / Transverse Mode Coupled Instabilities*

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Abstract

The CERN SPS at high intensities exhibits single bunch transverse instabilities induced by electron clouds and strong head-tail interactions. One proposal to mitigate these instabilities is to use feedback systems with enough bandwidth to sense the transverse position and apply correction fields to multiple sections of the nanosecond-scale bunch. To develop the feedback control prototype, different research areas has been pursed to model and identify the bunch dynamics, design the feedback control and implement the GigaHertz bandwidth hardware. This paper presents those R & D lines and reports the progress until present time.

INTRODUCCION

Intrabunch instabilities induced by electron clouds and strong head-tail interactions are one of the limiting factors to reach the maximum beam currents in SPS and LHC rings [1]. The effect of coating the chambers and adding grooves to the surface of those structures has been studied to mitigate intrabunch and collective effect instabilities induced by electron clouds (e-clouds) [2]. CERN is proposing a plan to coat large part of the SPS and LHC chambers in order to mitigate e-cloud instabilities. Continuous testing of the limitations of these techniques and the design of the necessary infrastructure to apply the coating are currently conducted al CERN [3]. These techniques cannot mitigate transverse mode coupled instabilities (TMCI) and research is conducted at CERN SPS to evaluate the maximum stable beam current that is possible to accelerate adjusting the beam chromaticity.

Feedback techniques can stabilize bunch instabilities induced not only by e-clouds but also induced by strong head-tail interactions (TMCI). Complementary to the plan previously described, US LHC Accelerator Research Program (LARP) is supporting a collaboration between US Labs and CERN to study the viability of controlling intrabunch instabilities using feedback control techniques. A collaboration among SLAC / LBNL / CERN (under the DOE LARP program) started evaluating the limitations of this technique to mitigate both instabilities and other possible head-tail distortions in bunches [4].

The application of feedback control to stabilize the bunch is challenging because it requires bandwidth sufficient to sense the transverse position and apply correction fields to multiple sections of a nanosecond-scale bunch. These requirements impose technology challenges and limits in the design [5]. Additionally, the intra-bunch dynamics is more challenging than the beam dynamics involving the interaction between bunches. The collaboration has defined different interdependent working lines to study the problem, to design a feedback control channel and to develop the hardware of a control system prototype to prove principles and evaluate the limitations of this technique by stabilizing a few bunches in the CERN SPS machine. This paper gives an overview of the research areas and plans, measurements and results of present studies, and goals and future directions.

RESEARCH & DEVELOPMENT PLAN - GOALS

The US and CERN collaboration was proposed recently (in October 2008) to mitigate via feedback e-clouds, TMCI, and other intra-bunch distortions and instabilities at SPS and LHC. The motivation of this collaboration is to control e-clouds and TMCI via GigaHertz bandwidth feedback systems. The immediate goal is to analyze and define design techniques for the system, study the limitations of the feedback technique to mitigate those instabilities, and build the hardware of a minimum prototype to control a few bunches and measure the limiting performance. The design of a final system is based on the results of this first stage.

The collaboration has defined different working lines that involve:

1. Development of reduced mathematical models of the bunch dynamics interacting with e-clouds and machine impedances. Identification of those reduced models based on machine measurements. Design of control feedback algorithms based on the reduced models.

2. Inclusion of realistic feedback models in advanced multi-particle simulation codes to test the models, possible feedback designs and diagnostic tools.

3. Measurements in the SPS machine to validate both the reduced and multi-particle models

4. Development of hardware prototypes to sense and drive the transverse position of different sections of the bunch. Development of hardware prototype of feedback control processing channel.

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SIMULATED PERFORMANCE OF AN FIR-BASED FEEDBACK SYSTEM TO CONTROL THE ELECTRON CLOUD SINGLE-BUNCH TRANSVERSE INSTABILITIES IN THE CERN SPS*

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Abstract

The operation at high current of high-energy proton machines like the SPS at CERN is affected by transverse single-bunch instabilities due to the Electron Cloud effect [1]. As a first step towards modeling a realistic feedback control system to stabilize the bunch dynamics, we investigate the use of a Finite Impulse Response (FIR) filter to represent the processing channel. The effect of the processing channel on the bunch dynamics is analyzed using the macro-particle simulation package Warp-Posinst. We discuss the basic features of the feedback model, report on simulation results, and present our plans for further development of the numerical model.

INTRODUCTION

Electron clouds in the SPS at CERN are responsible for the occurrence of large and fast growing transverse instabilities in high-intensity proton beams. A feedback (FB) control system to damp transverse instabilities has been proposed and is currently under study [2]. The particle-in-cell, macroparticle simulation code suite Warp-Posinst is being used to model the dynamics of the beam-electron interaction and the action of the feedback system on the beam with the intent to determine the basic requirements for the FB system such as minimum bandwidth and amplitude of the kicker signal necessary to achieve stability.

Figure 1 shows a schematic of the control loop.

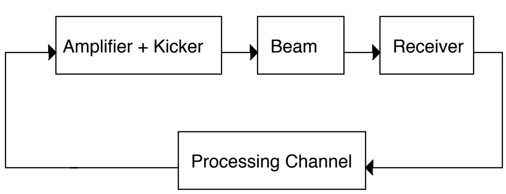

Figure 1: General scheme of the SPS Ecloud Feedback Control System.

The processing channel discussed in this paper is based on a simple bandpass FIR filter, which is more realistic than the model utilized in previous studies [3]. The filter limits the bandwidth around the nominal betatron tune frequency, eliminating spurious signals and advancing the phase at the tune frequency. Single-bunch simulation results are presented comparing open (FB off) and closed (FB on) loop cases and analyzing the vertical motion of bunch slices. The model of the kicker is ideal and has no bandwidth limitation. As a first pass towards evaluating the gain requirement of the amplifier driving the kicker, we performed several simulations limiting the kick signal to a nominal saturation level and studied how this affects the control of the beam dynamics. Conclusions and future developments of the numerical model are discussed in the last section.

FEEDBACK MODEL

The simple $5-$tap band-pass FIR filter used in our studies damps the beam vertical motion while limiting the bandwidth around the nominal fractional tune $[Q_y] = 0.185$ and performing a phase advance of 90 deg around the nominal tune value. The filter has 5 taps, *i.e.* it is based on 5 previous measurements $y_i(k)$ of the bunch vertical displacement taken at a fixed location around the ring. The output $z_i(k)$ is calculated as

$$z_i(k) = a_1 y_i(k-1) + a_2 y_i(k-2) + ... + a_n y_i(k-n) \quad (1)$$

where $i = 1, \cdots, N_{\text{slices}}$ identifies the bunch slice, k is the machine turn no., $n = 5 =$ is the # of taps, and the set of coefficients $a_1, a_2...a_n$ define the impulse response of the filter. This set of coefficients depends on the design of the transfer function chosen. The FIR Bode plot is reported in Fig. 2.

The output signal of the filter is used to kick each slice of the bunch. The kick is applied on a one-turn delay basis at the position along the accelerator where the beam is sampled.

The action of the feed-back system can be represented in terms of the following simplified linearized model of bunch dynamics

$$y'' + \omega^2 y = K(y_e - y) + \Delta_{p_\perp}, \quad (2)$$

where y is the amplitude of the transverse oscillation of a beam slice and y_e the transverse offset of the electron cloud baricenter corresponding to that slice; the constant K is a measure of the interaction between the beam and the electron cloud and $\Delta_{p_\perp}$ the signal from the kicker. A functioning feed-back will force the vertical displacement

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STUDIES OF THE ELECTRON-CLOUD-INDUCED BEAM DYNAMICS AT CESR-TA*

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Abstract

At CesrTA, we have developed the capability to make automated measurements of the self-excited frequency spectra of individual bunches, to look for signals for single-bunch instabilities. We can also drive single bunches and measure the rate of decay of selected lines in their frequency spectra. We have used these capabilities to explore the dynamics of the interaction of a multi-bunch beam with the electron cloud. The basic observation is that, under conditions of sufficiently high current and sufficiently low chromaticity, the multi-bunch frequency spectra exhibit vertical $m = \pm 1$ synchrobetatron (head-tail) lines, separated from the vertical betatron line by the synchrotron frequency, for many of the bunches along the train. The amplitude of these lines typically (but not always) grows along the train. The dependence of this effect on many of the parameters of the beam has been explored.

OVERVIEW

Introduction

To continue our studies of electron cloud related phenomena, we have developed the capability to make automated measurements of frequency spectra of individual bunches, to look for signals for single-bunch instabilities.

In this measurement, a button BPM at 33W (sensitive to both vertical and horizontal motion) is gated on a single bunch, and the signal is routed to a spectrum analyzer. Several frequency spectra are acquired, covering a range which spans the lowest betatron sidebands. Machine conditions, such as bunch current, magnet settings, feedback system parameters, etc. are automatically recorded and stored before and after each single-bunch spectrum is taken.

Using this system, during the recent July-August, 2010, and September runs, a number of observations were made which illuminate the dynamics of the electron-cloud/beam interaction at CesrTA. This paper will review results from these experiments.

General remarks

All experiments discussed here were done at 2.085 GeV in a low emittance lattice. The machine parameters are shown in Table 1.

Table 1: Nominal machine parameters. The emittances and tunes are those of a single bunch in the machine.

Parameter	Unit	Value
Energy	GeV	2.085
Lattice		2085mev_20090516
Horizontal emittance	nm	2.6
Vertical emittance	pm	~ 20
Bunch length	mm	10.8
Horizontal tune		14.55
Vertical tune		9.58
Synchrotron tune		0.065
Momentum compaction		6.8×10^{-3}
Revolution frequency	kHz	390.13

Trains having bunches numbering from 30-45, with a bunch spacing of 14 ns, and bunch currents in the range of $0.5 - 1.25$ mA ($0.8 - 2.0 \times 10^{10}$ particles) per bunch were studied. In all cases, except where specifically noted, the beam particles were positrons.

Several systematic checks were undertaken:

- Checks were made to rule out intermodulation distortion in the BPM electronics and in the BPM itself.
- The betatron and synchrobetatron (head-tail) lines moved as expected when the vertical, horizontal, and synchrotron tunes were varied.

The longitudinal feedback was off for these measurements. The vertical and horizontal feedback were turned down to 20% of full power. Some experiments explored the effect of turning the vertical feedback fully off.

More details on the experimental technique can be found in [2].

General observations

The basic observation is that, under a variety of conditions, the frequency spectra exhibit the vertical $m = \pm 1$ synchrobetatron (head-tail) lines, separated from the vertical betatron line by the synchrotron frequency, for many of the bunches along the train. The amplitude of these lines typically (but not always) grows along the train.

Typically, for the bunch at which the vertical synchrobetatron lines first appear above the noise floor (which is about 40 db below the vertical betatron line), we observe (on a bunch-by-bunch X-ray beam size monitor) growth in the beam size, which continues to increase along the train [3].

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ELECTRON CLOUD INSTABILITY IN LOW EMITTANCE RINGS

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Abstract

Electron cloud instability, especially single bunch instability, is crucial issue for the emittance preservation in low emittance positron rings. In Super B factories and ILC damping ring, the emittance preservation is directory connected to their performance. Cesr-TA in Cornell has been operated to study the electron cloud effects in a low emittance ring. We discuss threshold density and unstable mode for the single bunch instability in low emittance rings, Cesr-TA and Super KEKB.

INTRODUCTION

The single bunch instability induced by electron cloud in Cesr-TA has been studied. Cesr-TA can be operated low and normal emittance. It is interesting to observed and analyze the both emittance cases in a ring. The simulation results were published in Reference [1]. We review the results of Cesr-TA in the paper [1] and discuss Super KEKB case.

The single bunch electron cloud instability is caused by coherent motion of electrons in a bunch. The angular frequency of electrons is expressed by

$$\omega_e = \sqrt{\frac{\lambda_p r_e}{\sigma_y(\sigma_x + \sigma_y)}}c$$

This formula is derived from taking into account of electric field in the bunch. Space charge between electrons is negligible because beam field is much stronger than the space charge field. The instability is caused by corrective motion of electrons in a cloud and positrons in a bunch with the frequency.

The phase factor $\omega_e\sigma_z/c$ characterizes how many oscillation electrons experience in a bunch. The phase factor is around 3-7 for KEKB, while more than 10 for ILC damping ring and Super B factories, because of the very small beam size. We discuss the electron cloud instability with focusing the phase factor, $\omega_e\sigma_z/c$.

Cesr-TA is operated at very low emittance (ε_x=2.6 nm) in 2GeV, while is high (ε_x=40 nm) in 5 GeV. The phase factors are 11 and 3.2 in 2 and 5 GeV, respectively, where the average beta function is $\beta=L/2\pi\nu$=12 m. The factor is 18 for Super B factories.

ANALYTICAL ESTIMETE OF THE INSTABILITY THRESHOLD

The electron oscillation gives correlation of transverse motion between different longitudinal positions z. The correlation is represented by wake field, which is expressed by [2]

$$W(z) = K\frac{\gamma\omega_p^2\omega_e L}{\lambda_p r_e c^3} e^{\omega_e z/2Qc} \sin\omega_e z/c \qquad (1)$$

Electrons oscillate with a frequency spread due to the longitudinal and horizontal profile of the bunch. The quality factor (Q) characterizes how many period the electron oscillate for the damping due to the spread. A numerical analysis for the electron induced wake field gave Q_{nl}~7 [2]. The effective quality factor should be minimum of Q=min(Q_{nl}, $\omega_e\sigma_z/c$).

