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SPACE CHARGE EFFECTS IN RECTILINEAR MOTION: EMITTANCE COMPENSATION, PULSE LENGTHENING, AND HALO FORMATION (WORKING GROUP #1 SUMMARY)

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Abstract

This report summarizes the presentations and discussions over a wide range of topics in Working Group I at the Second ICFA Advanced Accelerator Workshop on Physics of High-Brightness Beams held at University of California at Los Angeles (UCLA), November 9-12, 1999. Latest developments towards to a better understanding of high-brightness photoinjectors were reported. The design and commissioning of the Los Alamos National Laboratory (LANL) Low-Energy Demonstration Accelerator (LEDA) Radio-Frequency Quadrupole (RFQ) were reported. The problem of beam halo formation was discussed in both beam transport systems and the SLAC 50 MW 11.4 GHz periodic permanent magnet (PPM) focusing klystron amplifier. A new class of corkscrewing elliptic beam equilibria was reported, and applications of such novel beam equilibria in controlling of charge-density and velocity fluctuations, beam halo formation and emittance growth were discussed. Pattern formation in proton rings was also discussed.

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1 INTRODUCTION

Realization of high-brightness beams requires further advances in the understanding of space-charge effects in high-intensity accelerators and high-intensity beam transport systems. The presentations and discussions in Working Group I focused on rectilinear accelerators and beam transport systems. The group had 12 presentations covering a wide variety of systems ranging electron photoinjectors, to proton RFQ's and proton storage rings, to heavy ion beam injectors. In these presentations, important analytical and simulation results were also reported. These include studies of wave breaking in ultrahigh-brightness beams, recent discovery of novel cold-fluid corkscrewing elliptic beam equilibria, modeling of halo formation and electron beam loss in the SLAC 50 MW 11.4 GHz periodic permanent magnet (PPM) focusing klystron amplifier, and studies of pattern formation in proton storage rings.

2 MODELING OF ELECTRON PHOTOINJECTORS

The theory of linear emittance compensation in a high brightness rf photoinjector was revised in the first part of J. B. Rosenzweig talk [1]. He reported the main results of the so-called invariant envelope solution of the rms envelope equations, in the ultra-relativistic approximation. In the space charge dominated regime, he recalled, the bunch behaves as a laminar flow and can be represented as a set of slices each one described by an envelope equation (in multi-slice approximation) including the local slice space charge field. The frequency of the plasma oscillations for each slice, due to mismatches between the space charge force and the external focusing gradient, is independent of the current to first order, although the current affects the amplitude of the oscillations. It is such a frequency independence that brings to reversible normalized emittance oscillations: an integral number of plasma oscillations give minimum emittance, and accelerating the beam through the invariant envelope just makes these oscillations damped like the square root of the beam energy. This brings the normalized emittance down to a steady state minimum at the injector exit, provided that the oscillations are properly tuned.

Based on a similar linear model is the HOMDYN code illustrated by M. Ferrario [2]. In the new version of the code, the beam can be modeled from the cathode surface up to the injector exit in a very limited amount of CPU time due to an analytical treatment of space charge field. The HOMDYN model is based on a numerical extension of the multi-slice technique to the low energy regime and accounts also for the longitudinal dynamics of the bunch. In his talk, M. Ferrario discussed a numerical study for the LCLS RF photoinjector re-design, and described the discovery of a new promising working point for a split photoinjector configuration which leads to a very low emittance of ~ 0.3 μ for a 100 A beam with transverse and longitudinal uniform charge distribution.

Comparisons of the HOMDYN results with PARMELA computations were reported by D. T. Palmer [3]. He also described a new corrected output coupler modelling by PARMELA for a traveling wave structure.

During the group discussions concerning space charge modeling in photoinjector simulations that followed the talks, the importance of using Quiet Start or Hammersley's sequence to generate an evenly particle distribution in the transverse plane was realized. The need for using ultra-high resolution meshes to avoid non-physical nonlinearities in space charge routines was recommended.

In a preliminary study, D. C. Nguyen [4] pointed out the possibility to compensate the nonlinear part of focussing and defocusing forces acting on a bunch due to solenoid field, space charge fields and RF field, by properly shaping the nose cones of the gun cavity. A more detailed study is under way related to the Advanced FEL Accelerator gun design.

In the second part of his talk, J. B. Rosenzweig [1] discussed the nonlinear energy conversion to emittance due to the intra-slice space charge nonlinearities, which is also known as wave breaking. By means of a simple slab model of the beam in a focusing channel, he showed analytically that wave breaking takes place in transverse phase space when an off axis fixed point occurs. And this effect is enhanced when the beam is matched to the beam line: half of the beam is destined for wave breaking after one quarter of one betatron oscillation. For a mismatched beam, such an effect becomes more localized in phase space compared with a matched beam.

S. Anderson [5] pursued the previous analysis on wave breaking by means of a numerical model of a coasting beam with nonlinear self fields. It was evident from his simulations that in the case of a constant focusing channel, large oscillations about the equilibrium result in a better emittance than a matched beam. The message included in Anderson's study is that one can take advantage of this behavior in transport by letting the beam get big before focusing back down. Both talks generated interesting discussions because they could have a significant impact on the emittance compensation technique. The envelope behavior in the first half of one plasma oscillation follows Rosenzweig-Anderson's prescription, namely, the beam spot size stays mismatched to the gun accelerating and solenoid fields. The question posed was whether matching to the invariant envelope can still be considered to be the optimum condition for emittance compensation when nonlinear self fields are taken into account. The first tentative answer they gave was yes. The working point reported by M. Ferrario was based on the invariant envelope matching, and a very nice confirmation was obtained by means of PARMELA simulations, including nonlinear self fields. Moreover, L. Serafini pointed out that the invariant envelope is not strictly an 'equilibrium' solution because the spot size decreases as $1\sqrt{\gamma}$. Further details are reported in the proceedings [1], [5] and additional investigations are still in progress.

