Nuclear Instruments and Methods in Physics Research A 618 (2010) 298–305

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Electron dynamics simulations with *Hellweg 2D* code

Sergey V. Kutsaev

Moscow Engineering Physics Institute (State University), Kashirskoe Sh., 31, 115410 Moscow, Russian Federation

ARTICLE INFO

Article history:
Received 12 January 2010
Received in revised form
9 February 2010
Accepted 10 February 2010
Available online 6 March 2010

Keywords:
Electron linac
Beam dynamics
Travelling wave
Disk-loaded structure
Hybrid accelerator

ABSTRACT

In this paper *Hellweg 2D* code is introduced. It is a special tool for electron dynamics simulation in waveguide travelling wave accelerating structure. The underlying theory of this software is based on the differential equations of motion. The effects considered in this code include beam loading, space charge forces and external magnetic field. *Hellweg 2D* is capable of dealing with multisectional accelerators. Along with the analysis of electron linacs, this program is able to synthesize accelerating structures. This paper provides the comparison of the *PARMELA*, *Hellweg 2D* and experimental data of the existing facilities. The results of beam dynamics simulation in a hybrid accelerator with a standing wave (SW) buncher and travelling wave (TW) regular section are presented.

1. Introduction

Today there are a lot of computer codes for beam dynamics simulations in particle accelerators such as *PARMELA*, *GPT*, *RTMTRACE*, etc. All these programs posses a number of disadvantages. For example, GPT is based on a simplified model of a beam loading effect, which can be used only for a relativistic beam. *PARMELA* uses pre-calculated fields but real amplitude in each cell has to be estimated by the user. *RTMTRACE* does not allow calculating dynamics in the bunching section of linac. Meanwhile, a rather simple and convenient method for intensive beam dynamics in TW accelerating structures analysis has been proposed in 1980s [1]. This method has been realized in Moscow Engineering Physics Institute (MEPhI) via *DYNAM-1* code for M220 type computers. At present time, the necessity to advance tools for beam dynamics simulations has arisen due to a rapid computer engineering development.

Earlier efforts to create such a code for PC include the program *LINACSOLVER2D* code [2]. Unfortunately, this work remained unfinished. The program was not able to consider the space charge effect or to generate the required initial distributions, etc.

This paper presents the description of *Hellweg 2D* code designed to replenish the mentioned disadvantages and to provide the user with synthesis tools along with analysis tools. This program's algorithm is based on the equations that can consider such effects as beam loading, space charge and solenoid filed focusing. It is possible to simulate dynamics in multisectional accelerators. With the help of the reference data entered into this program, it becomes feasible to automatically determine the attenuation coefficient and the aperture size of the DLW type cells with a known phase velocity and normalized electrical field strength. The possibility to synthesize the accelerating structure with desired beam parameters can be a very useful feature of the *Hellweg 2D* code. It includes the bunching cells parameters optimizer for achieving the maximum coupling and the acceleration cells parameters optimizer for achieving the necessary output energy. In case of a constant gradient structure, the aperture radii of the cells are automatically adjusted to satisfy the condition so that the real electrical field strength in each cell remains constant.

2. Code design

2.1. Input data

Hellweg 2D code is developed in C++ programming language and works in *MS Windows* operating system. The program's algorithm is organized on the principles of object-oriented programming. The input data for this program is provided via a text file where user can determine the beam (initial phase, energy and phase distributions, input current, Twiss parameters), structure (input power, frequency and cell parameters) and computational (space charge consideration, number of particles, mesh size) parameters.

The accelerating structure is modeled in accordance with the cell parameters determined in the input file. Each cell is divided by a given number of mesh points. Phase velocity and the

Abbreviations: DLW, disk-loaded waveguide; BAS, biperiodical accelerating structure; SW, standing wave; TW, travelling wave

E-mail address: s_kutsaev@mail.ru

0168-9002/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2010.02.090

electrical field strength functions can be interpolated either by a linear or a cubic spline. Multiple input couplers can be determined in the input file. Position of each coupler is also a beginning of a new section. To avoid the unphysical effects of a power jump, the drift spaces can be modeled though the field in these tubes exactly equals to zero.

To model the initial particles in a bunch, the user can specify the energy and phase distribution parameters such as initial energy and average phase values and their RMS deviations. Both homogeneous and Gaussian distribution types are available. In the transverse space ($x-x'$) the beam is characterized by the RMS Twiss parameters α, β and ε [3]. The elliptical parameters (Fig. 1a) can be associated with geometrical parameters of injected beam (Fig. 1b) via formulae:

$$\varepsilon=\frac{4r_{in}\varphi}{\pi},\quad \beta=\frac{r_{in}^2}{\varepsilon},\quad \alpha=-\frac{\beta\varphi}{r_{in}},\quad \varphi=\frac{r_{in}-r_{cross}}{z_{cross}} \tag{1}$$

2.2. Equations of motion

After the initial bunch and structure parameters are generated, the program begins to simulate beam dynamics. The numerical model is based on the self-consistent equation system [1] describing the electrons motion in waveguide structures with variable dimensions. This system includes a 2D motion equation in an axial-symmetrical structure; an equation for a self-consistent RF-field amplitude created by the beam; and an equation for a particle's phase in a self-consistent field.