The electron density near the beam is uniform before the interaction. The electrons are attracted by the beam electric force, which behaves 1/r for a long distance interaction, where r is the distance of bunch and an electron. The factor K characterizes how far electrons are gathered to the beam. The factor is assumed to be equal to the phase factor, K= $\omega_e\sigma_z/c$.

The threshold of the fast head-tail instability is estimated by analytical and simulation methods.

$$U = \frac{\sqrt{3}\lambda_p r_0 \beta}{\nu_s\ \gamma\ \omega_e\sigma_z/c}\frac{|Z_\perp(\omega_e)|}{Z_0} = \frac{\sqrt{3}\lambda_p r_0\beta}{\nu_s\ \gamma\ \omega_e\sigma_z/c}\frac{KQ}{4\pi}\frac{\lambda_e}{\lambda_p}\frac{L}{\sigma_y(\sigma_x+\sigma_y)} = 1 \qquad (2)$$

where Z is the transverse impedance correspond to the wake field in Eq.(1). The threshold density is solved using the relation $\lambda_e=2\pi\sigma_x\sigma_y\rho_{e,th}$, as follows:

$$\rho_{e,th} = \frac{2\gamma\nu_s\,\omega_e\sigma_z/c}{\sqrt{3}KQr_0\beta L}. \qquad (3)$$

The threshold densities of the electron cloud are estimated for the existing and proposed positron rings in Table 1. The threshold density for Cesr-TA is ρ_{th} =0.82x10^{12} and 5.0x10^{12} m^{-3} for 2 and 5 GeV, respectively. The threshold is 0.27 x10^{12} and 0.54x10^{12} m^{-3} for of Super KEKB and Super B, respectively.

SIMULATION OF THE INSTABILITY THRESHOLD

The threshold should be crosschecked using simulations, since the analytical estimate is somewhat ambiguous for K and Q. The simulation in this paper is performed by PEHTS, which is a particle in cell code for motion of macro-positrons in the beam and macro-electrons in the cloud.

Figure 1 shows the evolution of the vertical beam size for various electron density in Cesr-TA. The threshold is 1.0 x10^{12} and 6.0x10^{12} m^{-3} for 2 and 5 GeV, respectively. Slow beam blow up below the threshold seen in 5 GeV

E-CLOUD EFFECTS ON SINGLE-BUNCH DYNAMICS IN THE PROPOSED PS2 *

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Abstract

One of the options considered for future upgrades of the LHC injector complex entails the replacement of the PS with the PS2, a longer circumference and higher energy synchrotron. Electron cloud effects represent an important potential limitation to the achievement of the upgrade goals. We report the results of numerical studies aiming at estimating the e-cloud density thresholds for the occurrence of single bunch instabilities.

INTRODUCTION

The requirement for PS2 is to accelerate bunch trains up to 50 GeV kinetic energy (twice the energy reach of PS) in either the 25 ns or the 50 ns bunch spacing configuration, with 4×10^{11} and 5.9×10^{11} particles per bunch respectively.

In addition to space-charge effects [1] and classical instabilities [2], a potential limiting factor to the machine performance is the accumulation of electron cloud. E-cloud can affect the beam dynamics by triggering single or multi-bunch instabilities, or cause a growth of the beam emittance through incoherent effects. Extensive studies of electron cloud formation in the PS2 for various lattice elements, bunch-train structures were reported elsewhere [3]. Here we focus on the investigation of the impact of the electron cloud on the single-bunch dynamics. The study was carried out by macroparticle simulations using the Warp/POSINST code [4]. Preliminarily results were reported in [5].

PHYSICS MODEL

The physics model implemented in Warp is similar to that implemented in other already established codes for the analysis of e-cloud effects on the beam, like HEADTAIL [6]. Warp and HEADTAIL have been extensively benchmarked in the past and further spot-checks were carried out during these studies confirming a generally good agreement with each other. In the model, beam/e-cloud interactions occur at a finite number of discrete interaction points (or 'stations') along the machine circumference, where electrons are effectively confined to a transverse plane orthogonal to the beam orbit. An initially cold and transversely uniform electron distribution is assumed to exist before, and refreshed after, each bunch passage. In an actual machine the form of the distribution and peak value of the e-cloud density is generally strongly dependent on the lattice element type, and often on the exact location along the machine. However, for these studies it is assumed that the electron cloud, concentrated on uniformly distributed stations along the ring circumference, has the same density (peak value and form of transverse distribution) at all stations. The more realistic scenario in which the electron density can vary along the machine, reflecting, in particular, differences of e-cloud accumulation in dipoles and field-free regions as determined by e-cloud build-up codes like POSINST [7] or ECLOUD [8], should be investigated in future work for improved accuracy.

Table 1: Selected lattice/beam parameters used in the Warp simulations

	Extraction	Injection
Kinetic energy (GeV)	50	4
Trans. tunes $Q_{x,y}$	11.8, 6.71	11.8, 6.71
Rms emittance $\gamma\varepsilon_\perp$ (μm)	3	3
Trans. rms sizes $\sigma_{x,y}$ (mm)	1.33, 1.43	4.27, 4.59
Synch. tune Q_s (10^{-3})	1.24	12.1
Long. rms size σ_z (m)	0.30	1.41
Slippage η (10^{-3})	-1.82	-37.5

The electron dynamics during the bunch passage is determined by the self-fields and the fields generated by the beam particles, with an option to pin the electron motion to vertical lines to mimic the dynamics in a dipole magnet. The dynamics of the beam particles is determined by their response to the electron fields at the stations in the 'quasistatic' approximation [4] and optionally to the beam's own fields. The beam particles motion from station to station is modelled by linear transfer maps in the smooth approximation with chromatic effects accounted for by introduction of a phase-advance dependance on the particle momentum. The Poisson equation, yielding the fields generated by the electrons and the protons in the beam slices as the beam steps through each station, is solved on a rectangular grid with metallic boundary conditions. The horizontal and vertical dimensions $2a$=12.5 and $2b$=6.5 cm of the grid were chosen to match the values of the two axes of the proposed elliptical vacuum chamber design.

The goal of the study is to identify threshold values of the e-cloud density for the appearance of single-bunch instabilities. These can generally be captured by relatively short time-scale simulations. The results shown in the following were obtained by simulating the beam dynamics through 10^3 turns (corresponding to about 4.5 ms storage time) at injection and extraction on the assumption of steady (no energy ramping) machine conditions. We did not attempt to assess secular slow-rate emittance growth below instability

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IMPLEMENTATION AND OPERATION OF ELECTRON CLOUD DIAGNOSTICS FOR CESRTA*

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Abstract

The vacuum system of Cornell Electron Storage Ring (CESR) was successfully reconfigured to support CesrTA physics programs, including electron cloud (EC) build-up and suppression studies. One of key features of the reconfigured CESR vacuum system is the flexibility for exchange of various vacuum chambers with minimized impact to the accelerator operations. This is achieved by creation of three short gate-valve isolated vacuum sections. Over the last three years, many vacuum chambers with various EC diagnostics (such as RFAs, shielded pickups, etc) were rotated through these short experimental sections. With these instrumented test chambers, EC build-up was studied in many magnetic field types, including dipoles, quadrupoles, wigglers and field-free drifts. EC suppression techniques by coating (TiN, NEG and a-C), surface textures (grooves) and clearing electrode are incorporated in these test chambers to evaluate their vacuum performance and EC suppression effectiveness. We present the implementation and operations of EC diagnostics.

INTRODUCTION

With the successful reconfiguration of Cornell Electron Storage Ring (CESR) [1], CesrTA provides unique opportunities for study electron cloud growth and mitigation, and ultra-low emmittance lattice development and tuning, as well as beam instrumentation R&D, that are critical for the global design efforts of the International Linear Collider Damping Rings. As depicted in Fig 1, two long straight experimental sections and two very short experimental sections were created to provide flexibility of the CesrTA studies, to continue to support X-ray users at CHESS (Cornell High-Energy Synchrotron Sources). These experimental sections may be isolated via gate valves, so that test chambers could be exchanged without significantly impact overall accelerator operations. In these experimental sections, many new vacuum chambers were deployed with various EC diagnostics, such as retarding field analyzers (RFAs) for measuring steady-state EC build-up [2], RF shielded pickups [3] for studying EC growth, and TE wave transducer/receiver beam buttons [4]. With these EC diagnostics, effectiveness of many types of EC suppression techniques was evaluated in the test chambers. The details of these EC diagnostics and the corresponding measurements are described in separated papers in these proceeding. This paper is focussed on vacuum aspects of the implementation and the operational performances of these diagnostics and test chambers.

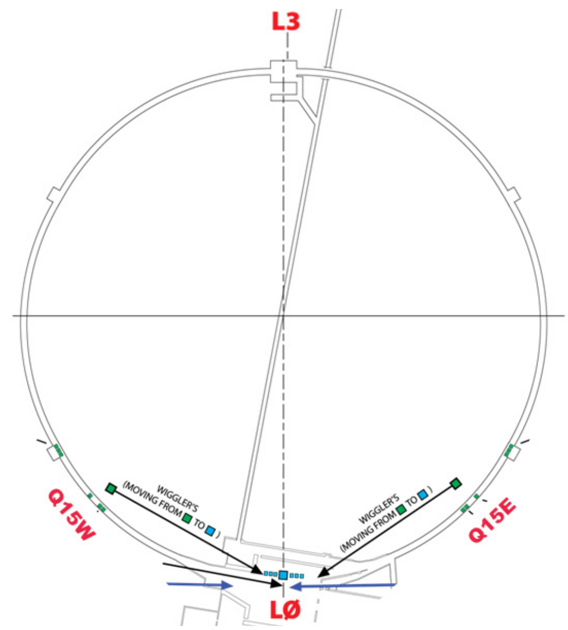

Figure 1: Four experimental sections were created after re-configuration of CESR vacuum system, including two long straights in south IR (L0), the north IR (L3) and two short sections in the arcs (namely, Q15W and Q15E). These sections may be isolated by gate valves to allow flexibility in deployments of various test chambers.

SOUTH IR EXPERIMENTAL SECTION

After removal of the center CLEO HEP Detector package, the South IR experimental section (~17.6 m in length), as shown in Fig 2, hosts a string of six superconducting wigglers (SCWs). The three SCWs in the West of L0 were fitted beampipes equipped with the thin-style RFAs [5]. A total of four RFA SCWs were constructed and rotated through this experimental section. The four RFA SCWs have different beampipe interior features, and they are (1) bare copper, (2) copper with TiN coating, (3) copper with a copper grooved bottom plate (which was later coated with TiN), and (4) copper with a EC clearing electrode at the bottom.

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BUNCH-BY-BUNCH INSTRUMENTATION UPGRADES FOR CESR, BASED ON REQUIREMENTS FOR THE CESR TEST ACCELERATOR RESEARCH PROGRAM*

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Abstract

The research focus of the CESR Test Accelerator program requires new instrumentation hardware, software and techniques in order to accurately investigate beam dynamics in the presence of electron cloud effects. These new instruments are also required to develop low emittance beam conditions which are key to the success of the damping ring design for the International Linear Collider. This paper will detail some of the architecture and tools which have been developed to support these efforts. Emphasis will be placed on the 4 ns bunch-by-bunch Beam Position Monitoring system as well as the 4 ns capable x-ray Beam Size Monitor.

CESR INSTRUMENTATION SUPPORT

A structure of supporting hardware and software has been developed to support the instrumentation required for the CESR Test Accelerator (CesrTA) program.. Some of the components of this structure are listed below:

- Matlab based control and analysis software
- Custom C based control and analysis software
- Standardized data formats with shared file input/output routines
- Common low level communication interfaces
- Common timing synchronization and triggering

BPM DEVELOPMENT

A new turn-by-turn beam position monitoring system has been developed. This system allows for turn-by-turn multi-bunch measurements of 4 nS spaced bunches. Some of the key design goals of the new system are as follows:

- Front-end bandwidth of 500 MHz
- Absolute position accuracy of 100 um
- Single-shot position resolution of 10 um
- Differential position accuracy of 10 um
- Channel to channel sampling accuracy of 10 pS
- BPM tilt errors of 10 mrad or less

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Performance of the bpm system has been shown to be in line with these goals. Fig.1 shows vertical orbit differences between pairs of detectors located close together on a single vacuum chamber. The histogram contains 256k turns of data. The single unit sigma is shown on each plot and is substantially consistent with our design goals.

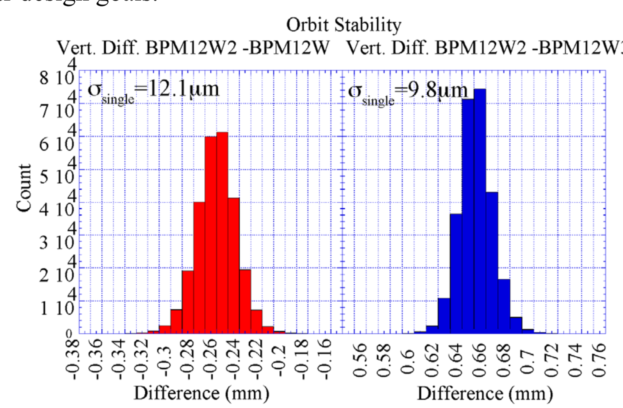

Fig 1: BPM Stability Measurement Results

XBSM HARDWARE

The x-ray Beam Size Monitor (xBSM) [1,2,3,4] has been developed in conjunction with the Cornell High Energy Synchrotron Source. Existing beam lines have been utilized while optics and detectors were designed specifically for the monitor. The x-ray source is a dipole magnet which is part of CESR. X-rays pass through the evacuated beam line and a set of optics elements. There are three optics elements that can be used: a vertically limiting slit, a Fresnel zone plate and a coded aperture. The layout of the XBSM experimental set up is shown in figure 2.

