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Upgraded TrapCAD Code[*]

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Abstract The TrapCAD code was developed in the 90s on DOS-platform in order to visualize the magnetic field line structure of ECR and other ion sources and to simulate the movement of individual charged particles in magnetic traps. Recently the code was re-written for Windows and underlied a major upgrading. The paper shows the new features. The spatial and energy structure of the non-lost and lost electrons are studied in a more detailed way for the case of the ATOMKI-ECRIS, as example. Using the datafiles of the lost electrons, their energy distribution is calculated and compared with known X-ray (bremsstrahlung) observations.

Key words plasma, simulation, ECR, ECRIS

1 Introduction

The original TrapCAD code[1] was developed in the 90s to visualize the magnetic field line structure of magnetic traps for charged particles with cylindrical and/or multipole geometry (that is usually used for many types of ion traps and sources, including ECRIS) and to simulate the movement of individual charged particles in the plasma chamber. It was a real mode MS-DOS application coded in C language having an event handling structure.

TrapCAD requires two input files containing the magnetic field data generated by solenoid coils and a multipole magnet. These files can be made by the user or by the SUPERFISH code[2]. The input files contain the value of the magnetic induction (B) in discrete points of a grid. To determine the B value in any continuous position two-dimensional linear interpolation was used. To draw a field line using the values of B a differential equation is solved by the 4th order Runge-Kutta method. For the charged particle trajectory simulation the motion equation is integrated by a simple but fast time-centered leapfrog scheme, where the time step is dynamically determined. The calculation contains the relativistic correction. All the functionalities of TrapCAD were described in detail in Ref. [1].

Recently TrapCAD was upgraded to get a more user-friendly graphical interface and to allow investigations of some carefully selected problems in the ECRIS plasma (e.g. spatial and energy structure of lost electrons, see below). In next sections a short summary reviews the new features and then some special phenomena will be discussed in more details.

One output of TrapCAD is the graphical display which helps the user to specify the input parameters and gives impression(s) on the result(s) of the current simulation. The main outputs however, are the 14 text files generated at each run. They contain the initial and final attributes of all particles (positions, energies, confinement times, etc.). The user usually needs professional graphical codes, as post-processors, to analyze these text files.

In this paper the most common configuration of the ATOMKI-ECRIS[3] was used to make the magnetic field input files and the plasma chamber geome-

try. The length and diameter of the plasma chamber are 225mm and 58mm, respectively, while the length of the hexapole is 200mm. The plasma chamber is longer than the hexapole by 25mm at the injection side. The hexapole field in the plasma chamber surface is 1.0 Tesla, coil mirror fields are 1.15-0.36-0.95 Tesla (max-min-max). The microwave frequency is 14.5GHz.

2 The menu

To start TrapCAD the user needs 4 files in the same folder: TRAPCAD.EXE, TRAPCAD.TXT, OUTPOI_T.TXT and OUTPAN_T.TXT. The first one is the application's executable, the second is a help file containing detailed information on running and on the structure of the output files. The last two files contain the magnetic field values of the given magnetic trap. We ran the code under Windows XP operation system on personal computers with different configurations. There are no special hardware requirements, but fast micro-processor, large memory and large size monitor are obviously advantages.

After starting the code the side and end views of the cylindrical plasma chamber are displayed. By moving the mouse the actual coordinates and magnetic values are shown. Using a pop-down menu the user can set some conditions and can start different simulations. The menu items are: FILE, SETTINGS, COMMANDS, FIELD LINES, 1 PARTICLE, N PARTICLE, and HELP. Below we give a short (not full) summary of this menu. The detailed description can be found in the TRAPCAD.TXT help file.

FILE menu item. The user can select one or both components of the magnetic trap to be taken into account (coils' field and/or multipole's field).

SETTINGS menu item. Some effects can be switched on/off. If the "Edge-effect" switch is on the code includes the modified magnetic field of the multipole magnet at the edges. Based on measured data at several ECRISs and approximating the permanent magnet multipoles by wire conductors a semi-empirical formula was found[1]. "ECR heating": the

exact, mathematical description of the electron heating by electron cyclotron resonance (ECR) is quite complicated because of the multiple RF modes inside the chamber. However, the stochastic process can be studied and one can get valid values for the energy gaining assuming a simple RF field in realistic magnetic field configuration. A circularly polarized plane wave is assumed propagating along the z axis. The electric vector of this type of wave is rotating in the x-y plane of the chamber. The amplitude of this field is estimated from the applied microwave power.

COMMANDS menu item. The resonance surface can be calculated and drawn. An optional two-dimensional magnetic map file can be generated at any plane for post-processing visualization.

FIELD LINES menu item. Single field lines or set of field lines can be calculated and drawn (full lines or end-points) optionally, including the resonance magnetic field values.