Finally, L. Serafini [6] showed how the linear invariant envelope theory can have interesting spin off in the framework of proton beam dynamics. He described an equilibrium solution of the envelope evolution of a laminar nonrelativistic space charge dominated proton beam, subject to acceleration in RF Linac. He also discussed the transition from laminar to thermal regime and the impact of this new beam equilibrium on the design of high intensity Linacs.

3 COMMISSIONING OF THE LANL LOW-ENERGY DEMONSTRATION ACCELERATOR (LEDA) RADIO-FREQUENCY QUADRUPOLE (RFQ)

The LANL Low-Energy Demonstration Accelerator (LEDA) Radio-Frequency Quadrupole (RFQ) is a CW 350 MHz RFQ accelerator producing a 100 mA 6.7 MeV proton beam. The LEDA RFQ is aimed at testing accelerator modules for the proposed accelerator production of tritium (APT) project. Vernon Smith of LANL gave an update on the commissioning of the LEDA RFQ [7], while his colleague L. Young discussed detailed design studies of the demo accelerator as well as comparisons between the design and experimental measurements [8].

The LANL term and their collaborators successfully integrated the LEDA injector, the low-energy beam transport system, RFQ, the high-energy beam transport systems, and beam stop into a complete demonstration accelerator. A 110 mA of RFQ pulsed output current was achieved at a repetition rate of 10 Hz and a pulse length of 20 ms, with a measured beam transmission of 94%. A 92 mA of RFQ output current was achieved during an uninterrupted runs of 56, 55 and 50 min. The designed RFQ output beam energy was achieved. An experiment for beam halo studies is under consideration.

4 BEAM HALO STUDIES

There were three presentations on beam halo studies. Chiping Chen of MIT discussed self-consistent simulation studies of electron beam halo formation and beam loss in the SLAC 50 MW 11.4 GHz PPM focusing klystron amplifier experiment [9]. Christopher Allen of LANL discussed some preliminary results from his analysis of beam halo formation in bunched beams using a multiscale perturbation approach [10]. Tai-Sen Wang of LANL discussed how to use transformed variables to better visualize halos around intense beams propagating through an alternating-gradient focusing channel without making the conventional smooth-beam approximation [11].

The basic findings of the MIT simulation studies of electron beam halo formation and beam loss in the SLAC 50 MW 11.4 GHz PPM focusing klystron are as follows [9]. In the absence of RF signal, the equilibrium beam transport is robust, and there is no beam loss in agreement with experimental measurements. During high-power operation of the klystron, however, the current-oscillation-induced mismatch between the beam and the magnetic focusing field produces large-amplitude envelope oscillations. Self-consistent simulations shows that for a mismatch amplitude equal to the beam equilibrium radius, the halo reaches 0.64 cm in size and contains about 1.5% of total beam electrons at the RF output section for a beam generated with a zero magnetic field at the cathode, which agrees qualitatively with the experimental observation of beam loss.

The MIT group plans to study electron beam halo formation and beam loss mechanisms in a 75 MW 11.4 GHz PPM klystron amplifier experiment which is currently being performed at SLAC.

In the multiscale analysis of halo formation in bunched beams by Allen [10], three normal modes of core envelope oscillations were considered, and test particle motion was studied under one of such normal modes. In particular, a set of slowly-varying amplitude and phase equations was derived. Further studies are under way to extract quantitative results on the magnitudes of halos.

By performing proper canonical transformations for the Hamiltonian describing test particle motion in an intense beam propagating through an alternating-gradient focusing channel, Wang was able to obtained Poincare surface-of-section plots which show smeared separatrices [11]. The existence of such a smeared separatrix was proposed as a possible mechanism for halo formation.

5 DISCOVERY OF NOVEL CORKSCREWING ELLIPTIC BEAM EQUILIBRIA

Renato Pakter of MIT reported that there exists a new class of cold-fluid corkscrewing elliptic beam equilibria for ultrahigh-brightness, space-charge-dominated beam propagation through a linear focusing channel consisting of uniform solenoidal, periodic solenoidal, and/or alternating-gradient quadrupole focusing magnets in an arbitrary arrangement including field tapering [12]. It was shown that in proper limits, such corkscrewing elliptic beam equilibria recover many familiar beam equilibria in beam physics. Examples and applications of the present equilibrium beam theory were discussed. In particular, as an important application, a general technique was developed and demonstrated for the controlling of beam hollowing and beam halo formation in ultrahigh-brightness beams. Detailed results were discussed about controlling of beam hollowing observed in the Lawrence Berkeley National Laboratory (LBNL) Heavy Ion Beam Injector Experiment.

6 PATTERN FORMATION IN INTENSE HADRON BEAMS

Stephen Tzenov of SLAC discussed, from a theoretical viewpoint, several possible scenarios for pattern formation in intense hadron beams such as proton beams in storage ring [13]. One of the scenarios for pattern formation was identified as formation of solitons in beam plasmas.

7 ACKNOWLEDGMENTS

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