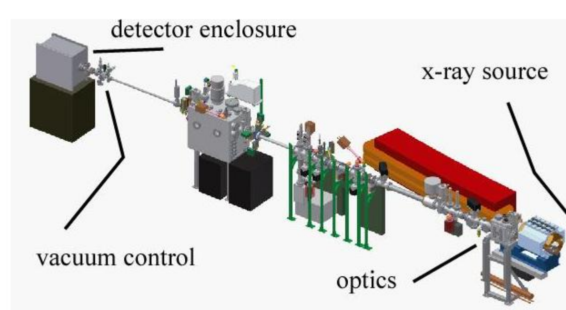

Fig 2: XBSM Layout

METHODS FOR QUANTITATIVE INTERPRETATION OF RETARDING FIELD ANALYZER DATA*

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Abstract

A great deal of Retarding Field Analyzer (RFA) data has been taken as part of the CesrTA program at Cornell. Obtaining a quantitative understanding of this data requires use of cloud simulation programs, as well as a detailed model of the RFA itself. In a drift region, the RFA can be modeled by postprocessing the output of a simulation code, and one can obtain best fit values for important simulation parameters using a systematic method to improve agreement between data and simulation.

INTRODUCTION

RFAs essentially consist of three elements [1]:

- Holes drilled into the beam pipe to allow electrons to pass through
- A retarding grid to which a negative voltage can be applied, rejecting any electrons which have less than a certain energy
- A collector which captures any electrons that make it past the grid. Often there are several collectors arranged transversely across the top of the beam pipe.

In principle, a single RFA measurement gives a great deal of information about the local behavior of the electron cloud. A typical "voltage scan," in which the retarding voltage of the RFA is varied while beam conditions are held fixed, is a measurement of the density, energy distribution, and transverse structure of the cloud [2]. In practice, however, it is a highly nontrivial task to map a data point from a voltage scan to any of these physical quantities. Typically, this gap is bridged through the use of cloud simulation programs, which track the motion of cloud particles during and after the passage of a bunch train. At CesrTA we have primarily used two such programs, POSINST [3] and ECLOUD [4].

The simplest method for simulating the output of an RFA for a given set of beam conditions is post-processing the output of one of these programs. More specifically, these codes can output a file containing information on each macroparticle-wall collision, and one can perform a series of calculations on this output to determine what the RFA would have seen had one been present.

A basic postprocessing script does the following:

- Determine if the macroparticle has hit in the azimuthal region where one of the RFA collectors exists.
- Calculate an efficiency (probability of passing through the beam pipe hole) based on the incident angle.
- Determine if the macroparticle has enough energy to make it past the retarding field.
- Deposit an appropriate amount of current on the grid and collector.

Note that by proceeding in this way one impicitly assumes that the presence of the RFA has no effect on the development of the cloud. This assumption is probably justified for a drift RFA, but may not be in the presence of a magnetic field [5]. This paper will focus on the drift case.

METHODOLOGY

The sheer volume of RFA data obtained so far at CesrTA necessitates a systematic method for detailed analysis. The goal is, given a set of voltage scan data, to find a set of simulation parameters that bring data and simulation into as close to agreement as possible. The best fit parameters obtained from this method should be close to the real values for the material under study. The following method was employed to accomplish this:

1. Choose a set of voltage scan data.
2. Choose a set of simulation parameters.
3. Do a simulation with the nominal values of each parameter.
4. Postprocess the output of the simulation to obtain a predicted RFA signal.
5. For each voltage scan and each parameter, do a simulation with a high and low value of the parameter, and determine the predicted RFA signals.
6. For each point in the simulated voltage scan, do a best linear fit to the curve of RFA signal vs parameter value. The slope of this line determines how strongly this point depends on the parameter.
7. Find a set of new parameters that should minimize the difference between data and simulation, assuming linear dependence of each voltage scan point on each parameter.
8. Repeat the process with this new set of parameters.

Table 1 lists one set of beam conditions that has been subjected to this method. All of these data were taken on the same day, at a beam energy of 5.3GeV. Note that it includes 20 and 45 bunch trains at different bunch currents,

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TE Wave Measurements at CesrTA*

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Abstract

TE Wave measurement stations have been installed in the L0 and L3 regions of CesrTA. The L0 region has quasi-rectangular beam pipe and is the location of 6 superconducting wiggler magnets. The L3 region has round beam pipe with a chicane dipole magnet (from PEPII). At both locations, coaxial relays are used to multiplex an rf signal from a signal generator output, through the beam pipe, to the input of a spectrum analyzer. Software is used to monitor accelerator conditions and can be triggered to take data on demand, or on changes in conditions such as beam current or wiggler fields. This paper will describe the TE Wave measurement technique, the installation of hardware at CesrTA and some measurement examples. It will also outline some problems in the interpretation of data, specifically the results of reflections and standing waves.

INTRODUCTION

Microwaves that are transmitted through a waveguide will be phase shifted by the presence of a plasma. The beam pipe of an accelerator, although not an ideal waveguide, can also transmit microwaves and the electron cloud produced by a train of bunches will phase shift microwaves transmitted through the beam pipe. Since the cloud lifetime is a fraction of a revolution period at CesrTA, a phase modulation of the carrier is produced at the beam revolution frequency. This results in phase modulation sidebands of the received carrier frequency, spaced at the revolution frequency of 390kHz [1].

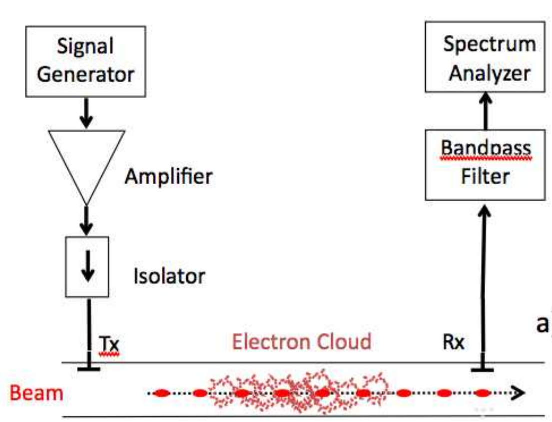

Figure 1: The basic TE Wave technique: a carrier is injected at Tx and the modulated signal detected at Rx.

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Beam position monitor (BPM) button detectors are used to couple microwaves into and out of the beam pipe. These detectors were originally installed at many location around CesrTA for the purpose of orbit and trajectory measurements. Some of these buttons were borrowed from the BPM system; others were installed specifically for TE Wave measurements. Thus far, we have only used the transverse electric $TE_{1,0}$ mode, since it is relatively easy to excite in the beam pipe and has a maximum electric field in the center of the pipe. A sketch of the method of coupling is given in figure 2. For convenience in making combinations of measurements, a transmitting and receiving pair are available at each location. While hybrid combiners can be used, many of the detectors at CesrTA use 0 degree combiners, with cable lengths chosen to give a differential signal at the desired frequency, usually at about 2GHz.

Notice that the button pairs are offset from the center of the pipe. Given this geometry, it would also be possible to excite the $TE_{2,0}$ mode, but this higher frequency has not been used. The $TE_{1,0}$ mode is sensitive to the electron cloud near the beam, in the center of the pipe, while the $TE_{2,0}$ mode is not. Also, the 5 watt amplifier that we are presently using is limited to a little over 2GHz.

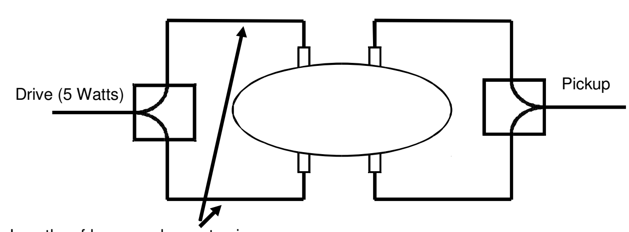

Figure 2: Top and bottom buttons are combined to give differential signals at the measurement frequency. This selects the TE microwaves while helping to reject direct beam signal sidebands. The button electrodes are ~1.7cm dia with a horizontal spacing of 2.8cm.

As an aid in analysis, the transmitted carrier is phase modulated at 410kHz with a depth of .001radian so that reference sidebands are visible near the cloud induced modulation sidebands. The carrier frequency is chosen to be somewhat above the cutoff frequency of the beam pipe's $TE_{1,0}$ mode, which at CesrTA is close to 2 GHz. As will be seen in a later section, the cutoff frequency for the beam pipe at CesrTA is not very clear and has many resonances. This feature has a significant effect on our ability to obtain a convincing calibration of the electron cloud density.

Progress on simulation of beam dynamics with electron cloud effects: An update*

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Abstract

This paper provides a brief review of progress on the simulation methods associated with studying the beam response to electron cloud effects. Comparison of results obtained from the program CMAD and other similar programs are reported. An update on recent developments and future planned upgrades to CMAD are discussed.

INTRODUCTION

Studying the influence of electron clouds on the dynamics of beams in storage rings has made steady progress in the last few years. Earlier methods involved using a constant focusing model with interacting points (IPs) at discrete locations around the ring. This was followed by modifying the transport mechanism to that of a simple FODO lattice in a ring with the strengths of the quadrupole magnets adjusted so that the betatron tunes of the model matched with the actual tunes. The latter model helps include several features not to be found in the former one. More recently, considerable progress had been made toward using the full lattice rather than an idealized one. The programs used to produce the results in this paper, namely HEADTAIL [1], WARP [2], and CMAD [3], are capable of all the simulation methods mentioned above.

Dedicated experiments are being performed on a regular basis at CesrTA to study the interaction between positron beams and electron clouds over a wide range of parameters [4]. These experiments are not only helping us understand the physics of electron effects, but also providing information on the extent of detail that needs to be introduced in order to reproduce the observed effects in the simulation. We have been regularly performing simulations using CMAD in our efforts to validate them with observations being made at CesrTA. The outcome of this effort will prove very valuable when studying future accelerators such as the ILC and CLIC damping rings, the super B factories and the upgrade of hadron machines such as the Fermilab MI, LHC and SPS.

The general method of performing these simulations involves tracking a certain number of beam particles around the ring with the help of transfer maps, and including electron cloud effects at discrete ”interacting points” (IPs) in the ring. The electron cloud is represented on a two dimensional grid and the beam represents a finite number of 2D grids referred to as slices. The beam is made to pass through the cloud slice by slice and both the electrons and beam particles are evolved dynamically with every cloud-beam slice interaction. This procedure is repeated at every IP. The electron cloud distribution gets refreshed after every interaction but the beam distribution evolves throughout the process. One also has the option of using a “frozen field” approximation where the electric field produced by the electron can be reused for a given time period before refreshing it again with a Poisson solver. The beam is usually tracked for several turns, the number depending upon the characteristic time scale of the phenomenon to be understood. For example, simulating head-tail interaction requires tracking for several synchrotron periods.

Despite the overall features of the simulation methods being fairly common, subtle differences exist in ways the calculations are carried out by different programs. For example, the program, CMAD divides the beam into slices such that the total charge on each slice is the same. Some other programs such as WARP and HEADTAIL divides the beam into slices of equal length. Both methods have their own advantages and disadvantages. Since the different programs have been developed independently by different groups, it is unlikely that a trivial mistake made in one of them would be repeated in another. Thus it very important to validate the results of such programs to (1) eliminate the possibility of a mistake or bug (2) to ensure that none of the subtle differences in calculation methods such as the one mentioned above lead to significant numerical errors.

There has been a continued effort in comparing results from different programs [5, 6] and this paper is meant to provide a summary of the latest on this. Besides comparing results from different programs, we are making an effort to study the effect of numerical noise on emittance growth. Emittance growth has been experimentally observed and very similar dependencies to physical parameters have been seen in simulations for CesrTA. At the same time, it is well known that particle-in-cell simulations cause numerical noise. The numerical noise could cause a particle confined on a trajectory exhibiting stable motion to artificially wander into a region of unstable motion. To study the possibility of this happening, one needs to compare emittance growth rates over a number of computational parameters. If emittance growth rate varies significantly with

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Effects of reflections on TE-wave measurements of electron cloud density *

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Abstract

The TE-wave transmission technique is a method for measuring the electron cloud (EC) density in an accelerator beam pipe. It involves transmitting an RF signal through the pipe and detecting the intensity of the phase modulation caused by the fluctuating EC density. Using physical and simulated data, the experiments described in this paper explore the effects of reflections on the phase advance of TE-waves. It is shown that introducing reflections to a waveguide can significantly distort phase measurements in some cases.