1 PARTICLE menu item. This is the same as in the original TrapCAD: using the mouse one can start a single particle from any position with any energy. Its path is visualized and saved.

N PARTICLE menu item. The simultaneous motion of any number of individual particles (electrons) can be simulated. The starting position of the electrons is random within the selected region which can be: (1) the whole plasma chamber, (2) the resonance surface or (3) a biased electrode. The code calculates and saves the starting and ending positions and energies of the electrons which remained in the plasma chamber after the simulation time (non-lost particles). These electrons draw out the actual shape and structure of the ECR plasma depending on the starting conditions and on the features of the electron cyclotron resonance phenomena. Other text files are generated containing the initial and final attributes (positions, energies) of electrons lost on the surface of the plasma chamber. In Fig. 1. a typical output of the new TrapCAD is shown with explanation texts.

We emphasize that TrapCAD was and still is a single-particle code. Particle-particle interactions are neglected. An estimation was given for the average collision times in[4]. Considering "usual" plasmas

generated by ECR ion sources the calculations by this code last from several hundreds of nanosecond to several microseconds. In the examples presented in this paper the calculation time was usually between 200 and 1000 nanosecond. We started 20000 electrons which resulted about 10^4-10^4 electrons both for the non-lost and lost populations. One simulation using a usual personal computer lasted 10—20 hours. The code needs ranges of starting energies for both the perpendicular and parallel energy components. In the presented examples the perpendicular component start-range was set to 10—20000eV, while the parallel was between 10—200eV. Between the minimum and maximum values the energy components are generated randomly. The applied microwave power was 500—1000 watt. In some simulations this value was artificially increased (as in[5]) which resulted in the same effect as a longer simulation time.
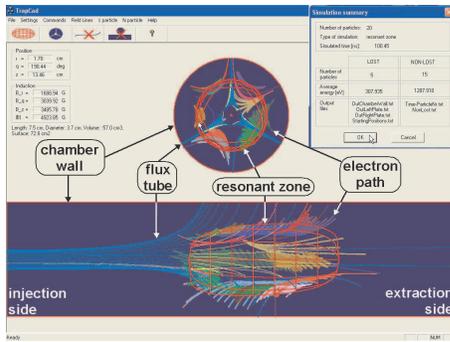
Fig. 1. Hardcopy of a typical TrapCAD display with bubble notes.

3 N-particle simulation: the plasma

As mentioned before, in the new code the movement of any number of electrons can be simulated and followed. If the number of electrons started is large enough, after a suitable simulation time the non-lost electrons draw out the spatial position and structure of the ECR plasma. This is shown in Fig. 2 together with projected plasma "slices" which may help understanding the still quite complicated spatial structure of the ECR electrons. Plasma ions are assumed to have similar structure and shape as the electrons due to the quasi-neutrality principle. We note that our plasma visualization fits well with earlier visi-

ble light and X-ray photos[6, 7] and also with other simulations[5].
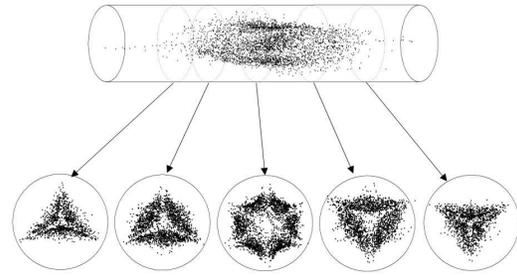
Fig. 2. The spatial distribution of electrons in ECR ion sources.

The energy structure and distribution of the plasma electrons were already studied in detail elsewhere[5]. In this paper we deal mostly with lost-electrons (see next section). Here we just make a prompt comparison between the energy spectra of lost and non-lost electrons (Fig. 3). Low energy electrons are lost rapidly, while the plasma can contain small number, but very high energy electrons. The simulation was made with the following starting conditions: start position - resonance surface, electron numbers – 10^5(both lost and non-lost), simulation time 500ns.
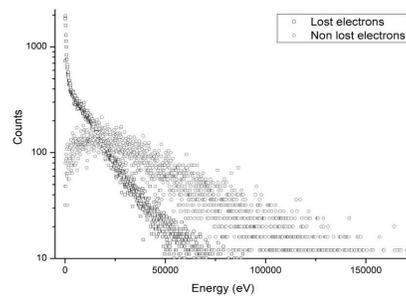
Fig. 3. The energy distribution of non-lost (plasma) and lost electrons.

