BEAM DYNAMICS AND SPACE CHARGE ASPECTS IN THE DESIGN OF THE ACCELERATORS FOR THE ENERGY AMPLIFIER

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Due to the large current intensity (of the order of 10 mA) that must be delivered to the core of the energy amplifier proposed by C. Rubbia at CERN, space-charge effects strongly affect the beam behaviour and must be suitably taken into account in the design codes. The models involved in the beam dynamics simulations for the three stages (injectors,intermediate and booster cyclotrons) are described in this paper. Depending on the energy range in each stage, various degrees of complexity and refinement of the models are needed.

1 Introduction

A new concept called "Energy Amplifier" for clean energy production through controlled nuclear fission has been developped by a team lead by C. Rubbia at CERN [1]. Basically, a particle accelerator is used to produce a proton beam in the 1 GeV energy range in order to produce neutrons by spallation (interaction of particles with a target) to feed a fuel/moderator assembly where the neutrons multiply by fission chain reactions. Thus, unlike a conventional reactor, the Energy Amplifier's fission reaction is not self-sustaining and subcritical and needs a continuous supply of neutrons If the accelerator stops, the reaction stops as well. A more detailed presentation of the project and in particular of the general features of the accelerator is given in a companion paper [2].

The accelerator complex consists of three stages of cyclotrons referred to as the compact injector (CIC), intermediate separated sector (ISSC) and booster separated sector (BSSC) cyclotrons accelerating a high intensity (of the order of 10 mA) proton beam up to an energy of the order of 1 GeV [3]. In this paper, we present the various models and programs that are used in the design of the various cyclotrons, beam lines and ion source. Emphasis is put on the lower energy part of the accelerator where stronger space charge effects are expected.

To study the general characteristics of the beam dynamics in the cyclotron the focussing properties are computed first using a classical matrix method including soft-edge effects for the magnetic field produced by sectors [4]. This enables to obtain a preliminary but close estimate of the sector shape. A more sophisticated program, EUQUIL, is used to calculate these properties more accurately from field maps. EUQUIL takes into account the transversal space charge effects on the focussing frequencies ν_r and ν_z according to approximate formulae [5]. Plots of these frequencies for the various stages are given in Fig. 1.

More refined beam dynamics computations are being carried out with a specific code to study the beam evolution under space charge during the acceleration process. Different space charge models are needed, depending on the beam energy [6]. At low energies, rather refined models must be used whereas at higher energies more crude ones can represent satisfactorily the forces affecting the beam behaviour.

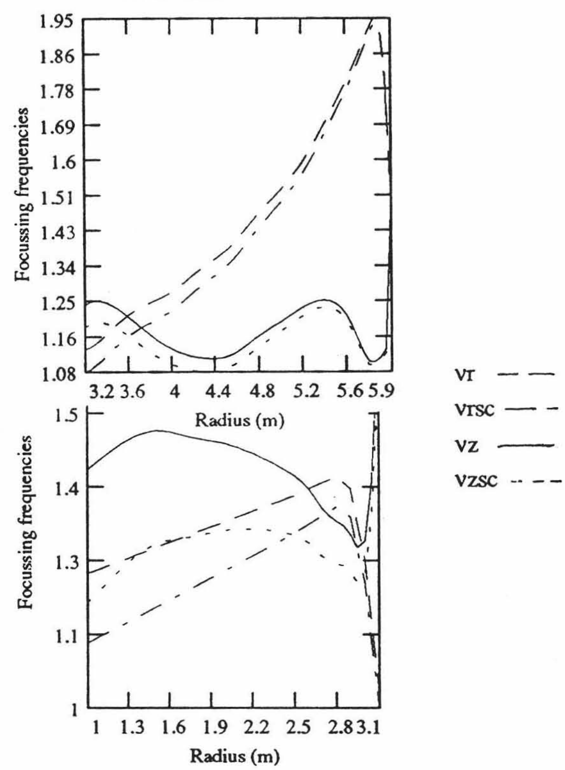

Fig. 1 : Focussing frequencies in the ten sector (above) and four sector (below) ring cyclotrons

2 Source

A 2D code SLAC used for the design of high intensity sources in fusion research [7] has been adapted to study the H multicusp source extraction electrode system in a first step. A Poisson solver is used iteratively together with an ion tracking routine until a satisfactory convergence on the position of the beamlet rays at the final electrode exit is obtained. It includes the effects of space-charge due to the negative ions, to the extracted electrons and to gas stripping in the plasma electrode region.

The collective-electron behaviour is taken into account by considering three different regions. Space-charge neutrality and fixed potential are required in the plasma region. An intermediate region where an electron diffusion model i.e. where the gradient of the electron density is related to the electron current density and a diffusion coefficient, is considered. Further, an electron beam region exists between this intermediate region and the front surface of the extraction electrode There, the electron density is related to the electron current density and velocity. The electron space charge in the various regions is added to the negative ion space charge before solving Poisson's equation.

