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PPPL Lorentz orbit code

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A code that integrates the Lorentz force equation has been developed to trace a single charged particle's trajectory under the influence of toroidally symmetric magnetic fields found in tokamaks. This code is used primarily to design and estimate the efficiency of charged fusion product probes, which detect escaping energetic ions such as the 1 MeV tritons, 3 MeV protons, 15 MeV protons, and 3.5 MeV alphas created in TFTR. This interactive code has also been used as a teaching tool to illustrate classes of orbits such as trapped and passing, as well as subtle orbital motions, e.g., precession of banana orbits in tokamaks, or orbits in dipole magnetic field configuration. This paper describes the code as well as recent modifications which (1) include Shafranov shifts of the magnetic surfaces, (2) use more realistic current density profiles, and (3) allow modeling of the detector and limiters.

I. INTRODUCTION

The ORBIT code traces a single charged particle's trajectory under the influence of static, toroidally symmetric, magnetic fields. It is primarily intended as a tool for the design of charged fusion product detectors in tokamaks with circular plasmas. It can also explore the physics of charged particle orbits. This program was based on one written for PLT[1,2] to design 15 MeV and 3 MeV proton detectors, and the code can now handle a variety of particle detectors. As a teaching tool, it illustrates the classes of orbits such as trapped and passing, as well as subtle orbital motions, e.g., precession of banana orbits.

II. PHYSICS ASSUMPTIONS

A given particle's orbital path is calculated from parameters defining the geometry and magnetic field of the environment. The code assumes Shafranov-shifted circular flux surfaces with the current distribution described by the rotational transform, q, on each surface. The code essentially integrates the Lorentz force $d\mathbf{v}/dt=\mathbf{v}\times\mathbf{\Omega}$, where $\mathbf{\Omega}$ is the cyclotron frequency $e\mathbf{B}/mc$. It also integrates $d\mathbf{x}/dt=\mathbf{v}$ at the same time. The integration is carried out by using the IMSL routine, DVERK.[3] Collisions are not included.

The code actually works in units where $|v|$ is unity, and hence by definition conserves energy. The magnetic moment ($\mu = W_\perp/|B|$, where $W_\perp$ is the particle perpendicular energy) is tested to check that its variation remains small. To obtain this conservation of μ requires that the magnetic field be divergenceless by defining the poloidal field in terms of the gradients of scalar potentials (assuming toroidal symmetry):

$$\mathbf{B}_{\text{poloidal}}=\nabla\phi\times\nabla\psi=\hat{\phi}/R\times\nabla\psi \tag{1}$$

and

$$\nabla\psi|_x=\frac{\partial\psi}{\partial r}\frac{\partial r}{\partial x}, \tag{2}$$

where the first term is the average poloidal field

$$\frac{\partial\psi}{\partial r}=B_p=\frac{B_{T_0}R_0}{q(r)}\frac{r}{[R+\delta(r)]^2} \tag{3}$$

and the second term $\partial r/\partial x=\cos\theta/(1+\delta'\cos\theta)$ includes the effects of the shifted circles, where θ is the poloidal angle and δ' is the derivative of the Shafranov shift.

Poloidal magnetic fields may be modeled by making the current density a parabola to some power, $J(r)=J_0[1-(r/a)^2]^\alpha$, where r is the radius of the flux surface and a is the plasma minor radius. The toroidal magnetic field is proportional to $1/R$, with the central value specified. The Shafranov shift can also be modeled as a square root function of minor radius. The source reaction rate density Sdl may also be modeled in the form of a parabola to some power, $S(r)=S_0[1-(r/a)^2]^\beta$, which is integrated along the orbit to determine the efficiency of particle collection by the detector versus μ and the particle energy E.[4]

The orbit may be followed forward in time from where it originates somewhere in the plasma. However, the default direction for tracing an orbit is usually "reversed" in time from the detector out into the plasma. When the forward direction is selected, the sign of the magnetic field is reversed by the code.

The external time step used in the code is normalized to be the time for the particle to go a fixed length, typically 1 cm. The orbit length is the total distance of the orbit path in cm. The step factor is the distance in cm over which to integrate the equations of motion between time steps. While the exact orbit is followed by the differential equation solver between time steps, plot points are generated and the efficiency is evaluated only at the positions at each time step. The code limits the delta time steps (orbit length/step factor) to $\leqslant$15 000.

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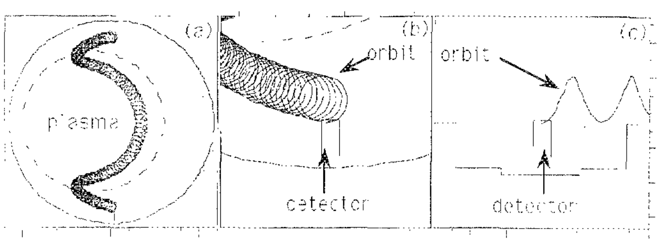

FIG. 1. Typical escaping 3.5 MeV alpha particle orbit. In poloidal views, (a), (b), circles represent minor radius of plasma, bellows cover plate, vessel wall, and detector port gap, from smallest to largest, respectively. (c) Side view of orbit and detector in the (y,z) plane.