INTRODUCTION

This paper focuses on the TE-wave transmission method for determining Electron Cloud (EC) density. This method, first proposed for the SPS at CERN [1, 2], involves using beam position monitor (BPM) buttons to transmit electromagnetic waves at microwave-range frequencies through a length of beam pipe. The method later was demostrated to work at the SLAC PEP II Low Energy Ring by using solenoid field setting to control the electron cloud density. [3] We explore the influence of internal reflections within the beam pipe on these measurements. Accelerator beam pipes are far from ideal waveguides, and the EC is not the only perturbation that the TE-waves encounter. Numerous measurement instruments alter the beam pipe walls, and the overall dimensions of the pipe change periodically as the beam passes through different regions of CESR. Such effects are likely to cause reflections and, possibly, resonances. If some waves reflect between two protrusions one or more times before reaching a detector, they will undergo a greater phase advance than those that transmit without reflection. Under such circumstances, phase shift measurements would not accurately represent the EC if reflections are ignored. The experiments and simulations described in the following sections wereintended to help elucidate the effects of reflections on guided waves in accelerator beam pipes.

EXPERIMENTAL SETUP

The effects of nonuniformities on TE-wave transmission were studied with physical waveguides and with numerical simulation software.

Physical Model

The physical waveguides were copper pipes with rectangular cross sections. The pipes had flanges affixed to each end, allowing for pipes to be connected to one another to increase overall length. Transverse dimensions were 0.072m x 0.034m; pipe lengths were on the order of one meter. On some occasions, washers were added between flanges at the junction of two lengths of pipe to allow an opening for the introduction of nonuniformities such as metal strips or Lexan plastic. The presence of the narrow ($\sim$0.002m) space between adjoined pipes itself had no noticeable effect on the TE-wave signal.

TE-wave signals were generated and recorded with an Aeroflex 3281A spectrum analyzer for some experiments and a Hewlett Packard 8753B network analyzer for others. The signal reached the waveguide through a coaxial cable with a characteristic impedance of 50Ω, and was transmitted to the pipe through an antenna. A receiving antenna picked up the signal at the other end, returning the signal to the generator through a similar cable that terminated at a 50Ω resistor. The signal generator repeatedly swept through a specified frequency range (less than 3 GHz) with a sampling period on the order of tens of microseconds. Signal intensity was about -20 dBm.

Simulation

VORPAL, a particle-in-cell plasma simulation code [4], was used for the numerical models described in this paper. VORPAL software maps three-dimensional space onto a grid, assigning values for physical quantities such as EM field components to each set of coordinates. Boundary conditions, as well as physical attributes such as current density, may be programmed directly into the simulation code. Yee's algorithm [5] was employed in these simulations to solve Maxwell's equations for the coordinates at each time step. Particle positions and velocities were updated using the relativistic Boris algorithm [6].

The boundary conditions used for these simulations were characterized by two types of cross-sectional geometry and two types of end behavior. The cross-sections were either those of the rectangular pipe described above or of the CESR beampipe. The latter consists of two circular arcs (radius 0.075m) connected with flat side planes. It is about 0.090m from side to side and 0.050m between the apices

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TECHNIQUES FOR OBSERVING BEAM DYNAMICAL EFFECTS CAUSED BY THE PRESENCE OF ELECTRON CLOUDS*

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Abstract

During the last several years CESR has been studying the effects of electron clouds on stored beams in order to understand their impact on future linear-collider damping ring designs. One of the important issues is the way that the electron cloud alters the dynamics of bunches within the train. Techniques for observing the dynamical effects of beams interacting with the electron clouds have been developed. The methodology and examples of typical measurements are presented here.

OVERVIEW OF MEASUREMENT REQUIREMENTS

The storage ring CESR has been reconfigured and operates as a test accelerator Cesr-TA, studying the effects electron clouds in the presence of trains of positron or electron bunches[1]. With a 500 MHz RF acceleration system, CESR can store bunches with as little as a 2 nsec spacing, however for higher current operation the beam position monitor (CBPM) system and beam stabilizing feedback (BSF) systems are configured for bunches with at least a 4 nsec spacing. The most common bunch spacings employed during machine studies have been 4 nsec and 14 nsec, however higher multiples of 2 nsec spacing also have been utilized. The range of several Cesr-TA operating parameters are given in Table 1.

Table 1: Cesr-TA Operating Parameters

Parameter	Typical Range	Units
Beam Energy	2.0 - 5.3	GeV
Circulation Time	2.56×10^{-6}	sec
Number of Superconducting (SC) Wiggler Magnets	0 - 12	
Horizontal Emittance	1×10^{-6}	m-rad
Bunch Spacing	4, 6, 8, 10, 12, 14, …	
Maximum Bunch Charge	25.6	nC
Maximum Single Beam Current	3 – 200 (depending on beam species and powering of SC wigglers)	mA

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There are several beam parameters, which are particularly relevant for the study of electron cloud effects. Since the electron cloud can produce focusing of the stored beam, measuring the betatron tunes of bunches through the train gives information about the density of the cloud along the length of the train. The electron cloud can also produce unstable motion in bunches later in the train. To observe the unstable motion, it is necessary to detect the amplitude of the betatron frequency and any other frequencies representing different modes of oscillation (e.g. head-tail modes) of bunches within the train. The unstable motion may also result in enlargement of the vertical beam size, so the measurement of the vertical beam size for each bunch in the train is important.

MEASUREMENT HARDWARE

Several instruments have been added or modified for use with the CESR-TA program. They include the bunch-by-bunch beam position monitors, position detectors, which measure the tunes and detect some of the internal modes of oscillation, vertical beam size monitors and beam kickers.

Beam Position Monitors

During the Cesr-TA project the beam position monitoring system underwent an upgrade throughout the entire storage ring. The new CBPM system[2] has independent processing electronic readout modules at or near each of the quadrupole magnets, which can measure the position of every bunch, spaced by as little as 4 nsec, with better than 10 μm turn-by-turn resolution. As shown in figure 1, each module incorporates four front end boards with dual parallel 16-bit digitizer chains based on the Analog Devices AD9461 operating at digitization rates of 125 MHz. When operating with 4 nsec-spaced bunch trains, digitizing is interleaved between the two chains while, for times when CESR operates for synchrotron light users with dual species of 14 nsec-spaced bunches, each digitizer chain handles either the electron or positron bunches. The front-end boards have both a fixed gain amplifier optimized for precision measurements for bunches with approximately 1×10^{10} particles per bunch and a digital variable gain amplifier for measurements over a wide dynamic range. The triggering and timing configurations are carried out by a dedicated timing board integral to each module. This board takes a turn marker signal from the CESR master timing system and provides overall digitization rate control, adjustment capability for channel-to-channel digitization times, and global adjustment capability for the module digitization time

Synrad3D Photon propagation and scattering simulation *

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Abstract

As part of the Bmad software library, a program called Synrad3D has been written to track synchrotron radiation photons generated in storage rings. The purpose of the program is primarily to estimate the intensity and distribution of photon absorption sites, which are critical inputs to codes which model the growth of electron clouds. Synrad3D includes scattering from the vacuum chamber walls using X-ray data from an LBNL database. Synrad3D can handle any planar lattice and a wide variety of vacuum chamber profiles.

INTRODUCTION

The Bmad software library[1] has been used very successfully at Cornell for modeling relativistic charged particles in storage rings and linacs. Associated with this library are a number of programs used for lattice design and analysis. Recently, a new program that uses the Bmad library, called Synrad3D, has been developed to track synchrotron radiation photons generated in storage rings and linacs.

The motivation for developing Synrad3D was to estimate the intensity and distribution of photon absorption sites, which are critical inputs to codes which model the growth of electron clouds. Synrad3D includes scattering from the vacuum chamber walls using X-ray data from an LBNL database[2]. Synrad3D can handle any planar lattice and a wide variety of vacuum chamber profiles.

In the following sections, the general approach used in Synrad3D will be described, and two examples of its use will be presented.

APPROACH

Synrad3D uses Monte Carlo techniques to generate photons based on the standard synchrotron radiation formulas for dipoles, quadrupoles and wigglers, in the lattice of an accelerator. Any planar lattice can be handled. The lattice can be specified using Bmad, MAD, or XSIF formats. Photons are generated with respect to the particle beam's closed orbit, so the effect of variations in the orbit can be studied. In a linear accelerator lattice, since there is no closed orbit, the orbit is calculated from the user supplied initial orbit. The particle beam size is also taken into account when generating the photon starting positions. The emittance needed to calculate the beam size can be supplied by the user or is calculated from the standard radiation synchrotron radiation formulas.

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REFLECTIVITY MODEL

Photons are tracked to the wall, where the probability of being scattered is determined by the angle of incidence and the energy of the photon. The model used to determine the scattering angle, which is taken from an X-ray database [2], is shown in Fig. 1. This is for an aluminum vacuum chamber surface, but a model for a different surface could be used.

For comparison, we also show in the figure the relative synchrotron radiation spectra for a 2 GeV beam in an arc dipole and a wiggler at CesrTA. Also shown is a direct measurement [3] of reflectivity at 5° from an aluminum surface made at DAPHNE.

Currently, only specular reflection is included, but diffuse scattering can also be simulated by altering the reflectivity model.

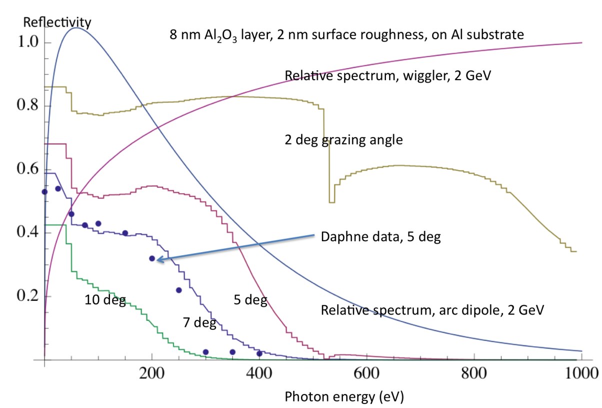

Figure 1: Reflectivity model from LBNL X-ray database

VACUUM CHAMBER MODEL

The vacuum chamber wall is characterized at a number of longitudinal positions by its cross-section. The cross section model is shown in Fig. 2. As shown in the figure, antechambers can be included. A vacuum chamber wall cross-section may also be characterized using a piecewise linear outline.

In between the cross-sections, linear interpolation or triangular meshing can be used. Linear interpolation is faster but is best suited for convex chamber shapes.

ELECTRON CLOUD MODELING RESULTS FOR TIME-RESOLVED SHIELDED PICKUP MEASUREMENTS AT CesrTA

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Abstract

The Cornell Electron Storage Ring Test Accelerator (CesrTA) program [1] includes investigations into electron cloud buildup, applying various mitigation techniques in custom vacuum chambers. Among these are two 1.1-m-long sections located symmetrically in the east and west arc regions. These chambers are equipped with pickup detectors shielded against the direct beam-induced signal. They detect cloud electrons migrating through an 18-mm-diameter pattern of holes in the top of the chamber. A digitizing oscilloscope is used to record the signals, providing time-resolved information on cloud development. Carbon-coated, TiN-coated and uncoated aluminum chambers have been tested. Electron and positron beams of 2.1, 4.0 and 5.3 GeV with a variety of bunch populations and spacings in steps of 4 and 14 ns have been used. Here we report on results from the ECLOUD modeling code which highlight the sensitivity of these measurements to model parameters such as the photoelectron azimuthal and energy distributions at production, and the secondary yield parameters including the true secondary, rediffused, and elastic yield values. In particular, witness bunch studies exhibit high sensitivity to the elastic yield by providing information on cloud decay times.

INTRODUCTION

The CesrTA program includes the installation of custom vacuum chambers with retarding-field-analyzer (RFA) ports and shielded pick-up detectors of the type shown in Fig. 1. The RFA port is shown on the left end, and two circular shielded pickup modules are shown on the right end of the chamber, each with two ports. In one case the two ports are placed longitudinally, with only one of the two being read out, and in the other case the two ports are arranged transversely, providing laterally segmented sensitivity to the cloud electrons. Thus the centers of buttons are 0, and ± 14 mm from the horizontal center of the chamber. The ports consist of 169 30-mil-diameter holes arranged in concentric circles up to a maximum diameter of 18 mm. The top of the vacuum chamber has been machined such that the holes point vertically. The transparency factor for vertical trajectories is 27%. The approximate 3:1 depth-to-diameter factor is chosen to effectively shield the detectors from the signal induced directly by the beam.

* Work supported by the U.S. National Science Foundation, the U.S. Department of Energy, and the Japan/USA Cooperation Program

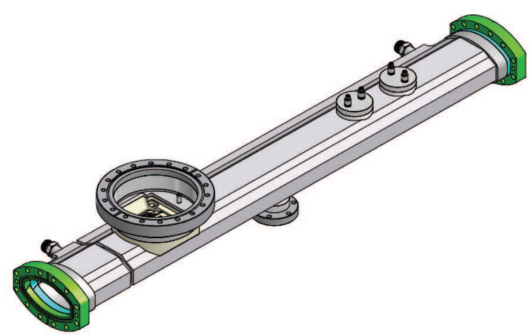

Figure 1: Custom vacuum chamber with RFA port and shielded pickup detectors.