In a following step, a 3-D program should be used for more refined computations since the application of the transverse magnetic field used for eliminating electrons breaks the cylindrical symmetry. It should be checked that the electrons will be correctly deflected onto the front surface of the extraction grid. Three-dimensional computer codes based on a rather sophisticated description of the physics involved in the source plasma and extraction system region have been successfully developed in other laboratories [9].

3 Beam lines

A dedicated transport code BEAMLINSC has been developed in order to design the various beam lines with linear space-charge effects included. It is based on the usual methodology for designing beam lines with space charge effects [9]. It has been used in the first design step of the low energy beam transport system between the source and the injector cyclotrons. In addition to the classical optics elements (drift, quadrupole, dipole, solenoid), more exotic elements like bunchers and spiral inflectors can be included.

A more accurate code using multiparticle is being developed in order to take into account non-linear effects due to space charge and to the bunching process. These effects are also present in the spiral inflector, where a strong coupling between the various beam coordinates is encountered. The magnetic field in the center of the cyclotron being rather non-uniform, analytical expressions for the particle trajectories can not be used reliably and must be replaced by numerical integration. Static magnetic and electric field maps have been generated with the electromagnetic computer-aided design code MAFIA. The trajectories are then integrated by the code SPISC using the equations of motion without space charge. Knowing the particle positions, the electric field due to space charge is computed via FFT and smoothing procedures, particle trajectories are computed again and so on until a satisfactory convergence (a few iterations) is obtained on the particle position at the inflector exit. Another method has been proposed for designing spiral inflectors in the presence of space charge [10]. The ion motion is described by using a coordinate system moving with the central trajectory and integrating a set of non-linear differential equations where the electric field is computed from the potential expressed into a power series of the coordinates around the central trajectory. No 3-D computation of the electric field is needed in this formulation. Both methods will be compared in the next future.

4 Injector cyclotron

A dedicated code TRACKORB has been written in order to compute the reference particle trajectory in the cyclotron median plane and tune the isochronous magnetic field.

The magnetic field data used as input in our equilibrium orbit EUQUIL code is interpolated from maps computed with the code MAFIA [11] for various sector geometries. The sector angle is modified until the time for traveling along equilibrium orbits is equal to the fixed design revolution time. The map obtained after these iterations is used in TRACKORB in order to check the correct isochronism and centering of the central particle. This code is based on the micro-gap concept [12]. In the central region, potential maps in the gaps have also been generated with MAFIA. From these maps, a certain number of equipotential lines are parametrized so that their positions in each gap is known. Between two equipotentials, the direction of the electric field is assumed to be constant. The particle is then tracked until it reaches the following equipotential line and so on.

A 3-D multiparticle code TRACKSC3D is being developed in order to take into account the various effects that occur in the injector cyclotron and particularly in the central region. The magnetic field is computed via the classical expansion from the median plane map. The finite difference scheme proposed in ref. [13] has been introduced in order to filter out high-frequency noise components that appear when high-order derivatives are computed. As far as the electric field provided by the RF cavities is concerned, it is obtained either from 3-D maps generated by MAFIA or by series expansion from potential maps in the median plane with careful filtering procedures. In order to study the dynamics in the first turn in the cyclotron where phase selection and collimation occurs to get a "clean" beam for futher acceleration, the same kind of iterative technique described for the inflector is used. Once a bunch structure is created (after the first turn), space charge effects are taken into account with the same method (described in the next section) than in the intermediate cyclotron.

No detailed investigation of the extraction beam dynamics has been done up to now. A dedicated tracking code INJEXTSC based on the methodology given in ref. [14] will be used in order to get an accurate description of the beam behaviour in the extraction region of the CIC. It could also be used for the design of the injection and extraction system of the ISSC and BSSC.

5 Intermediate cyclotron ISSC

One of the fundamental parameter of the accelerator complex is the intermediate cyclotron injection (or injector extraction) beam energy. Following preliminary simulations of the beam bunch behaviour under space-charge effects at various beam energy in the transfer lines between the injector and intermediate cyclotrons and in the intermediate cyclotron itself, it has been determined that 10 MeV would be an acceptable value of this parameter. In order to reduce the longitudinal debunching of the beam in the transfer lines, it is planned to combine an H^+ beam (extracted by stripping H^- ions) and an H^- beam (extracted by a conventional electromagnetic channel). These two beams are synchronized so that the bunches are superposed in a straight portion of the ISSC injection line. A stripper is installed at the end of this line before the beam enters the ISSC magnetic field in order to get a "pure" H^+ beam [2]. The beam bunches have been approximated as a set of cylinders, each of them being allocated a given charge density in order to account for the longitudinal intensity variation within the bunch. Fig. 2 shows typical plots of the electric fields and bunch phase extension (debunching) due to space-charge along the beam line if a single type of beam is used (intensity 12.5 mA, initial bunch length 30 deg. RF). A more detailed study of the "bunch mixing" and stripping needs to be undertaken to get an accurate description of the injection conditions in the ISSC.

