STEPS TO ENHANCE THE KNOWLEDGE ON SPACE CHARGE EFFECTS

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Abstract

At the Paul Scherrer Institute the routine operation of the proton accelerator facility at a beam power of 1 megawatt and more [1] has been a strong motivation to steadily enhance the knowledge on space charge effects. Various tracks are followed to serve this goal. Reporting on these activities will proceed using some selected examples. Predictions from analytical and empirical formulas and simple simulation models are compared to observed beam behavior. The two dimensional space charge simulation programs have been enhanced to become easily portable and to be able to model the actual phase space density distribution more exactly. A leading edge three dimensional space charge simulation framework is being developed in collaboration with CERN and Los Alamos. Various validation runs for the different space charge simulation tools are using analytically solvable configurations and cross-validation against other codes. At PSI detailed measurements of beam properties for different intensity levels have been made and new beam diagnostic equipment is being developed to reveal further information on beam properties, depending on space charge.

1 THREE ASPECTS OF KNOWLEDGE ON SPACE CHARGE EFFECTS

The sources of information that belong into the context of beam dynamics with space charge can be categorized into three main groups: the theoretical group comprises predictions of beam behavior based on analytical models and computer simulations, the group of observations is based on experience with high intensity beams and a third, very important group is striving to establish bridges between the two former ones. As accelerator projects become more and more ambitious, in particular in the field of high intensity accelerators, this third group rapidly gains in importance, because theoretical models and computer simulations all need some validation and observations of complex beam behavior await conclusive interpretation.

Some similarities to particle physics with its two main lines of theory and experiment exist, but also some essential differences. In beam dynamics the basic physical principles are firmly established. On the side of theory and simulation various approaches reach different degrees of approximation to the extremely complex reality of an accelerated beam. Improving the degree of approximation usually requires a high effort to be invested into the method. On the side of observations an important difference is that cyclotrons are built to produce beams for research in particle and solid state physics, not for the purpose to enhance beam dynamical knowledge. Usually, also the beam diagnostic equipment of a particle accelerator is taylored to its beam production purpose. Thus, enhancing the beam dynamical knowledge on the side of beam observations and validations of theoretical models is bound to be a kind of a parasitic activity. In this situation, the establishing of correlations between beam dynamical models and beam measurements becomes the essential substitute for the missing counterpart of a typical particle physics experiment.

2 SPACE CHARGE IN DC BEAMS

For the beam transfer line between the 870 keV Cockcroft Walton DC accelerator and the Injector 2 cyclotron at PSI the original layout was conceived to work without a buncher. As the buncher, having been added later, is located towards the end of this beam line, the first part of the 870 keV beam line is transporting a DC beam of 10 to 12 mA. To predict the effects of the purely lateral space charge forces in DC beams there exist well established models [2]. An almost unknown factor however, on which these models depend directly, is the degree of space charge neutralization by electrons coming from the ionization of the residual gas.

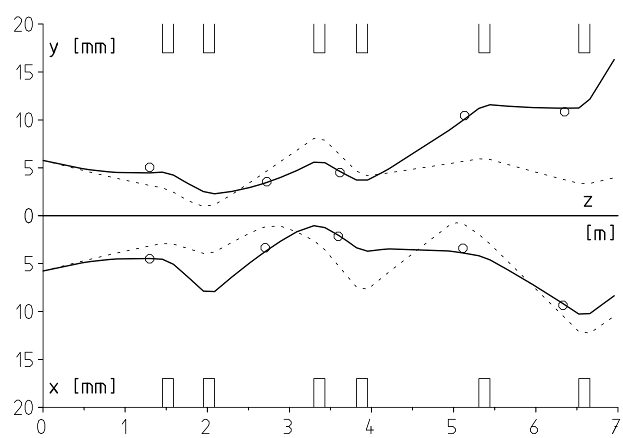

Figure 1: Transport envelope fit in 870 keV beam line. Solid: best fit with space charge effects; 14% neutralization yielded the best result among the runs with different values of this parameter. Dashed: envelopes with zero space charge effects, but same initial condition.