Time-resolved measurements provide time structure information on cloud development, in contrast to the time-integrated RFA measurements [2]. However, they have relatively primitive energy selection, since they have no retarding grid and position segmentation is more coarse, the charge-collecting electrodes being of diameter 18 mm. Data has been recorded with biases of 0 and ± 50V relative to the vacuum chamber. The studies described here address exclusively the data a with bias $+50$ V in order to avoid contributions to the signal from secondary electrons escaping the pickup. Such secondaries generally carry kinetic energy insufficient to escape a 50 V bias. This choice of bias obviously provides sensitivity to cloud electrons which enter the port holes with low kinetic energy. The front-end readout electronics comprise operational amplifiers with 50 Ω input impedance and a gain factor of 100. Digitized oscilloscope traces are recorded with 0.1 ns step size.

USE OF A WEAK SOLENOIDAL MAGNETIC FIELD

One type of measurement which has been obtained with the shielded-pickup detectors is illustrated schematically

USING COHERENT TUNE SHIFTS TO EVALUATE ELECTRON CLOUD EFFECTS ON BEAM DYNAMICS AT CESRTA*

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Abstract

One technique used at CesrTA for studying the effects of electron clouds on beam dynamics is to measure electron and positron bunch tunes under a wide variety of beam energies, bunch charge, and bunch train configurations. Comparing the observed tunes with the predictions of various simulation programs allows the evaluation of important parameters in the cloud formation models. These simulations will be used to predict the behavior of the electron cloud in damping rings for future linear colliders.

THE MEASUREMENTS

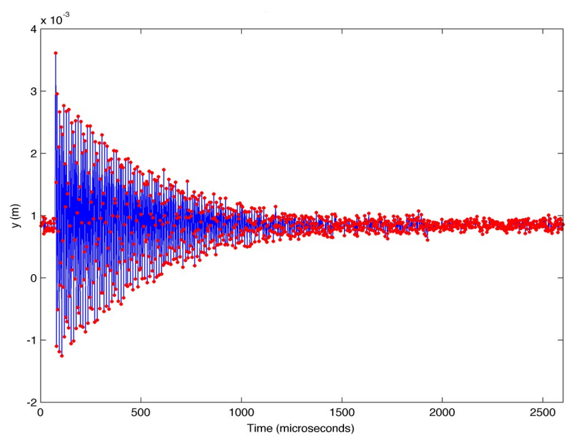

Figure 1: Sample beam position data.

Beams were set into oscillation by displacing them horizontally or vertically for one turn. We measure their turn-by-turn positions at up to six places around the ring for up to 4096 (but typically 1024) turns, and then Fourier transform. Tunes of the bunches of the cloud-inducing train and of “witness” bunches spaced 14 to 490 nsec after the train's passage allowed the cloud buildup and decay to be followed. Figure 1 shows the vertical displacement vs. time taken at one of the six beam position monitors used for this measurement. The 1024 red dots represent the y displacement of bunch 1 on successive turns around the CESR ring. A measurement involves six beam position monitors times 45 bunches. The tune shifts we use are the tunes of subsequent bunches minus the tune of the first bunch. We are tacitly assuming that the cloud dissipates in the 2.5 μsec it takes for the first bunch to go around the ring.

DETERMINING PARAMETERS

Initial parameters for driving the POSINST[1] simulations were determined by trial and error on measurements made at 1.9 GeV with 1.2×10^{10} positrons per bunch. In simulating the ring-averaged tune shifts, we ignored all ring elements except the drift regions and the dipoles, and used the calculated number of synchrorotron-radiated photons weighted by beta values[2]. The parameters we varied and their initial values were

· Total SEY yield (2.0)

· Energy at which the SEY is maximal (310 eV)

· Elastic SEY peak (0.5)

· Quantum efficiency of photoelectron production (0.12)

· Fraction of photons reflected (0.15)

· Yield of rediffused electrons (0.19)

54 data runs with electron and positron beams at 1.9, 2.1, 4.0, and 5.3 GeV energy, in trains of 3 to 45 bunches, with bunch populations of 0.32 to 2.60×10^{10} were simulated and matched to the data. All six parameters were varied ~±10% individually and in selected pairs. As an example, shown in figure 2 are data (in black) for a 21-bunch train of 0.8×10^{10} positrons per bunch at 2.1 GeV followed by 12 witness bunches. Three different POSINST simulations (in color) with total secondary emission yields of 1.8 , 2.0 (nominal), and 2.2 were run.

The program did not lead to a significantly improved parameter set because 1) the original set did surprisingly well describing all data and 2) it is hard to find an optimum in a 6-dimensional space when the parameters are highly correlated and the error bars on the data are not reliably determined.

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CesrTA LOW EMITTANCE TUNING*

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Abstract

Low emittance tuning and characterization of electron cloud phenomena are central to the CesrTA R&D program. A small vertical emittance is required in order to be sensitive to the emittance-diluting effects of the electron cloud. We have developed techniques to systematically and efficiently compensate optical and alignment errors that are the sources of vertical emittance. Beam–based measurements are utilized for centering Beam Position Monitors (BPMs) with respect to adjacent quadrupoles, determining relative gains of BPM button electrodes, and measuring BPM tilts. These calibrations allow for precision measurement of transverse coupling and vertical dispersion. Achieving low emittance also requires the tune plane be relatively clear of nonlinear coupling resonances associated with sextupoles. We report on tests of a sextupole distribution designed to minimize resonance-driving terms. We also report on beam-based measurements of sextupole strengths.

BEAM BASED QUADRUPOLE CENTER MEASUREMENT

The Beam Position Monitors (BPMs) are referenced with respect to the center of their adjacent quadrupole magnets. Magnet survey and repositioning is an ongoing process, therefore it is essential that beam-based calibration of BPM offsets require a minimum of beam time. The new CesrTA BPM system[1] allows for simultaneous measurement of the orbit and betatron phase at each BPM. With this measurement technique, orbit and phase data taken at two quadrupole settings can be combined quickly to accurately determine the quadrupole center with respect to BPM center. This reduces the number of orbit difference measurements that need to be taken, and therefore reduces the time required to center BPMs.

The procedure for centering quadrupoles is illustrated in Figure 1-3.

1. Begin with a model of the lattice. Measure the orbit and betatron phase and fit the model betatron phase advance to the measured phase advance by varying the strengths of the model quadrupoles as shown in Fig. 1. This will be referred to as the base fit.

2. Change the strength of the target quadrupole in the machine and remeasure phase and orbit. In the model, vary the strength of that quadrupole until the newly–measured and model phases agree as shown in Fig. 2.

3. Horizontal and vertical kicks are superimposed on the target quadrupole. Starting from the model fit to the second data set, vary these kicks such that the modeled orbit difference matches the measured difference as shown in Fig. 3.

The orbit difference dx is

$$dx(s) = (\tilde{x} - x_0(\bar{s}))dK_1 L \frac{\sqrt{\beta(s)\beta(\bar{s})}}{2\sin\pi\nu}\cos(|\phi(s) - \phi(\bar{s})| - \pi\nu)$$

and the quadrupole center is given by

$$\tilde{x} = \frac{\text{kick}}{L\,dK_1} + x_0(\bar{s})$$

The ability to simultaneously measure the orbit and betatron phase provides a fast and accurate method for measuring quadrupole centers with respect to BPMs. This technique avoids problems with hysteresis and quadrupole calibration inaccuracies. Presently, a single iteration of this procedure takes roughly 20 seconds.

BEAM-BASED MEASUREMENT OF BPM ELECTRODE GAINS AND TILTS

Non-uniformity in the response of BPM electrodes and physical misalignment or tilts of the BPMs will introduce a systematic error into measurements of coupling and vertical dispersion. We can determine the relative gain of the four electrode BPMs by sampling the response of the electrodes to a beam that is scanned over the cross-section of the BPM[2]. The sampling is accomplished by resonantly exciting the horizontal and vertical normal modes of the beam and collecting turn-by-turn position measurements. The best-fit gains based on three distinct sets of turn-by-turn data are combined and shown in Figure 4.

The distribution of the fitted gains is shown in Figure 5

Determination of BPM tilts

The transverse coupling is measured by resonant excitation of the horizontal and vertical normal modes. Measurement of the relative phase and amplitude of the motion at the normal mode frequencies at each of the BPMs gives the $\bar{C}_{11}$, $\bar{C}_{12}$, and $\bar{C}_{22}$ elements of the coupling matrix. The measured coupling after correcting $\bar{C}_{12}$ but before gain correction is shown in Figure 6. Coupling after gain correction is shown in Figure 7. $\bar{C}_{12}$ measures the out-of-phase component of the coupling and is therefore very nearly independent of BPM tilts. $\bar{C}_{11}$ and $\bar{C}_{22}$ measure the in-phase components. If $\bar{C}_{12}$ is small, then $\bar{C}_{22}$ is a measure of the BPM tilt. We may therefore fit the gain-corrected coupling data to determine BPM tilts. The fitted tilts are shown in Figure 8.

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IN SITU SEY MEASUREMENTS AT CesrTA*

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Abstract

Two in-situ secondary electron yield (SEY) measurement stations were developed at Wilson Laboratory and installed in the L3 section of the Cornell Electron Storage Ring (CESR) in order to track the evolution over time of the SEY peaks of technical surfaces in an accelerator environment, with exposure to direct and scattered synchrotron radiation (SR). Samples were positioned flush with the inner diameter of the beam pipe with one positioned horizontally in the radiation stripe, exposing the sample to direct and scattered radiation, and one at 45° beneath the radiation stripe, exposing the sample to only scattered radiation. Additionally, both samples are exposed to bombardment by electrons from the "electron cloud" in the stainless steel beam pipe. In this paper, we describe the in-situ SEY measurement systems and the initial results on bare aluminum (6061-T6) and TiN-coated aluminum samples.

INTRODUCTION

One mechanism that can limit the performance of a particle accelerator is associated with the formation of an electron cloud inside the vacuum chamber. The electron cloud can disrupt the beam, limit the current, or degrade the beam quality. Electron cloud issues are particularly important for rings, because the impact of small perturbations from the cloud can have a large effect on the stored beam over many turns around the ring. Consequently, control and mitigation of electron cloud effects are an important part of the design effort for the damping rings for the International Linear Collider (ILC) [1] and other future accelerators.

Emission of secondary electrons from the inside surface of the accelerator vacuum chamber is one source of electrons for the cloud. A key quantity is the secondary electron yield (SEY), the ratio of emitted secondary electrons to incident "primary" electrons striking the surface. The SEY depends on the kinetic energy and incident angle of the primary electrons. Because the secondary electrons must leave the surface, the surface characteristics, including surface contaminants, influence the SEY. In order to make accurate predictions about electron cloud effects, it is important to know the SEY under realistic surface conditions.

Because secondary emission happens at the surface, it is possible to change the SEY of a material. Methods to reduce the SEY include coatings [2], grooving the surface [3], and processing the surface with electron bombardment [4]. Lowering the SEY can reduce the number of secondaries contributing to the electron cloud, thereby lessening the adverse impact on the beam.

A research program with the Cornell Electron Storage Ring (CESR) was established to study effects that will impact future rings such as the ILC damping rings. Electron cloud studies are a major part of this CESR Test Accelerator (CesrTA) program [5]. One aspect of the CesrTA program is the study of the SEY of technical surfaces in a realistic accelerator environment.

SEY studies have been previously done on samples exposed to an accelerator environment [2]. However, the time between measurements has often been several months, because the sample must be physically removed from the accelerator vacuum chamber for SEY analysis, an operation which can be done only infrequently. Hence, the SEY as a function of SR dose is difficult to determine with good resolution. One goal of the CesrTA program was to study surface conditioning with improved time resolution.

In our studies, we measure the SEY on samples as a function of the SR dose from a bending magnet, using an in-situ SEY station to take measurements roughly once a week. The typical CESR energy is 5.3 GeV and typical beam currents are 200 mA for electrons and 180 mA for positrons. The SEY station is located in CESR L3 East, so the SEY samples are exposed predominantly to SR from the electron beam. As shown in Figure 1, measurements are taken at 9 points of a 3×3 grid (6.4 mm $\times$ 6.4 mm) on

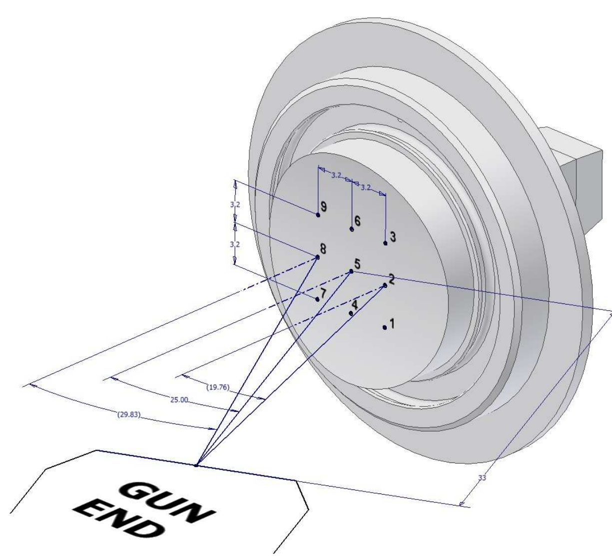

Figure 1: Isometric view of a sample showing the 9 grid points where the SEY is measured.

