

# NUMERICAL STUDY OF BEAM DYNAMICS IN HIGH INTENSITY CYCLOTRONS INCLUDING NEIGHBORING BUNCH EFFECTS

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## Abstract

For high intensity cyclotrons with small turn separation, single bunch space charge effects are not the only contribution. The interaction of radially neighboring bunches is also present but its effects have not yet been investigated in greater detail. In this paper, for the first time, a new PIC based self-consistent numerical simulation model is presented, which covers neighboring bunch effects and is implemented in a three-dimensional object-oriented parallel code OPAL-CYCL, a flavor of the OPAL framework. We present simulation results from the PSI 590 MeV Ring cyclotron in the light of the ongoing high intensity upgrade program, with the goal of 1.8 MW CW beam power on target.

## INTRODUCTION

Space charge effects play an important role in high intensity cyclotrons, as the most important collective effect. In the past, several analytic, semi-analytic and PIC based macro-particle models have been developed to investigate the space charge effects of a single bunch [1, 2, 3, 4, 5].

For high intensity cyclotrons with small turn separation, single bunch space charge effects are not the only contribution. Along with the steady increase of beam current, the mutual interaction of neighboring bunches in radial direction becomes more and more important, especially at large radii where the distances between neighboring bunches get increasingly small, and even overlap can occur. One good example is PSI 590 MeV Ring cyclotron [6] with a production current of about 2 mA in CW operation and a beam power on target of approximately 1.2 MW. An ambitious upgrade program for the PSI Ring cyclotron is funded and in progress, aiming for 1.8 MW CW beam power on target. After the planned upgrade, the total turn number can be significantly reduced, e.g. from more than 200 turns to less than 170 turns. In consequence the turn separation is increased, but remains at the same order of magnitude as the radial bunch size, as shown in Fig. 1. Therefore, when the beam current increases from 2 mA to 3 mA, the mutual space charge effects between radially neighboring bunches will have more impact on the beam dynamics and need to be considered seriously.

Because of the complexity of the problem, it is impossible to evaluate neighboring bunch effects precisely and self-consistently by explicit analytic expressions. How-

Figure 1: Comparison of calculated turn separation for centroid particles before (red line) and after (blue line) upgrade of the PSI Ring Cyclotron.

ever, the fast developing computer hardware and high performance computation (HPC) makes it possible to treat this problem in greater detail. To our knowledge, very few research efforts have been done on neighboring bunch effects, the only published work so far is the one of E. Pozdeyev's work [7]. He introduced "rigid auxiliary bunches" in his serial code CYCO which uses the azimuthal angle as the independent variable.

We have developed a new PIC based self-consistent numerical simulation model which covers neighboring bunch effects and developed a new three-dimensional object-oriented parallel simulation code.

## NEIGHBORING BUNCH EFFECTS

In cyclotrons the turn separation  $\Delta R$  is affected by many factors which include the machine characteristics such as magnetic field map, voltage profile and the accelerating phase of the RF resonators. In addition the initial centering conditions of the injected bunches have to be considered. The typical tendency is that  $\Delta R$  reduces gradually with increasing beam energy. For some machines,  $\Delta R$  stays sufficiently large from injection to extraction, and in such cases, neighboring bunch effects are negligible. For others,  $\Delta R$  decreases strongly during the course of acceleration resulting in the need to consider neighboring bunch effects in order to obtain a correct description of the physical behavior.

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Figure 2: Schematic plot of the top view of 5 bunches and the grid of computation domain. The grid size on  $X' - Y'$  plane is  $N_x \times N_y$ , and the broken lines represent the orbits of beam centers.

In our model, initially one bunch with  $N_p$  particles is injected at the radial position  $R_0$  and tracked for one turn. After exactly one revolution period  $T_r$  the new radial position  $R_1$  is recorded again. If the condition

$$\Delta R \equiv R_1 - R_0 \leq M \times r_{\text{rms}}, \quad (1)$$

is fulfilled, where  $r_{\text{rms}} = \sqrt{x_{\text{rms}}^2 + y_{\text{rms}}^2}$  and  $M$  is the parameter given by the user, the 6D phase space data  $(x, p_x, y, p_y, z, p_z)$  at this time step is stored. After it is further tracked for another  $T_r$ , the code is switched to multi-bunch mode. A new bunch is injected by reading the 6D phase space data stored before and the two bunches are tracked simultaneously. The third bunch is then injected in the same way after another turn, and so forth, until the maximum bunch number  $N_B$  is achieved in the simulation.  $N_B$  is also set by the user. The underlying assumption for this is that all bunches have the same phase space distribution when they reach a certain position. This is realistic and reasonable when the machine is running in a steady state.