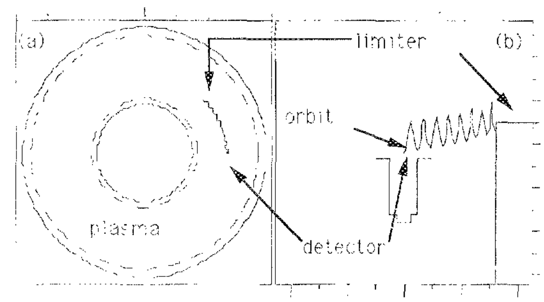

FIG. 2. Orbit intersection with limiter. (a) Interruption of orbit in toroidal plane. (b) Closeup of orbit intersection with limiter.

The properties of the particle are defined by the charge, atomic mass, and energy (in MeV). Typical energies for particles are 3.5 MeV alpha for $d(t,n)\alpha$, 3.4 MeV alphas for $d(^3He,p)\alpha$, 14.7 MeV protons for $d(^3He,p)\alpha$, 1.0 MeV tritons for $d(d,p)t$, 3 MeV protons for $d(d,p)t$, and 0.8 MeV ^3He in $d(d,n)^3He$ reactions.

In Fig. 1, the orbit of a 3.5 MeV alpha particle at a plasma current I_p of 2.2 MA and B_{T_0} of 4.1 kG is calculated backwards in time from the detector for a pitch angle of 60° and a gyro angle of 0°. The orbit starts at 103 cm below the plasma midplane, and passes by the local obstacles without intersecting them.

III. DETECTOR DESIGN

Parameters describing the detector location, and pitch and gyro angles of the particle as they hit the detector, are used to determine the orbit. The code defines the pitch angle with respect to the toroidal field. If the detector location is placed inside the plasma minor radius, the code will calculate the orbit as though the detector is not there.

The code uses the orbit to calculate the efficiency ϵ of particle detection, i.e., the ratio of the detected flux at a given μ and E to the total particle creation rate (typically $\epsilon \approx 10^{-8}$). To do this, it uses a detector solid angle specified by two rectangular detector apertures of variable size and separation. The code integrates *Sdl* over the orbit passing through the center of the apertures; for more precise calculations the aperture is subdivided into a rectangular array of initial orbit directions for which orbits and efficiencies are calculated separately, then summed.

Limiters which can intercept particles near the plasma boundary may be defined by their poloidal extent, minor radius of the leading edge of the limiter with respect to the center line of the tokamak, major radius from the center of the tokamak to the center of the circle defined by the radius of the leading edge, and the limiter halfwidth. The code checks for orbit intersection with the limiters(s) by determining if the orbit is within prescribed bounds (Fig. 2). No limiter intersection checking is done when the position of the particle's orbit is less than the plasma minor radius.

Machine parameters describe the vessel major radius, vessel minor radius, bellows cover plate width and radius, and detector port gap width and radius. This information is critical in determining whether orbits can pass by local obstacles near the detector.[5] Considerable effort has been made to try to generalize the description of the machine geometry to allow flexibility in design.

More realistic modeling of plasma conditions can be obtained by using actual data from the Tokamak Fusion Test Reactor (TFTR) SNAP database for any shot try from a TFTR run. Parameters returned to the ORBIT code are: number of radial zone boundaries (usually 20), position of zone boundaries, plasma current, toroidal field, plasma major and minor radii, Shafranov shift $\delta(r)$, and $q(r)$ profile. At present, the magnetic fields outside the last closed flux surface are not correctly modeled with a Shafranov-shifted equilibrium with either the modeled or SNAP magnetic profiles. Although using a $\delta(r)$ profile inside the last closed flux surface correctly approximates the force balance of the equilibrium, the force from the external vertical field is not added outside the plasma. Attempts to include the correct external field structure[6] exhibit difficulties with realistic, high β_p (>1) equilibria as the assumption of circularity breaks down at the same time $\delta'(r)$ approaches unity at the last closed flux surface. Work is under way to improve this modeling.

A SNAP shot try may also be used to obtain the source reaction rates. The SNAP database stores three types of reactions (thermal, beam-thermal, beam-beam). For each type of reaction rates there can be D-D, D-T, D-^{3}He, T-T, and T-^{3}He sources. The available reaction rates for the selected sources are summed to produce a total rate. The $\int Sdl$ for efficiency calculations is calculated by interpolating the values at the zone boundaries.