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ANALYSIS OF SYNCHROTRON RADIATION USING SYNRAD3D AND PLANS TO CREATE A PHOTOEMISSION MODEL

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Abstract

Using current models of synchrotron radiation production and propagation, work is being done on a realistic photoelectron model from Retarding Field Analyzer (RFA) data. This proposed photoelectron production model will be better able to predict the level of electron cloud density in the vacuum chamber. In this paper SYNRAD3D is used to simulate the production and propagation of photon radiation in in International Linear Collider(ILC) Damping Rings. Analysis of this radiation with photon reflections off the chamber wall has been completed. This data will be used in the future to study photoelectron production as a function of parameters such as minimum absorbed photon energy and lattice element type. The results show that wigglers are regions which create the most photons and therefore have the ability to produce the most photoelectrons.

INTRODUCTION

SYNRAD3D provides a 3-dimensional model of synchrotron radiation, allowing a study of radiation reflection around the perimeter of the chamber as a function of the longitudinal position, s [1]. This program will allow us to study various antechamber designs and other photon absorbers. The final goal is to have a photoelectron model which includes photoelectron emission energy. Comparison will be made to the photoemission in various lattice elements such as dipoles and wigglers to RFA data.

SYNRAD3D

SYNRAD3D is an extension of SYNRAD, a 2-dimensional program which calculates the radiation on the inner and outer most point of the chamber wall. SYNRAD3D uses the Better Methodical Accelerator Design(BMAD) library [1]. SYNRAD3D is a photon production and propagation code, which tracks photons. It uses radiation integrals to determine the probable initial position and energy of a specified number of photons around the ring. It then tracks the photons as they move and reflect in the chamber. SYNRAD3D uses data from the Berkeley's Center for X-Ray Optics to determine the probability of reflection and absorption of each photon as a function of energy and grazing angle (seen in Figure 1 [2]) As seen in the figure the chamber wall is assumed to have an 8 nm Al_2O_3 (aluminum oxide) layer on an Al substrate with 2nm surface roughness. Currently all scatters are specular and elastic.

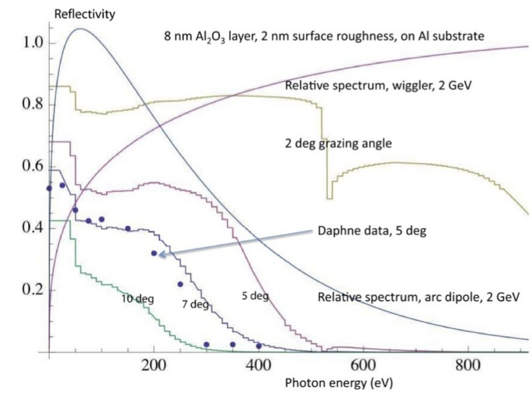

Figure 1: An example of the reflectivity of photons on a specified surface. The reflectivity is based on the photon energy and grazing angle. Data was taken from the Berkeley Center for X-Ray Optics [2] [1].

INTERNATIONAL LINEAR COLLIDER (ILC)

To decrease the cost of the ILC damping rings (DR) it has been proposed to decrease the circumference of the damping rings from 6.4 km to 3.2 km [4]. One of the concerns with a smaller ring is the build up of the electron cloud from photoemission and other effects.

A general schematic of the DR can be seen in figure 2 [4]. The main source of synchrotron radiation are wigglers (to cool the beam) and sector bends in the arcs. To make a better comparison of the photon flux between the current and proposed damping ring the first cut in data ignored all photons with energy less then 4 eV. 4eV was chosen because it is the work function for the chamber wall, which is Al. In addition to the energy cut all wiggler magnets are modeled as alternating dipoles and drifts. Normalization was done using equation 1.

$$\text{photons/m/beam particle} = \frac{N_L * I}{L} \quad (1)$$

L is the length of the section to average over, and N_L is the number of photons incident on the wall in length L [1]

Analysis for the 3.2 km proposed ring (DSB3)

For the analysis of the 3.2 km ring 101,000 photons were generated. Figure 3 a&b show the normalized photon flux along the inside and outside wall of the damping ring, respectively, where s = 0 is between the injection and extraction points as seen in Figure 2. The main feature of the

ACCURATE SIMULATION OF THE ELECTRON CLOUD IN THE FERMILAB MAIN INJECTOR WITH VORPAL*

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Abstract

We present results from a precision simulation of the electron cloud (EC) in the Fermilab Main Injector using the code VORPAL. This is a fully 3d and self consistent treatment of the EC. Both distributions of electrons in 6D phase-space and E.M. field maps have been generated. This has been done for various configurations of the magnetic fields found around the machine have been studied. Plasma waves associated to the fluctuation density of the cloud have been analyzed. Our results are compared with those obtained with the POSINST code. The response of a Retarding Field Analyzer (RFA) to the EC has been simulated, as well as the more challenging microwave absorption experiment. Definite predictions of their exact response are difficult to obtain, mostly because of the uncertainties in the secondary emission yield and, in the case of the RFA, because of the sensitivity of the electron collection efficiency to unknown stray magnetic fields. Nonetheless, our simulations do provide guidance to the experimental program.

MOTIVATION

The electron cloud (EC) phenomena in high intensity proton storage rings and synchrotrons can limit the performance of such machines [1], [3]. This phenomena is characterized by an exponential growth of the number of low energy (eV) electrons emitted at the surface of the beam pipe wall. Such electrons are then accelerated by the field induced by the passage of the proton beam, which itself causes more secondary emission of electrons at the beam pipe wall. This is reminiscent to the multipacting phenomena observed in R.F. cavities, where one field emission region is replaced the proton beam itself. Such EC can generate fast beam instabilities, as they strongly perturb the electric field in the vicinity of the proton beam. This has been predicted by many models, observed in many e^+e^- storage rings, and studied in detail at CesrTA [4]. The Fermilab Main Injector (MI) is no exception. In the "Project X"[5] era, the delivered beam power on target will go from the current value of 300 MW to 2.1 GW. In a first upgrade, the MI cycle time will be reduced to 1.33 seconds from its current value of 2.2 seconds, thereby increasing the 120 GeV beam power to 700 kW. The second upgrade will require a new injector as the bunch charge will increase by a factor of three. While the MI currently delivers the designed beam intensity, we are concerned that a significant increase of the bunch charge will trigger the formation of a much denser EC, and significantly increase beam losses due to fast instabilities that are hard to control.

Therefore, an R&D initiative has started aiming at providing a robust mitigation strategy. Unlike some e^+e^- storage rings (e.g. KEKB), the MI has relatively short straight sections compared to the length of the arcs, which almost entirely consist of dipoles and quadrupole. Thus, an EC solution based on the use of solenoidal fields that confine the EC away from the beam is simply not applicable. A well established solution would consist in coating the beam pipe with a thin layer of either TiN or amorphous carbon [10], but such a solution could be expensive. Thus, despite the success of numerous previous effort in describing the EC, further R&D on the EC in the MI is well justified, because both the phenomenology and the mitigation strategy have always been site specific.

Furthermore, we present here detailed results on the EC morphology and related fields. This is acccomplished using VORPAL [11]. This is a code used for accurate simulation of plasma and beams problems where complicated collective effects are important. Unlike POSINST [3, 7] and QuickPic [6], two distinct codes originally written to simulate "positrons beam instabilities" and used extensively to simulate the response of the beam to the perturbation due to EC, VORPAL is a fully consistent, 3D electromagnetic code using relativistic electrons. Results on a specific benchmark POSINST vs VORPAL will be briefly discussed. While VORPAL allows us to obtain a more precise description of the EC, this can only be done for relatively short sections (2 to 16 m.) of the machine, due to computational limitations. Over such short distances and for relatively short periods of time compared to a full synchrotron cycle, ($\approx 1.0\,\mu$ sec), the electromagnetic fields induced by the EC are not strong enough to perturb the trajectories of the ≈ 20 GeV proton beam. Therefore, the proton beam is assumed to be perfectly rigid, i.e., no changes to its associated current occur throughout the simulation.[1]

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[1] Evidently, this is not true over long distances and many turns. However, our simulation produces field maps that can and hopefully will be

MODELING ELECTRON CLOUD BUILDUP AND MICROWAVE DIAGNOSTICS USING VORPAL *

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Abstract

Electron cloud effect may seriously limit future accelerator performance when electron plasmas build up enough to cause instabilities in beams. Detailed simulations of electron cloud buildup, effects on beams, and mitigation will increase future accelerator performance and provide aid in the effective design of future accelerators. We present results of recent VORPAL simulations directed at modeling of microwave diagnostic experiments for measuring electron cloud effect. We focus on the effects of spatial non-uniformity of electron clouds on phase shift measurements and on directly correlating observed side-band amplitudes with cloud density.

SIMULATION OF ELECTRON CLOUDS ENHANCES ACCELERATOR PERFORMANCE

VORPAL

The VORPAL [1] code, a 3D finite-difference time-domain (FDTD) electromagnetics code, is designed for massively parallel distributed computing as well as for running in serial on desktop computers. Domain decomposition, a technique in which a large computational physical domain is split up into smaller pieces, which are then distributed on many different processes, is a powerful method for parallel computing, and is used extensively in VORPAL in order to improved computational performance and enable researchers to address very large simulation problems with short time scale resolution. VORPAL is appropriate for simulating traveling-wave diagnostics of electron clouds, both because it has the ability to span large spatial scales (determined by the system geometry) as well as short time scales (determined by the frequency of the rf and the spatial resolution), and because it can capture 3-Dimensional effects, such as the role of quadrupole magnets on electron density profiles. VORPAL also includes full models for complex electromagnetic-particle-boundary interactions, including embedded cut-cell geometry (2nd order accurate for the calculation of EM fields), self-consistent EM fields, including the effects of space charge, secondary electron emission, and self-consistent kinetic particle motion.

Figure (1) shows a typical VORPAL simulation layout. The beam pipe can be constructed with different cross-sections, such as circular, elliptical, or rectangular, depending on the system being modeled. The ends of the simulation domain contain Matched Amplitude Layers (MALs) or Perfectly Matched Layers (PMLs) which absorb EM waves and damp them out so that there are not numerical reflections off the end of the simulation domain. The electron cloud is represented by kinetic particles which evolve under the influence of electric and magnetic fields from various sources, such as a simulated rf signal traveling down the beam pipe, a beam current, externally defined magnetic fields, and space charge. Typically, an artificial current density at one end of the simulation, oscillating at the rf frequency, is added to generate a traveling rf signal, which passes through the electron cloud and can be measured on the other side. Phase shifts induced in this rf signal can be measured by comparing simulations with and without an electron cloud. In addition, long time-scale simulations to address electron cloud buildup under different conditions (external magnetic field configurations, secondary electron yield profiles, simulation geometry) have been carried out using a similar simulation setup, and are reported elsewhere [2].

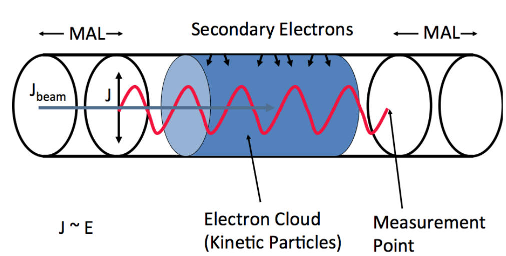

Figure 1: Typical diagram of a VORPAL electron cloud and microwave diagnostic simulation.

Simulation of Traveling Wave rf Diagnostics

In the simulation setup described above, traveling rf waves are emitted from the source current in both directions. The backward-propagating wave is almost immediately absorbed by the MAL or PML which is specifi-

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TRAPPING OF ELECTRON CLOUD IN ILC/CESRTA QUADRUPOLE AND SEXTUPOLE MAGNETS

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Abstract

The Cornell Electron Storage Ring (CESR) has been reconfigured as an ultra low emittance damping ring for use as a test accelerator (CesrTA) for International Linear Collider (ILC) damping ring R&D [1]. One of the primary goals of the CesrTA program is to investigate the interaction of the electron cloud with low emittance positron beam to explore methods to suppress the electron cloud, develop suitable advanced instrumentation required for these experimental studies and benchmark predictions by simulation codes. This paper reports the simulation of the electron-cloud formation in CESRTA and ILC quadrupole and sextupole magnets using the 3D code CLOUDLAND. We found that electrons can be trapped with a long lifetime in a quadrupole and sextupole magnet due to the mirror field trapping mechanism. We study the effects of magnet strength, bunch current, ante-chamber effect, bunch spacing effect and secondary emission yield (SEY) in great detail.

INTRODUCTION

The development of an electron cloud in magnets is the main concern where a weak solenoid field is not effective. Quadrupole and sextupole magnets have mirror field configurations which may trap electrons by the mirror field trapping mechanism [2]. Fig.1 shows the orbit of a trapped electron in a quadrupole magnet. The electron makes gyration motion (called transverse motion) and also moves along the field line (called longitudinal motion). At the mirror point (middle of the field line), there is a maximum longitudinal energy and minimum transverse energy. When the electron moves away from the mirror point, its longitudinal energy reduces and the transverse energy increases as the magnetic field increases. If the magnetic field is strong enough, the longitudinal energy becomes zero at one point and then the electron is turned back by the strong field. Note that the electrons are trapped in the region near the middle of the field lines. Although all quadrupole and sextupole magnets can trap electrons in principle, the trapping mechanism is also greatly sensitive to the detail dynamics of the electrons [3]. Both the positron beam and the spacing charge force of electron cloud itself play important roles. This paper reports the simulation of electron cloud in CESRTA/ILC quadrupole and sextupole magnets. Table 1 shows the main parameters used in the simulation.