A set of 10 non-interceptive profile monitors has been installed in the first section of the 870 keV beam line [3]. These monitors analyze the light emitted from the interaction of the high intensity DC beam with the residual gas. This diagnostic equipment provided us with a large series of beam profile measurements that could be taken in parallel to regular beam production.

These profile data sets showed that the beam properties

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are highly reproducible in the 870 keV beam line. A representative sample of profile data has then been used to run a series of fits with the program TRANSPORT [4] including space charge, but with various degrees of neutralization. Assuming 14% neutralization, as shown in figure 1, yields an excellent agreement between measurement and calculation. For the two fitting attempts without space charge forces, using fixed or variable initial conditions, the agreement was substantially worse. This demonstrates that for these high intensity DC beams space charge forces must be taken into account to achieve a good modeling of the beam.

3 BEAM BUNCHING EFFECTS

In 1991 the maximum beam intensity extracted from PSI Injector 2 could be raised from approximately 0.7 mA to more than 1 mA. This step has been guided by simulations of longitudinal space charge effects in the bunched beam [5] using the program SPUNCH from R. Baartman [6] based on a simple one-dimensional longitudinal space charge model. The multi-particle simulation program MATADOR was then used to model the phase selection mechanism in the center of Injector 2 for these bunched beams.

A number of properties of the bunched beam [1] at its injection into Injector 2 could be verified with beam measurements to be in agreement with the predictions by these simple models:

- The conceptual model of an acceptance window limited both in phase and energy deviation, in combination with the simulation of the buncher, was in agreement with the observation that the accepted beam intensity had a local maximum at about half the buncher voltage needed to produce a time focus at the phase selecting collimator.
- The observed rapid raise of beam intensity passing the phase selecting collimator vs. its position change strongly supported the model of a central part of very low energy spread around the time focus of the beam.
- The need for a radial cleaning collimator approximately a quarter turn after the phase selecting collimator was predicted by the simulations. The substantial improvement of beam quality after the realization of such a collimator proved this prediction true.

4 SPACE CHARGE DOMINATED BEAMS IN ISOCHRONOUS CYCLOTRONS

The prediction that elongated beam bunches are transformed into round charge distributions caused by space charge forces had been imposed by the predecessor of the 2D simulation program PICS already in 1984. An overview on the 2D space charge simulation programs PICS and PICN used at PSI has been given at the Cape Town Cyclotron Conference in 1995 [7], where further references are listed.

A first evidence that this transformation of the bunch shape really occurred was found in the fact that the flattop system could be turned off in the Injector 2 while a good extraction rate could be conserved. This fact was a proof that the beam bunches had an extremely narrow phase width on major parts of the radial range. Later, the phase of the 3rd harmonic, former flattop, RF system could be reversed to gain additional acceleration. This mode of operation imposed an even narrower limit on the phase width of the bunches. A round charge density distribution with a radial diameter of 10 to 12 mm in Injector 2 has a total phase width between 3 and 1.5 degrees, clearly below the limits of 5 degrees allowed by an acceleration voltage with 11% of third harmonic added (flattop with reversed phase).

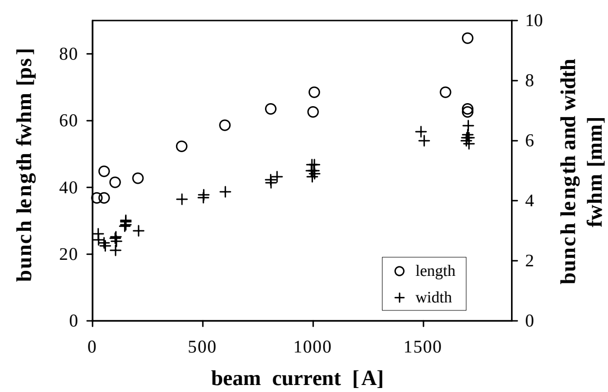

Figure 2: Phase width and radial width of beam bunches, measured at extraction from PSI Injector 2 for different beam intensities [8].