To the contrary, if the condition of Eq. (1) is not fulfilled, the code continues to track a single bunch until Eq. (1) is valid.

Here another question raises. How many bunches should be simulated to evaluate neighboring bunch effects? A pragmatic approach is given by doing the simulation for 3 bunches and 5 bunches and comparing phase space results first. If the discrepancy is visible, one needs to do the simulation for 7 bunches, and compare its result with 5 bunches, and so forth. Eventually, with the proper setting of  $N_B$  and  $M$ , neighboring bunch effects can be evaluated precisely. For instance, the setting with  $N_B = 9$ ,  $M = 4.5$  gives a precise result for the PSI Ring cyclotron of 3 mA beam current. We will discuss this in more detail in the following section.

In a multi-bunch simulation the energy of bunches in different turns is quite different. One can't find a single beam rest frame in which the relative motions of particles are non-relativistic. Consequently it is not sufficient to use only one rest frame and a single Lorentz transformation. In order to calculate space charge fields more precisely, an adaptive energy binning technique is applied to improve the computational accuracy.

## IMPLEMENTATION UNDER OPAL FRAMEWORK

Above model and algorithm are implemented in the object-oriented parallel PIC code OPAL-CYCL. OPAL-CYCL is one of the flavors of the OPAL (Object Oriented Parallel Accelerator Library) framework [8], a generic library initialized by A. Adelmann. This framework is a powerful tool for charged-particle optics in general accelerator structures and beam lines. Using the MAD languages with extensions, OPAL is derived from MAD9P [5] and is based on the CLASSIC [9] library and IPPL framework (cite?). CLASSIC library is a C++ class library which provides services for building portable accelerator models and algorithms and input language to specify complicated accelerator systems in general. IPPL is a Object-Oriented C++ class library which provides a flexible environment for data-parallel programming of scientific application. It provides an integrated, layered system of objects. The upper layers contain global data objects of physical/mathematical quantities, such as particles, fields and matrices of meshes and typical methods performed on these objects such as binary operators and FFT. the lower layers contain the object's relevant to parallelization and efficient node-level simulation, such as data distribution, domain decomposition and communication among processors, load balancing and chained-expression optimization. The intermediate phase space data of all particles and some interesting parameters, including RMS envelop size, RMS emittance, energy, path length, bunch numbers and tracking step, are stored in the H5Part[10] file-format and can be analyzed using the visualization tool H5PartRoot [11].

In addition, apart from the multi-particle simulation mode, OPAL-CYCL also has two other serial tracking modes for conventional cyclotron machine design. One mode is the single particle tracking mode, which is a useful tool for the preliminary design of a new cyclotron. It allows to compute basic parameters, such as reference orbit, phase shift history, stable region and matching phase ellipse. The other one is the tune calculation mode, which can be used to compute the betatron oscillation frequency  $\nu_r$  and  $\nu_z$ . This is useful for evaluating the focusing characteristics of a given magnetic field map.

A more detailed description of the hierarchical layout, the parallelization and the implementation issues of the OPAL framework and OPAL-CYCL code can be found in the User's Reference Guide [8].

## APPLICATIONS

### *Different phase widths study of PSI Ring*

Although a very compact beam of about  $2^\circ$  phase widths can be extracted from the Injector II, it expands in the longitudinal direction on the 72 MeV beam line because of the space charge effects and chromatic dispersion. For the future 3 mA beam, this will bring big pressure on the Ring cyclotron. A 10th harmonic buncher is planed to be in-

stalled on the beam line to make bunch as short as possible at the injection point of the Ring. Therefore, how short the bunch should be achieved at the injection point of the Ring is a critical question.