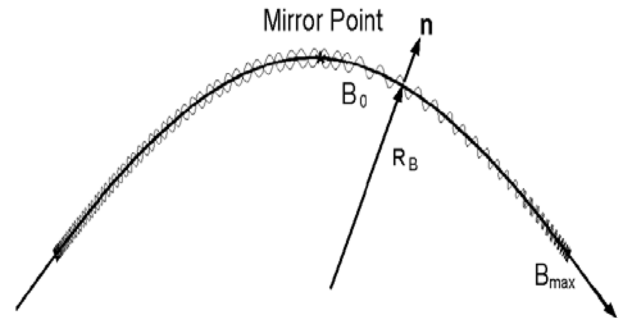

Fig.1: Trapping of an electron by a mirror field (quadrupole field here) from CLOUDLAND code

Table 1: Main simulation parameters for CESRTA and ILC positron damping ring

Description	CESRTA	ILC
Beam energy (GeV)	5.289	5.0
Circumference (m)	768.43	3238
Bunch length (mm)	15.0/17.24	6.0
Beam size (mm)	1.56/0.15	0.27/0.005
Bunch spacing (ns)	14	3/6
Bunch number per train	45	45
Bunch intensity ($\times 10^{10}$)	0.75~1.6	2.1

TRAPPING IN CESRTA QUADRUPOLE

In principle, electron cloud can be trapped in a quadrupole magnet due to the mirror field trapping. However, certain conditions are required for a deep trapping [3]. Electron cloud in a quadrupole magnet is sensitive to other parameters besides secondary emission, bunch current and beam filling pattern. Fig. 2 shows the build-up of the electron cloud in a quadrupole magnet with a field gradient of 0.517 *T/m*. The beam has one bunch train consisting of 45 bunches followed by a long train gap of 1.93μs. The electron cloud reaches saturation level after 10 turns (25μs). In contrast to the dipole magnet case, where electrons couldn't survive such long train gap, the electrons in quadrupole magnets surviving from the long train gap are trapped electrons. About 50% electrons can survive from the long gap as shown in the figure. Fig. 3 shows the evolution of an electron cloud during the train gap. The 1st picture in the figure is the

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ELECTRON CLOUD STUDIES IN THE FERMILAB MAIN INJECTOR USING MICROWAVE TRANSMISSION*

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Abstract

In this paper, we present recent results from our measurement at the Fermilab Main Injector through microwave transmission in a beam pipe. We present three types of measurement techniques. In the first technique, we use time-resolved direct phase shift measurement to measure the e-cloud density. In the second and third techniques, we look for side bands in the frequency spectrum with or without frequency span by collecting turns of data. We present experimental results taken from MI40 and MI52 test section of the main injector.

INTRODUCTION

Project X is a multi-megawatt proton facility planned for construction at Fermilab. To achieve this goal, high current proton beam will have to be transported through the main injector [1]. The main injector is a synchrotron that accelerates 53 MHz proton bunches from 8 GeV to 120-150 GeV. During the passage of a high intensity proton bunch, low energy background electrons can interact with the proton bunch and develop instabilities. This could potentially limit the performance of the accelerator by increasing the vacuum pressure, emittance growth, shifting the tune of the machine among other things. Hence it is important to measure, model and mitigate electron cloud in such machines.

In this work, we report our results from measuring electron cloud density using microwave techniques in the main injector at the Fermilab. We begin with a brief introduction to the principle behind the measurement and then discuss three different techniques to measure e-cloud density. Finally, we summarize our results and conclude by suggesting future plans.

Microwave measurement Principle

By sending EM waves through an electron cloud of uniform distribution and measuring the phase shift of the EM waves, the electron cloud density can be measured. The phase shift φ of an electromagnetic wave of frequency ω through a uniform, cold plasma (of plasma frequency ω_p and density ρ) per unit length is given by [2]:

$$\frac{\emptyset}{L} = \frac{\omega_p^2}{2c\sqrt{\omega^2 - \omega_c^2}}; \;\; \omega_p^2 = 4\pi\rho r_e c^2$$

where c is the speed of light, r_e is the classical electron radius, and ω_c is the cut-off frequency of the pipe. The above formula assumes that the e-cloud density is static but in the main injector and other machines, the e-cloud density varies as a function of time. The reason being the proton bunch which generates the electron cloud has a time pattern. Hence, the e-cloud density varies as a function of time. So, sending a carrier wave into the cloud should result in a phase-modulation of the carrier wave. In other words, in frequency spectrum, we expect to see sidebands to the carrier [3]. By measuring the amplitude of the sideband, in theory, we can estimate the electron cloud density.

Here we summarize three different techniques used to measure e-cloud density in the main injector. The three techniques are called as direct phase shift, sideband spectrum and zero span measurement. All these techniques are based on the same general principle of measuring the phase shift of the carrier wave. In the sideband spectrum measurement, we send a carrier wave (1.5 GHz) and any phase modulation will show up as a side band. In the zero span measurement, we set the spectrum analyzer to the expected side band frequency (measured using the sideband spectrum technique) and collect data over the full injector cycle. In other words, we make power measurement at a single frequency. Any increase in the amplitude of the signal at this frequency will then indicate phase modulation. The direct phase shift measurement is similar to microwave interferometry. The carrier is split into two paths: one is sent through the e-cloud and to the receiver while the other is sent directly to the receiver. At the receiver, both the signals are demodulated to baseband, mixed and the mixer output recorded in a scope and time averaged to yield the phase shift. We use a filter to minimize the beam induced AM. Additionally, as this signal occurs at random phase each turn with respect to the microwave carrier, it simply averages away out many turns.

*Operated by Fermi Reserach Alliance, LLC under Contract No. DE-AC02-07CH11359 with US Department of Energy
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The Ecloud Measurement Setup in the Main Injector*

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Abstract

An ecloud measurement setup was installed in a straight section of the Main Injector in 2009. The goal of the setup was to compare the characteristics of different beam pipe coatings when subjected to proton beam. The setup consists of one coated and one uncoated beam pipe with the same physical dimensions installed at the same location. Four RFAs (retarding field analyzers) and three BPMs (beam position monitors) used for microwave measurements have been used to measure the ecloud densities. The RFAs have performed very well and have collected both the time evolution and energy distribution of the ecloud for bare and two types of beam pipe coatings.

INTRODUCTION

Ecloud has been observed in many high intensity accelerators which can limit the amount of current that can be stored in them. In particular, for ProjectX, the amount of beam current that will be stored in the MI (Main Injector) will be $\sim 160 \times 10^{12}$ protons while the present maximum intensity is $\sim 45 \times 10^{12}$ protons which is about $3.5\times$ less beam. Although ecloud has been observed in the MI, it has not caused instabilities at the present running conditions. However, there is no guarantee that instabilities caused by ecloud will not be a problem at ProjectX intensities. Therefore, a program has been started to study the ecloud effects with both computer simulations and experiments.

In this papers, we will be focusing our attention on how coatings can affect the production of secondary electrons. We have installed an ecloud measurement setup in a straight section of MI which consists of one coated and one uncoated beam pipe with the same physical dimensions and at the same location, together with four retarding field analyzers (RFAs) and three sets of beam position monitors (BPMs) which can be used for the microwave measurements.

In the following sections we will introduce the installed setup and discuss the design of the RFAs and briefly touch on the microwave measurements. The experimental results of both titanium nitride (TiN) and amorphous carbon (aC) coated beam pipes when conditioned by proton beams will also be discussed here.

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Oral Session

MAIN INJECTOR

The MI is a 2 mile ring which nominally ramps protons from 8 GeV to 120 GeV for the experiments and for antiproton production or at 150 GeV for proton or anti-proton injection into the Tevatron. Figure 1 shows a bird's eye view of the Fermilab site and MI-52 where the ecloud measurement setup is located.

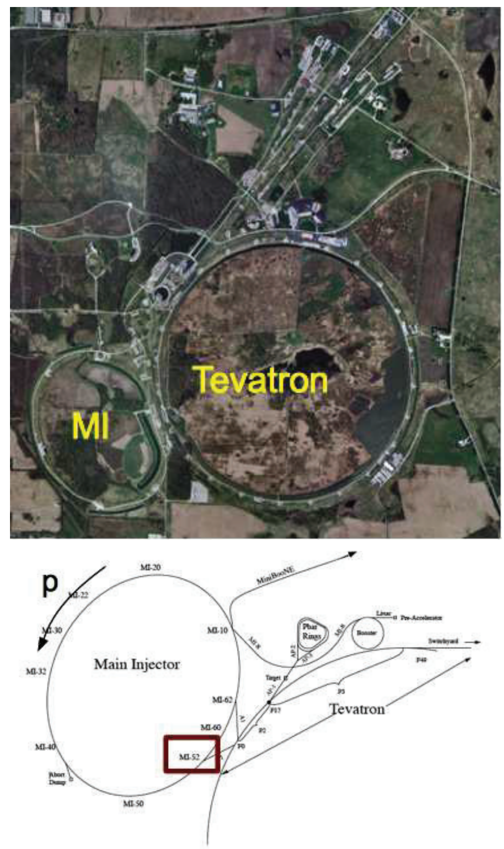

Figure 1: A bird's eye view of the Fermilab site and MI-52 where the the ecloud measurement setup is located.

The MI has many modes of operation. The highest proton intensity 40×10^{12} protons is achieved for the NuMI (Neutrinos from the Main Injector) experiment. In normal operations, NuMI is spilled from MI every 2.2s.

THE ECLOUD MEASUREMENT SETUP

The ecloud measurement setup is shown in Figure 2. The coated and uncoated beam pipes are 6" in diameter and are each 1 m long. The detectors on the setup are:

- RFAs. There are four RFAs installed. Three of the

ANALYSIS OF THE ELECTRON CLOUD DENSITY MEASUREMENT WITH RFA IN A POSITRON RING*

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Abstract

In a positron ring such as KEKB LER, clouding electrons receive an almost instantaneous kick from circulating bunches. Therefore, high energy electrons in the cloud are produced locally around the beam just after the interaction with the bunch. The authors gave an estimation of their density using a high energy electron current measured with RFA and a calculated volume neglecting their initial velocity before the interaction with the bunch [1][2]. To evaluate the accuracy of this estimation, the process of the measurement is analyzed using the phase space density for the motion of electrons in the transverse plane of the beam. The expressions that can evaluate the accuracy of the estimation with the help of simulation are obtained. One of the authors has shown that the accuracy for a drift space is within ±5% error [3]. For other applications such as in a solenoid field or in a quadruple field, the evaluation is not yet given. In addition to this discussion, some examples of the estimation of the electron cloud density with RFA are shown.

INTRODUCTION

The electron cloud in the accelerator ring of positively charged particles is one of serious obstacles to achieve a stable low emittance beam. The study of the electron cloud to clarify and to mitigate the effect is now a major issue for the design of the positron damping ring of ILC or for the upgrade of LHC. The positron storage ring of KEK B-Factory (LER), which was shutdown June 2010, had been suffering from the electron cloud problem in increasing the stored current to achieve a higher luminosity. During the study of the electron cloud in LER, a simple idea to estimate the density with a retarding field analyzer (RFA) attached to a vacuum chamber is developed.

The idea arises from the efforts to explain the measurement in a drift space. Most of bunches in LER are spaced by 6 ns (3 bucket space). The typical bunch population during collision experiment is around 7×10^{10}. The major part of electrons arrive at an RFA have low energies less than 20 eV. A time-resolved observation shows these low energy electrons arrive almost continuously except large train gaps. On the other hand high energy electrons, for example, with energies more than 2 keV, are observed as a rapidly changing current which has regular peaks corresponding to the bunch pattern [1].

Obviously the peak consists of electrons which get their energy through the interaction with the high electric field near a circulating bunch. Since the electric field of a relativistic positron bunch is contracted into the transverse plane of the beam, the resulting acceleration occurs essentially in this plane. The radius of the transverse area, where these high energy electrons stayed just before the interaction with the bunch, can be calculated from the bunch charge and the retarding bias with sufficient precision. A possible ambiguity due to the initial energies of electrons is small because the energy of most electrons before the interaction is less than few×10 eV. If the retarding bias is set so that electrons in the corresponding area can reach the duct wall before the next bunch arrives, from the pulse of electron current the density near the beam (and in front of the bunch) can be known. Usually, an RFA is set behind a small aperture of the duct wall. Therefore it cannot receive the whole electrons of the area but observes a finite portion of it. The estimation of this observed area is not simple because of the initial energies of electrons [3]. The point of our idea is to propose an approximation for the observed area to use the area obtained by assuming electrons are at rest before the interaction. Using the calculated observed area, the near beam electron cloud density (just before the interaction with a bunch) is estimated as:

$$\text{Density} = \frac{\text{No. of electron per bunch}}{\text{Observed area} \times \text{Detector length}}. \qquad (1)$$

This idea was first applied to drift spaces and gave a reasonable estimation of density [1]. The idea is further developed to apply for the measurement in a solenoid field and in a quadrupole magnetic field. The resulting estimation of the electron cloud density seems also reasonable [2].