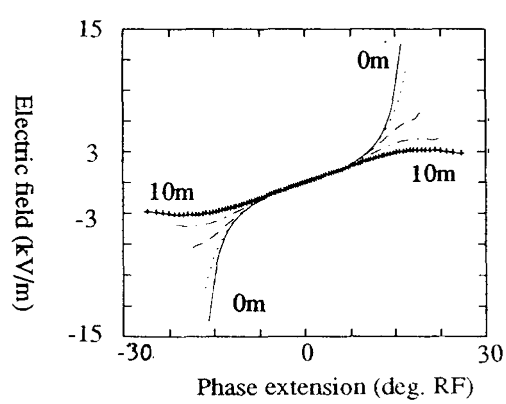

Fig. 2: Longitudinal electric field and bunch phase extension due to space charge at various locations in the ISSC injection line (see text)

Space-charge effects in the intermediate cyclotron have been taken into account by introducing in our tracking programs a relatively simple model [15]. At regular locations along the accelerated path, energy and momentum increments are added to the values obtained by tracking in order to take into account space charge forces. These increments are computed from the analytical expression providing the electric field generated by an ellipsoidal bunch with a gaussian density distribution. This model is attractive because the ananlytical expressions for the field can be computed rather quickly and it can be easily implemented. It was decided to use it in the first design step. At low energies, the beam tends to depart from this kind of shape, the size of the beam (related to the gaussian factors σ_r, σ_ϕ and σ_z) is overestimated and the electric field values underestimated. Fig. 3 shows the results of a simulation with the following parameters: beam energy 10 MeV, energy spread 0.05 MeV, current intensity 20 mA, bunch +/- 15 deg. RF.

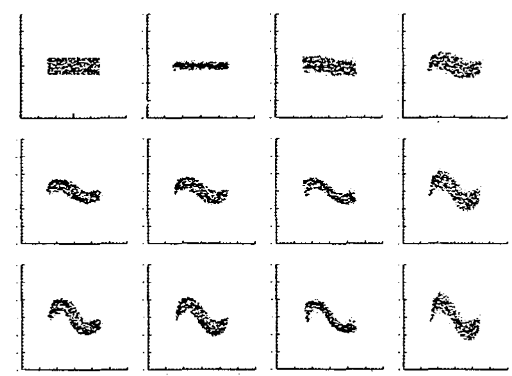

Fig. 3: First 12 turns in the intermediate cyclotron (see text for references)

Preliminary computations with another model in which the beam is considered as a set of gaussian beamlets (the initial distribution is fitted with a set of distributed gaussian superparticles of which interactions are computed easily analytically) have been done. Unfortunately, only a restricted number of particles has been used and noise in the computed space charge electric field occcur after a few turns. When the number of particles is too large, the computational time becomes prohibitive. However, these simulations tend to show that the beam shape is somewhat different from the one obtained with the gaussian ellipsoid. A more refined PIC (Particle-In-Cell) code combining computations of the electric field due to space charge by solving Poisson's equation on a rectangular grid with FFT and smoothing algorithms and our tracking subroutines will be used in a next step. This kind of code has been developed to design various high intensity linac applications [16] and the apace-charge formalisn can be adapted for our purpose. In addition, various types of beam density profiles in the transverse and longitudinal directions can be used in the simulations. An alternative would be to follow the approach developed by S. Adam at PSI [17]. It is assumed that the radial and axial motions are decoupled, which allows to compute the space-charge forces by a PIC method applied to a median plane distribution only. The beam is divided into rods (of fixed height), which mutual repulsive force can be determined analytically.

6 Booster cyclotron BSSC

Up to now, no detailed beam dynamics simulations have been undertaken since space-charge effects should not be as strong in this stage. The same beam dynamics code BDWAASC (as in the previous section) will be used for the booster cyclotron with a simpler model for approximating the space charge effects of the beam [6]. The bunch is approximated by a set of small cylinders, each of them being allocated a given space-charge density. The coordinates of the cylinders are smoothed before space-charge forces are calculated.

7 Conclusion

The various space-charge models and beam dynamics programs used and being developed for the design of the various accelerator stages of the energy amplifier have been presented. Particular attention must be paid to the correct evaluation of the space-charge effects at low energy in the cyclotrons where the beam behavior depends strongly on the space-charge model. More refined models based on particle-in-cell methods will be tested in the next future in the injectors and intermediate cyclotrons.

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