If we consider the part of the beam with a wavelength width divided by N "large" particles, the dimensionless RF-filed amplitude $A=eE\lambda/W_0$ affecting each particle and the particle's phase, the ψ in this field can be calculated using the following formulae:

$$\frac{dA}{d\xi}=A\left\{\frac{1}{2}\frac{d}{d\xi}(\ln R_b)-w\right\}-\frac{2B}{N}\sum_{n=1}^{N}I_0\left(\frac{2\pi}{\beta_w}\sqrt{1-\beta_w^2}\eta_b\right)\cos\psi_n, \tag{2a}$$

$$\frac{d\psi}{d\xi}=2\pi\left(\frac{1}{\beta_w}-\frac{1}{\beta_\xi}\right)+\frac{2B}{AN}\sum_{n=1}^{N}I_0\left(\frac{2\pi}{\beta_w}\sqrt{1-\beta_w^2}\eta_b\right)\sin\psi_n \tag{2b}$$

Here and in the further text, the following symbols are used: z—longitudinal coordinate, x—transversal coordinate; λ—operating wavelength; β_w—phase velocity of wave; J_0—accelerated current; P—input power; E—electrical field strength; B_m—magnetic field induction; c—velocity of light; W_0—electron's rest energy; W—particle's energy; α—attenuation of structure (if mentioned α stands for a Twiss parameter). Also the following expressions are assumed:

$$\xi=z/\lambda,\quad \eta=x/\lambda,\quad \gamma=W/W_0,\quad w=\alpha\lambda,\quad \Lambda=\frac{E\lambda}{\sqrt{P}},\quad R_b=\Lambda^2/2,$$
$$B=eJ_0R_b/2W_0 \tag{3}$$

The components of the dimensionless electric A and magnetic $H=ecB_m\lambda/W_0$ field amplitudes that affect each particle can be found using the formulae:

$$A_\xi=A(\xi)I_0\left(\frac{2\pi}{\beta_w}\sqrt{1-\beta_w^2}\eta\right)\cos\psi+A_\xi^{coul} \tag{4a}$$

$$A_\eta=-\frac{\beta_w}{2\pi\sqrt{1-\beta_w^2}}I_1\left(\frac{2\pi}{\beta_w}\sqrt{1-\beta_w^2}\eta\right)\times\left\{\frac{dA}{d\xi}\cos\psi-\left[\frac{2B}{N}\sum_{n=1}^{N}I_0\left(\frac{2\pi}{\beta_w}\sqrt{1-\beta_w^2}\eta_n\right)\sin\psi_n+\frac{2\pi}{\beta_w}A(\xi)\right]\sin\psi\right\}+A_\eta^{coul} \tag{4b}$$

$$H_\theta=\frac{\beta_wA(\xi)}{\sqrt{1-\beta_w^2}}I_1\left(\frac{2\pi}{\beta_w}\sqrt{1-\beta_w^2}\eta\right)\sin\psi \tag{4c}$$

Apart from RF field, these expressions also consider a space charge field. To simulate the self-consistent dynamics of the particles, it is necessary to insert the expressions (4) in the equations of motion:

$$\frac{d\beta_\xi}{d\xi}=\frac{1}{\gamma\beta_\xi}((1-\beta_\xi^2)A_\xi+\beta_\eta(H_\theta-\beta_\xi A_\eta)-\beta_\theta H_\eta^{EXT}) \tag{5a}$$

$$\frac{d\beta_\eta}{d\xi}=\frac{1}{\gamma\beta_\xi}(A_\eta-\beta_\xi H_\theta-\beta_\eta(\beta_\xi A_\xi+\beta_\eta A_\eta))+\frac{\beta_\theta}{\beta_\xi\gamma}H_\xi^{EXT}+\frac{\eta\theta^{\bullet 2}}{\beta_\xi} \tag{5b}$$

$$\eta^2\gamma\beta_\xi\frac{d\theta}{d\xi}=\frac{1}{2}(C-\eta^2H_\xi^{EXT}) \tag{5c}$$

Here the constant C determines the initial conditions of the injected beam. In case of electron gun without magnetic field $C=0$.

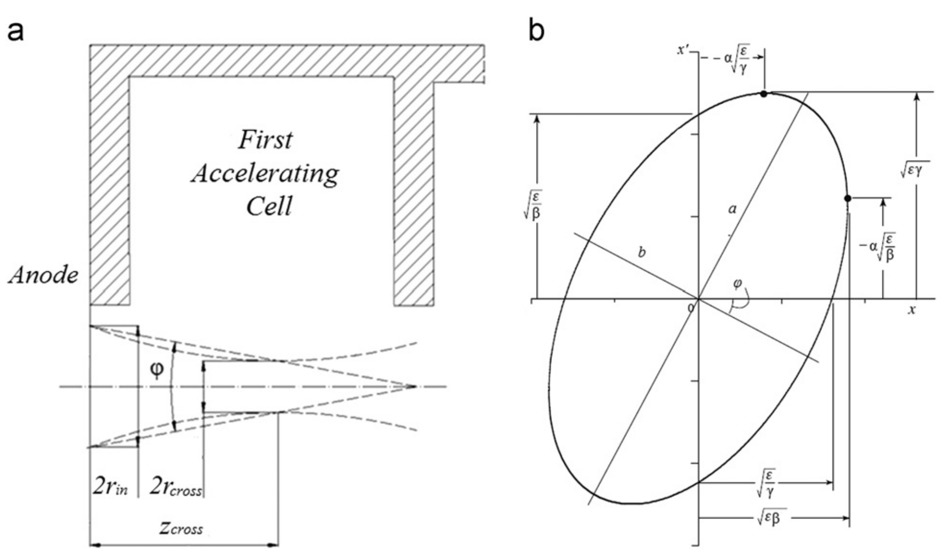

Fig. 1. Twiss parameters presentation.