In the following, the process of the high energy electron measurement with RFA is analysed using the phase space density of electrons and how the validity of the approximation adopted in our estimation can be checked with the help of the simulation on electron motion is shown. In addition the result of the density estimations under different types of a magnetic field is

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STATUS OF COLDDIAG: A COLD VACUUM CHAMBER FOR DIAGNOSTICS

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Abstract

One of the still open issues for the development of superconducting insertion devices is the understanding of the beam heat load. With the aim of measuring the beam heat load to a cold bore and the hope to gain a deeper understanding in the beam heat load mechanisms, a cold vacuum chamber for diagnostics is under construction. The following diagnostics will be implemented:

i) retarding field analyzers to measure the electron energy and flux,
ii) temperature sensors to measure the total heat load,
iii) pressure gauges,
iv) mass spectrometers to measure the gas content.

The inner vacuum chamber will be removable in order to test different geometries and materials. This will allow the installation of the cryostat in different synchrotron light sources. COLDDIAG will be built to fit in a short straight section at ANKA. A first installation at the synchrotron light source Diamond is foreseen in June 2011. Here we describe the technical design report of this device and the planned measurements with beam.

INTRODUCTION

Superconducting insertion devices (IDs) have higher fields for a given gap and period length compared with the state of the art technology of permanent magnet IDs. This technological solution is very interesting for synchrotron light sources since it permits to increase the brilliance and/or the photon energy at moderate costs. One of the key issues for the development of superconducting IDs is the understanding of the beam heat load to the cold vacuum chamber.

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Possible beam heat load sources are:

1) synchrotron radiation,
2) resistive wall heating,
3) electron and/or ion bombardment,
4) RF effects.

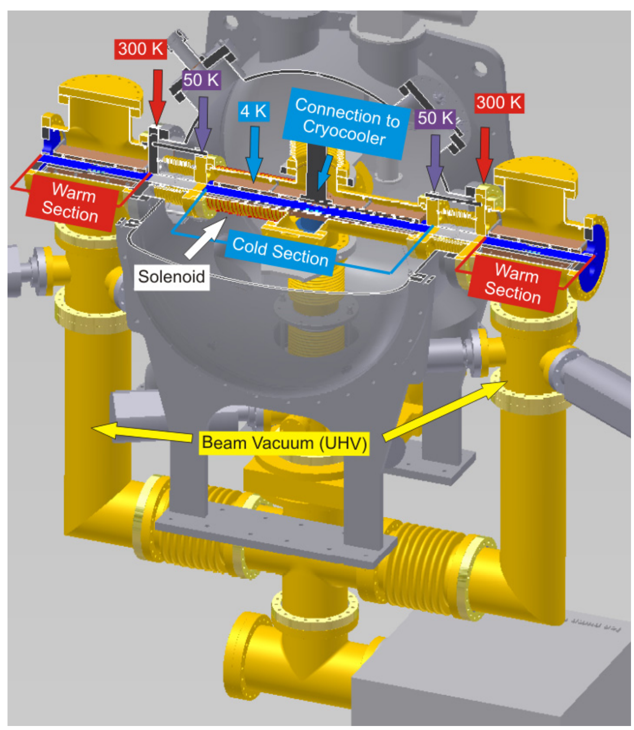

Figure 1: Sketch of the cryostat

The values of the beam heat load due to synchrotron radiation and resistive wall heating have been calculated

ILC Damping Rings: Benefit of the Antechamber or: Antechamber vs. SEY*

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Abstract

We present simulation results of the build-up of the electron-cloud density n_e for the two proposed ILC damping ring lattices, DC04 and DSB3, with particular attention to the potential benefit of an antechamber. We examine a field-free region and a dipole bending magnet, with or without an antechamber. We assume a secondary electron emission model for the chamber surface based on approximate fits to measured data for TiN, except that we let the peak value of the secondary emission yield (SEY), $\delta_{\max}$, be a variable. We conclude that there is a critical value of $\delta_{\max}$ below which the antechamber provides a substantial benefit, roughly a factor ~ 40 reduction in n_e relative to the case in which $\delta_{\max}$ exceeds the critical value. We estimate the steady-state value of n_e as a function of $\delta_{\max}$, and thereby obtain the critical value of $\delta_{\max}$ for all cases considered. Thus, from the perspective of the electron-cloud effect, the inclusion of an antechamber in the design is justified only if $\delta_{\max}$ is below the critical value.

The results presented here constitute a slight extension of those previously presented in March and September, 2010 [1, 2].

INTRODUCTION AND ASSUMPTIONS

The desire to limit the potentially serious adverse consequences from the electron cloud effect (ECE) in the proposed ILC positron damping ring has led to the consideration of adding an antechamber to the vacuum chamber [3], a design decision similar to the one adopted many years ago for the positron ring of the PEP-II collider [4]. The antechamber provides the obvious benefit of extracting from the vacuum chamber a large fraction η (η =antechamber clearing efficiency) of the synchrotron-radiated photons, which are therefore unavaliable to generate photoelectrons.

Fighting against the photon clearing effect of the antechamber is the process of secondary electron emission off the walls of the chamber. The number of secondary electrons grows in time in a compound fashion, and can therefore readily negate the clearing effect of the antechamber. The secondary electron density is a nonlinear function of bunch intensity and of $\delta_{\max}$, and exhibits threshold behavior in both of these variables, hence the resulting balance between the antechamber and the SEY of the chamber material is non-trivial.

We consider both proposed lattices, DC04 ($C = 6$ km) and DSB3 ($C = 3$ km), and for each of these we examine field-free regions and dipole bending magnets. For each case, we simulate the build-up with and without an antechamber of clearing efficiency $\eta = 98\%$ (Fig. 1). In all cases we set the bunch spacing $t_b = 6$ ns, and then repeat the analysis for most cases for $t_b = 3$ ns. The beam energy and bunch intensity are fixed throughout. The SEY function $\delta(E_0)$ used here is shown in Fig. 2. The emission spectrum corresponds, approximately, to that of TiN, but we let $\delta_{\max}$ be an adjustable input parameter on the range $0 - 1.4$. A detailed set of parameters is listed in Tables 1-2.

This being a build-up simulation, the beam is a prescribed (non-dynamical) function of space and time, with bunches of specified sizes, intensity and spacing. The fill pattern simulated consists of 5 trains, as defined in Table 1, whether the bunch spacing is 3 or 6 ns. The electrons, on the other hand, are fully dynamical. The analysis is carried out with the electron-cloud build-up code POSINST [5–8].

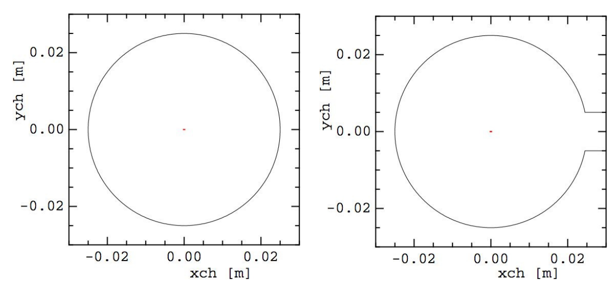

Figure 1: Cross section of the vacuum chamber, without and with an antechamber. The red dot at the center represents the approximate one-sigma beam profile.

RESULTS

Figure 3 shows the build-up of n_e for a field-free section when $t_b = 6$ ns. It is clear that (1) n_e reaches steady state for all values of $\delta_{\max}$ examined, (2) the steady-state value is slightly larger for DSB3 than for DC04, and (3) when an antechamber is present, the steady-state value of n_e is a factor ~ 40 lower than the no-antechamber case.

Figure 4 shows the corresponding results for a dipole bending magnet. In this case, one sees that the antechamber also provides a protection factor of ~ 40 only if $\delta_{\max}$ is sufficiently low: the critical value of $\delta_{\max}$ is ~ 1.2 for DC04, and ~ 1.1 for DSB3. If $\delta_{\max}$ exceeds this value, the build-up runs away in time until it reaches the level of the

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CESRTA PRELIMINARY RECOMMENDATIONS FOR THE ILC POSITRON DAMPING RING

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Abstract

The first phase of the CesrTA experimental program is now complete. Electron cloud research over the course of the last 2.5 years has focused on two principle topics. The first is the characterization of methods to mitigate the electron cloud build-up in each of the magnetic field regions of concern for damping ring design. The second is the characterization of the cloud's impact on ultra-low emittance beams. Our intent is now to incorporate these results into the technical design of the positron damping ring for the International Linear Collider. Implications for the ILC DR design will be discussed.

While no paper is available here, two references were published recently covering our recommendations:

M. T.F. Pivi, L. Wang, L. E. Boon, K. C. Harkay, J. A. Crittenden, G. Dugan, M. A. Palmer, T. Demma, S. Guiducci, M. A. Furman, K. Ohmi, K. Shibata, Y. Suetsugu, J. Urakawa, C. Yin Vallgren, "Recommendation for Mitigations of the Electron Cloud Instability in the ILC", Proceedings of IPAC 2011, San Sebastian, Spain.

J. A. Crittenden, J. V. Conway, G. Dugan, M. A. Palmer, D. L. Rubin, L. E. Boon, K. C. Harkay, M. A. Furman, S. Guiducci, M. T.F. Pivi, L. Wang, "Investigation into Electron Cloud Effects in the ILC Damping Ring Design", Proceedings of IPAC 2012, New Orleans, Louisianna, USA.

SIMULATION OF ELECTRON CLOUD INDUCED INSTABILITIES AND EMITTANCE GROWTH FOR CESRTA*

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Abstract

The program CMAD is being used to study single bunch instabilities induced by electron clouds. In the results presented in this paper, we studied the motion of the bunch centroid, the emittance evolution and motion of single test particles within the bunch. A series of studies were performed with varying cloud densities. The spectrum of centroid motion which showed indications of head tail motion was closely examined. The emittance evolution of the beam was computed. The trajectories of single test particles were analyzed qualitatively.

INTRODUCTION

CMAD is a two species Particle-in-cell (PIC) program capable of studying interactions between beams and electron clouds [2]. A comparison between results from CMAD and other similar codes has been carried out [1] for some simple cases. In this paper, we have performed similar simulations with several additional features included. All of them represent the parameters and conditions that occurred in CesrTA during experiments being carried out to study the influence of electron clouds on the dynamics of positron beams. Several features such as head tail motion and beam emittance calculations show similar features as to what has already been observed [3].

In observations, we have typically used trains varying from 20 to 45 bunches with a 14 ns spacing. Depending upon its properties, each bunch creates a certain amount of cloud and as a result the lagging bunches experience a higher cloud density compared to the leading ones. CesrTA instrumentation has the ability to observe the turn by turn position and the beam size of each of the bunches. CMAD tracks a single bunch and so in order to simulate the effect of different bunches along the train, we need to perform a set of independent calculations with varying prespecified cloud densities. The cloud densities seen by the different bunches can be estimated from build up codes or by the observed tune shifts. The tune shifts calculated from build up simulations have agreed well with observed tune shifts [4]. CMAD starts with a uniform distribution of electrons while work is underway to have the program be able to use any distribution as an initial condition.

In the results presented in this paper, we used a 2.08GeV beam, which is the energy most of the experiments have been performed so far. In these simulations, particles are tracked across the full lattice, where each element of nonzero length in the lattice consists of a cloud-beam "interacting point". Thus, the simulation takes into account the variation of the beam size based upon the beta function and dispersion all around the ring. In the model, the bunch had 96 slices, and the charge from each slice was distributed over a 128×128 grid, with 300000 macro particles (positrons) and 100000 macro electrons. The bunch current used was 1mA, corresponding to 1.6×10^{10} positrons. The bunch length was 12.2mm, vertical emittance was 20pm and horizontal emittance 2.6nm. The relative energy spread was 8.12×10^{-4}. The betatron tunes were 14.57 (horizontal) and 9.62 (vertical). The synchrotron tune was 0.055. The chromaticities were 0.6 (horizontal) and 2.3 (vertical) in units of $dQ/(dp/p)$. Overall, care was taken to match the parameters as closely as possible to the machine conditions that existed during the time of one of the observations made at CesrTA.

MOTION OF BUNCH CENTROID

In this section, we show the behavior of the centroid motion for varying cloud densities. The bunch initially had no offset. Nevertheless, the finite number of macro particles, however large, are enough to trigger a self excitation of the centroid motion, that increases with cloud density. A very similar trend in the self excitation has been seen in measurements. Of course, the mechanism of the initial perturbation in the beam offset is different in experiments, *ie* it is not numerical. The self excitation is produced by nonlinear coupling between the two transverse degrees of freedom. In addition, the effect of longitudinal motion would also play a role due to the presence of dispersive coupling between the longitudinal and horizontal motion.

Figure 1 shows the horizontal bunch displacement with respect to the initial beam size. We do not see a significant variation in oscillation amplitude with cloud density. For lower cloud densities, of the order of $1 \times 10^{10}/m^3$ shown in Fig 1a we do not see any significant self excitation. For cloud densities an order of magnitude higher, $ie \sim 1 \times 10^{11}/m^3$ shown in Fig 1b there is a clear indication of self excitation. In the next level of cloud densities, Fig 1c, we see that the all bunches get excited to about the same amplitude, but the transient state to reach the final amplitude of oscillation is longer in duration for the lower densities within this category of electron densities.

Figure 2 shows the vertical bunch displacement with respect to the initial beam size. for the same values of cloud densities. These show that the extent of self excitation

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