In order to obtain a clear perspective on this issue, OPAL-CYCL was applied to do numerical simulation on the Ring by tracking Gaussian type beams with 3 different initial conditions. The initial longitudinal phase widths ( $6\sigma$ ) are set to  $2^\circ$ ,  $6^\circ$  and  $10^\circ$ , respectively, and the initial energy spread is neglected. The initial conditions on the horizontal and vertical directions are the same. The initial distribution is not correlated in phase space.

Fig. 3 shows the development of the beam rms size on the transverse and the longitudinal directions. We can see the beam is compressed gradually in the longitudinal direction. Meanwhile in the transverse direction, the beam size increases fast during the first several turn because of the mismatch of initial conditions. Thereafter it does not change sufficiently until the beam arrives at the extraction region where it is distorted by the external magnetic field. Fig. 4 plots the histogram along the longitudinal direction at  $112^\circ$  azimuthal position of turn 0, 50 and 150. The bunch the initial phase width of  $2^\circ$  maintains very compact shape with a stable round core and no any halos at all. When the initial phase width increases, the size of core only widens for less than 5 mm, but the spiral tails expands in the longitudinal direction and can't develop stable halos. However, the beam does not expand notably in radial direction, which means no substantial increase of the beam loss on the extraction septum is expected for the bunch with initial phase width less than  $10^\circ$ .

### *Neighboring bunch effects in PSI Ring*

As discussed above, neighboring bunch effects may have appreciable influence on beam dynamics in the Ring. This can be evaluated by comparing the difference of single bunches simulation and multiple bunches simulation as describes in section III. We tested for 3, 5, 7 and 9 bunches and found that the difference between the center bunch of 7 scenarios and that of 9 bunches scenarios is trivial as shown in Fig. 5. As we can see from Fig. 6, the FWHM of beam transverse profile from multi-bunch simulation is 1 mm narrower than that of single bunch and that the FWHM of energy spread is reduced slightly. This is caused by squeezing space charge force from the bunches at the smaller radius and those at the bigger radius.

From the comparison, we conclude that neighboring bunch effects impose visible impacts on the beam dynamics when the beam current get beyond 1 mA in PSI Ring. The bunch becomes more compact in the transverse direction and the energy spread is reduced slightly. Therefore neighboring bunch effects have positive influence on reducing beam loss in high intensity operation.

## CONCLUSIONS AND DISCUSSIONS

In this paper, we presented a physical model for the beam dynamics in high intensity cyclotrons, which includes for the first time the space charge effects of neighboring bunches in a self-consistent way. This model is implemented in an object-oriented three-dimensional parallel PIC code, as a flavor of the OPAL framework.

This code has been successfully applied to study the behavior of the PSI Ring cyclotron at high intensities. As the results show, the generation of beam tails can be avoided if short bunches with a phase length of  $2^\circ$  or less are injected. An upgrade plan is under way to generate such short bunches with the help of a 10th harmonic buncher. Furthermore it is observed that the neighboring bunch effects can help to narrow the transverse beam size and reduce the energy spread.

It is planned to refine these simulations within the next year by a more detailed determination of the initial particle distribution at the injection of the PSI Ring cyclotron. A quantitative comparison of the results with measured beam properties will be presented in a future paper.

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Figure 3: Comparison of the rms beam size in the transverse direction (left) and longitudinal direction (right) at  $112^\circ$  azimuthal position of each turn in PSI Ring cyclotron.

Figure 4: Histogram of 3 mA bunch distributions with  $2^\circ$ ,  $6^\circ$  and  $10^\circ$  initial phase widths at initial position(left), turn 50(middle) and 150(right) in PSI Ring cyclotron.

Figure 5: Top view of 1 mA bunch distributions at the turn 130 in the local frame at  $112^\circ$  azimuthal position of turn 130 in PSI Ring cyclotron. The results are obtained from single bunch(left), 7 bunches(middle) and 9 bunches(right) simulations, respectively.

Figure 6: Comparison of the histograms along the transverse direction in the local frame (left) and the energy spectra (right) of 1 mA beam at  $112^\circ$  azimuthal position of turn 130 in PSI Ring cyclotron.