We performed some preliminary runs with Trap-CAD using the biased disc as the source of the electrons. The result of these simulations can be summarized in two points: (1) Majority of biased disc electrons do not approach the resonance surface so their energy is unchanged. (2) Majority of biased disc electrons are lost radially at the chamber wall in several nanoseconds. Fig. 4 shows a comparison between the three groups of non-lost (plasma) electron numbers as the function of time. Depending on the starting positions (resonance surface, whole chamber,

biased disc) the electron loss-rate differs very much. In this simulation the distance of the biased disc from injection wall was 25mm, its diameter was 20mm, the energy of the electrons at start was 100eV, the direction of the electrons was random at one side of the disc. We note that a more systematic study is possible and necessary (e.g. effect of the disc position and voltage etc.).
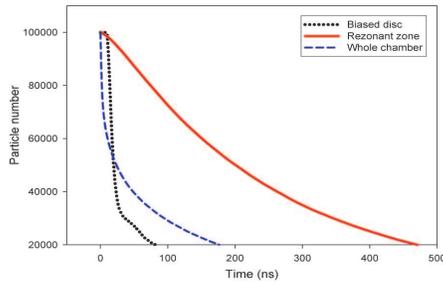
Fig. 4. The time-evolution of the non-lost (plasma) electron population depending on the starting positions.

4 N-particle simulation: lost electrons

In this section we show the capabilities of Trap-CAD to simulate electron losses. All electrons were started from the resonance surface (of the ATOMKI-ECRIS). In Fig. 5 the lost points of the electrons on the three main components of the cylindrical plasma chamber (injection plate, chamber wall, extraction plate) are shown. These patterns are in very good visual agreements with those (produced by ions) observed in all ECRISs.
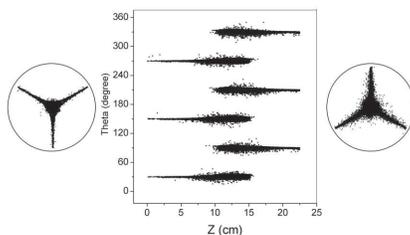
Fig. 5. The end-points of paths of the lost electrons at walls of the plasma chamber.

If we concentrate only to radial losses 3D visualization gives better impression on the energy distribution of the lost electrons (Fig. 6). Fig. 7 shows one of the six axial loss patterns; upper part: number of electrons, lower part: total energy of electrons.

It can be seen that both the particle concentration and energy is the highest close to the resonance zone (actually the center of the plasma chamber).
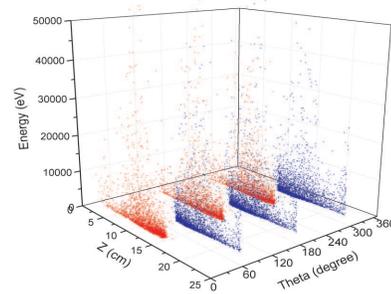
Fig. 6. The energy of radially lost electrons depending on their positions.

We can make a comparison between the radially and axially lost electrons (Fig. 8). The cylindrical chamber wall collects mostly the low energy electrons and only a small fraction of them can reach high energies. The highest energy X-rays produced by electron hitting however, are generated at the injection and extraction plates. This observation is in good qualitative agreement with experimentally measured X-ray energy distribution curves (see e.g.[8]). In our simulation there is a slight difference between the injection and extraction loss curves, caused by the asymmetrical arrangement of the ATOMKI-ECRIS (both magnetical and geometrical).
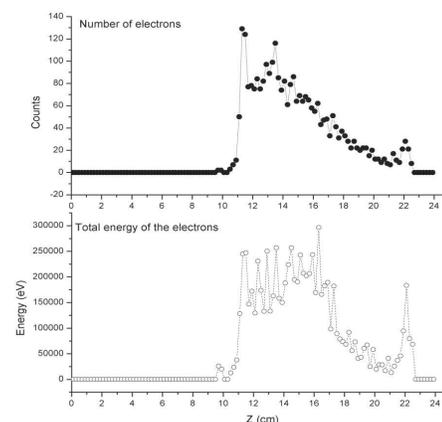
Fig. 7. Electron distribution and total energies of radially lost electrons.
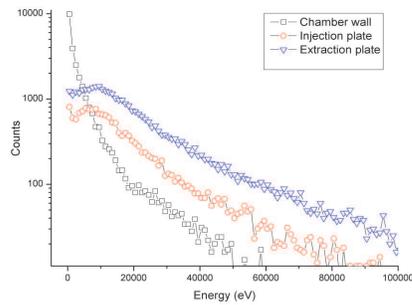
Fig. 8.　Energy distribution of the axially and radially lost electrons.

5　Conclusion

The new TrapCAD can visualize the magnetic trap of ECR and other ion sources (including multipole edge effects). The simulation of large number of individual electrons (including the electron cyclotron resonance phenomena) gives realistic spatial information on the non-lost (plasma) and lost electrons. The energy distribution curves of lost electrons at different parts of the plasma chamber can be compared with X-ray measurements.

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