IV. OTHER USES

ORBIT is also used as a teaching tool to illustrate the two classes of orbits in a torus, trapped (or banana) and passing. The pitch angle of a particle determines whether it freely circulates around the torus (passing) or is reflected at regions of higher magnetic field intensity at smaller major radii. These latter orbits, called banana trajectories because of their shape in a poloidal view, have a width approximately inversely proportional to I_p. The tips of the banana orbits may precess around the torus (in the toroidal direction) with a direction determined by the location of the banana tips in the poloidal direction (Fig. 3).

Besides determining the efficiencies for fusion product detectors, ORBIT has been used to compute the trajectories of various groups of charged particles whose pitch

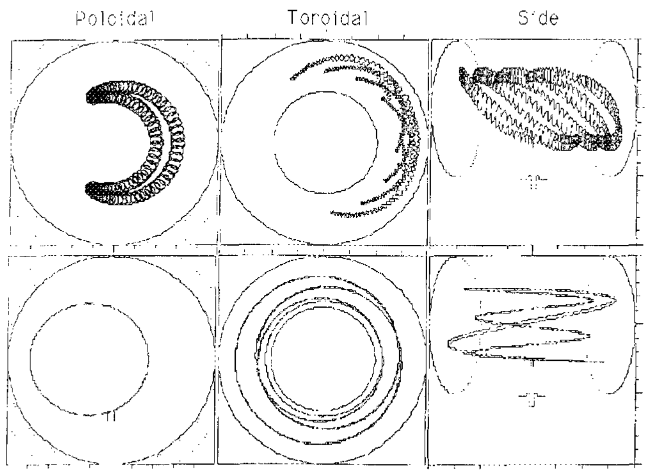

FIG. 3. Classes of orbits. Top: Banana orbit and precesses. Bottom: Passing orbit exhibiting deflection toward tokamak central line.

angle is varied. Such calculations help to assess whether there is any tendency for certain groups of ions to be lost to either the top or the bottom of the vacuum vessel, thus causing up/down asymmetries in the scrape off plasma. They also help to assess the contribution of various classes of particles to edge power and heat fluxes. Figure 4 shows how beam particles born on counter orbits have a much greater tendency to transport toward the edge plasma while those born on co-orbits tend to be better confined toward the center of the plasma.

Orbits in pure dipole fields can be simulated by setting B_{T_0} to approximately 0, and confining I_p to a narrow ring.

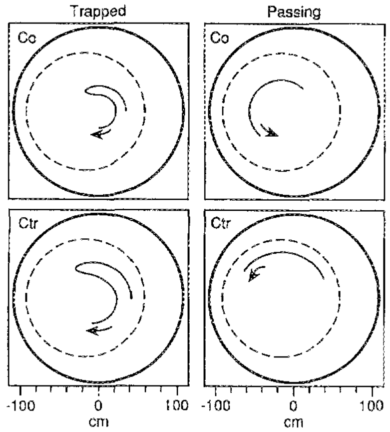

FIG. 4. Co and counter prompt neutral beam particle orbits in TFTR plasma showing radial drift tendencies.

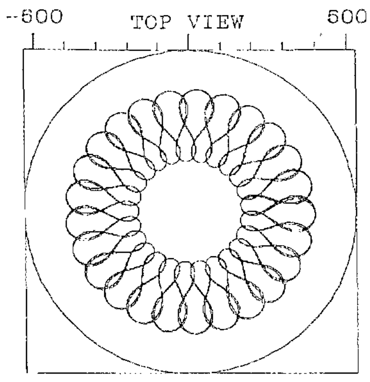

FIG. 5. Figure 8 orbit in dipole magnetic field as seen in the toroidal plane.

In Fig. 5, a launched particle has 0 energy in the z direction in a B field for which the current profile is flat from $0<r<265$ cm, and is hence confined to the midplane. It moves in a figure 8 pattern across the null in plasma current, reversing the curvature of its orbit. In spite of loss of μ conservation, the motion is nearly periodic.

V. SUMMARY

The ORBIT code is a useful tool not only in designing charged fusion product detectors, but as an illustrative tool in assessing charged particle orbits under actual experimental conditions, as well as demonstrating classes of orbits. It is used to determine whether limiter placements interfere with orbital paths, to predict trajectories based on detector location and dimensions, and to calculate absolute efficiencies of those detectors. Trajectories can be simply modeled, or more detailed plasma conditions can be defined to evaluate a given particle's behavior.

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[1] R. E. Chrien, Ph.D. thesis, Princeton University, 1981.
[2] W. W. Heidbrink, Ph.D. thesis, Princeton University, 1984.
[3] *IMSL User's Manual: Math/Library*, 9th ed. (IMSL, Houston, 1982).
[4] W. W. Heidbrink and J. D. Strachan, Rev. Sci. Instrum. **56**, 501 (1985).
[5] S. Zweben, Rev. Sci. Instrum. **60**, 576 (1989).
[6] V. S. Mukhovatov and V. D. Shafranov, Nucl. Fusion **11**, 605 (1971).