Recently, the time resolution of the beam probe for time structure measurements could be substantially improved. This allowed to measure the phase width of the beam bunch in the extraction region of Injector 2 with sufficient precision as shown in figure 2. The results of these high resolution time structure measurements are the first directly measured evidence of the expected formation of a nearly round charge distribution.

Motivated by a growing interest of colleagues from other laboratories to use the 2D space charge simulation programs of PSI, a major revision of these programs has been started. The modifications should make the programs easily portable between various computer platforms, translate all German comments and user dialogs to English and add some new features. It is also planned to reduce the differences between the user interfaces of the simulation based on charged spheres, PICS, and the simulation based on vertical needles, PICN. The first two tests of portability have been passed successfully when the programs, developed on VMS, were installed on Linux, at PSI, and on AIX, at RIKEN.

A useful new feature was the introduction of radially cutting collimators into the PICN simulation. This allowed to investigate how cleaning collimators in the center region could help to reduce tails of the beam profile at extraction.

The feasibility of such a reduction of tails, which had been found in beam tuning, was showing up in simulations as well.

Simulating the phase selection mechanism also helps to find the initial charge density distributions to be expected in the cyclotron. In earlier simulation runs initial charge density distributions had been constructed with analytical density functions. Figure 3 shows the charge density distribution resulting from a simulated cutting of the beam bunch with two radially cutting collimators in comparison to a bunch shape based on starting conditions using analytical functions, as common in the older simulation runs. The similarity of the two density distributions underlines the validity of the assumptions on initial charge density distributions having been used in earlier simulations.

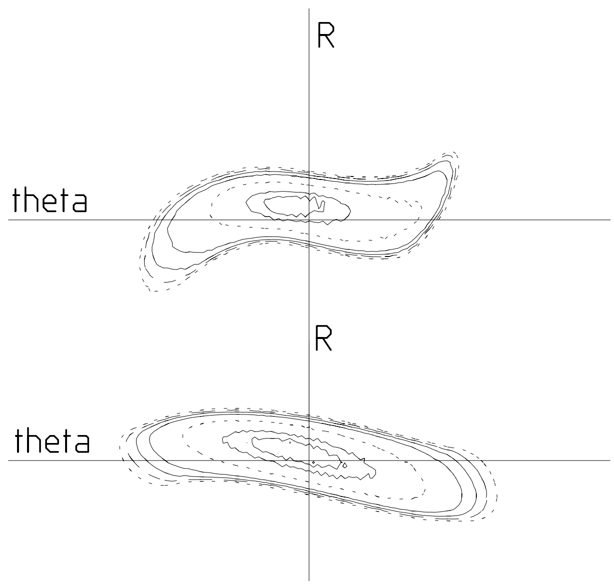

Figure 3: Charge density distributions of a beam bunch on the first turn of Injector 2. Above: Simulated with radial collimation of a wide phase beam. Below: Produced with standard initial conditions of the program PICN.

5 A NEW RANGE OF PRECISION FOR BEAM SIMULATIONS

The permanent wish to improve the precision of beam simulations with space charge resulted in an effort to create a top level beam simulation environment.

MAD Version 9 [9] is based on the CLASSIC framework, which fully covers the single particle dynamics. Thanks to an elaborate design, it is fairly straightforward to parallelize CLASSIC's particle tracker using the POOMA [11] (parallel object oriented design and application) framework. Besides this, a parallel 3D FFT field solver and a Barnes-Hut tree-based field solver are implemented. Having this at our disposal, we can use a split operator method to combine single- and multiparticle dynamics.

The new program environment MAD9P [10] is in its validation phase and beam simulation results related to PSI Injector 2 are to be expected within the next year.

6 CONCLUSIONS AND ACKNOWLEDGEMENTS

The PSI accelerator crew has actively pushed the frontiers of knowledge on space charge effects ahead on all three levels: theory and simulation, beam diagnostic equipment and beam measurements, as well as theory based interpretation of beam measurements. Given the extremely high complexity of the subject, many problems remain to be solved. Together with the international network of collaborating colleagues who contribute with their individual work, with active discussions and, directly being involved with the investigations carried out at PSI, we will carry on.

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