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Geometric integrator for charged particle orbits in axisymmetric fusion devices

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Abstract

A semi-analytical geometrical integrator of guiding center orbits in an axisymmetric tokamak is described. The integrator preserves all three invariants of motion up to computer accuracy at the expense of reduced orbit accuracy and it is roughly an order of magnitude more efficient than a direct solution of the equations of guiding center motion with a standard ODE integrator.

Key words: plasma physics; kinetic modelling; numerical integrators

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I. INTRODUCTION

An evaluation of the distribution function and/or its moments by direct modelling of particle orbits is widely used in plasma physics (see, e.g., codes like EUTERPE^{1,2} or ASCOT³). An efficient algorithm for calculation of trajectories of charged particles in complex (quasi-)stationary magnetic and electric fields is one of the key issues in such codes because of the high number of test particle orbits required to minimize the statistical error of such calculations, which scales inversely with the square root of the number of test particles. This issue is especially important for global transport modelling (e.g., see Ref. 4) where the profiles of plasma parameters are calculated self-consistently from test particle trajectories, which have to be traced over the profile relaxation (confinement) time.

Within transport modelling, computation of stochastic test particle orbits⁵ requires the solution of guiding center equations^{6,7}, which is usually performed with help of general-purpose ODE integrators. In case of axisymmetric systems (tokamaks) the guiding center motion is fully integrable, because there exist three integrals of motion, which fully determine each orbit in the 5D phase space: The total energy w , magnetic moment μ and the canonical toroidal angular momentum p_φ , respectively given by

$$w = \frac{m(v_\perp^2 + v_\parallel^2)}{2} + e\Phi, \quad \mu = \frac{mv_\perp^2}{2B}, \quad p_\varphi = mv_\parallel \frac{B_\varphi}{B} + \frac{e}{c}A_\varphi, \quad (1)$$

with electrostatic potential Φ , magnetic field module B , co-variant toroidal component of the magnetic field B_φ , co-variant toroidal component of the vector potential A_φ , speed of light c , particle charge e , mass m , perpendicular velocity v_\perp , and perpendicular velocity v_\parallel . An accurate conservation of the invariants (1) is of primary importance for transport modelling while other accuracy requirements related to orbits can be significantly relaxed. Algorithms with such exact (up to computer accuracy) conservation of invariants are called *geometrical integrators* (see, e.g., Ref. 8).

In the following sections we will introduce and study such an integrator suitable for transport modelling of axisymmetric fusion devices. In a comparison with commonly used general-purpose ODE integrators one can expect two advantages: First, in numerical efficiency; and second, such an algorithm should be less sensitive to the accuracy of the representation of the electromagnetic field allowing also for statistical noise in these data.

II. DERIVATION OF THE INTEGRATOR

In general magnetic field geometry, equations of guiding center motion with invariants w and μ used as velocity space variables are⁷

$$\dot{\mathbf{r}} = \frac{v_{\parallel} \mathbf{B}^*}{B h_{\parallel}^*}, \quad \mathbf{B}^* = \nabla \times \left(\mathbf{A} + \frac{m c v_{\parallel}}{e B} \mathbf{B} \right), \quad h_{\parallel}^* = \frac{\mathbf{B} \cdot \mathbf{B}^*}{B^2}, \quad (2)$$

where \mathbf{B} and \mathbf{A} are magnetic field and vector potential, respectively, and $v_{\parallel} = v_{\parallel}(\mathbf{r}, w, \mu)$ is determined by the first two Eqs in. (1). In axisymmetric geometry using cylindrical variables (R, φ, Z) , equations of motion omitting the symmetry variable φ take the form

$$\begin{aligned} \dot{R} &= -\frac{1}{R h_{\parallel}^*} \left(\frac{\partial A_{\varphi}}{\partial Z} \frac{1}{m B_{\varphi}} \left(p_{\varphi} - \frac{e}{c} A_{\varphi} \right) + \frac{m c B_{\varphi}}{2e} \frac{\partial}{\partial Z} \left(\frac{v_{\parallel}}{B} \right)^2 \right), \\ \dot{Z} &= \frac{1}{R h_{\parallel}^*} \left(\frac{\partial A_{\varphi}}{\partial R} \frac{1}{m B_{\varphi}} \left(p_{\varphi} - \frac{e}{c} A_{\varphi} \right) + \frac{m c B_{\varphi}}{2e} \frac{\partial}{\partial R} \left(\frac{v_{\parallel}}{B} \right)^2 \right). \end{aligned} \quad (3)$$

The varying part of $B_{\varphi} = B_{\varphi}(\psi)$ as a function of poloidal flux $\psi = -A_{\varphi}$ is of the order of plasma beta or of the square of the ratio of the poloidal and toroidal field strengths. In most tokamaks this variation is only a few percent and can be safely ignored. With this assumption, Eqs. (3) are rewritten as

$$\dot{R} = -\frac{1}{R h_{\parallel}^*} \frac{\partial}{\partial Z} \mathcal{H}, \quad \dot{Z} = \frac{1}{R h_{\parallel}^*} \frac{\partial}{\partial R} \mathcal{H}, \quad (4)$$

where a Hamiltonian like function \mathcal{H} is

$$\mathcal{H} = \frac{c B_{\varphi}}{e} \left(\frac{w}{B^2} - \frac{\mu}{B} - \frac{e \Phi}{B^2} \right) - \frac{e}{2 m c B_{\varphi}} \left(A_{\varphi} - \frac{c}{e} p_{\varphi} \right)^2. \quad (5)$$

Particle orbits are then determined by the condition $\mathcal{H} = 0$. A numerically efficient low order approximation of these orbits can be obtained if one uses in (5) a linear interpolation for the following functions of coordinates $\mathbf{x} = (x^1, x^2) \equiv (R, Z)$,

$$f_A(\mathbf{x}) \equiv A_{\varphi}, \quad f_B(\mathbf{x}) \equiv \frac{1}{B}, \quad f_{\Phi}(\mathbf{x}) \equiv \frac{\Phi}{B^2}, \quad (6)$$

discretized on a triangular mesh. As a result, \mathcal{H} (5) becomes a continuous piecewise quadratic function,

$$\mathcal{H} = \frac{1}{2} \sum_{i,j=1}^2 a_{ij} (x^i - x_a^i) (x^j - x_a^j) - \frac{1}{2} \sum_{i,j=1}^2 a_{ij} (x_0^i - x_a^i) (x_0^j - x_a^j), \quad (7)$$

where the coefficients a_{ij} are constant within a given triangle and are determined by initial values of the particle coordinates \mathbf{x}_0 and the velocity components $v_{\perp 0}$ and $v_{\parallel 0}$ in this triangle as follows,

$$a_{ij} = \frac{1}{\alpha} \left(v_{\perp 0}^2 + v_{\parallel 0}^2 + \frac{2ef_{\Phi}(\mathbf{x}_0)}{mf_B^2(\mathbf{x}_0)} \right) \frac{\partial f_B}{\partial x^i} \frac{\partial f_B}{\partial x^j} - \alpha \frac{\partial f_A}{\partial x^i} \frac{\partial f_A}{\partial x^j}. \quad (8)$$

Here, $\alpha = e(mcB_{\varphi})^{-1}$, and the constants x_a^i are the solution to the following linear equation set,

$$\sum_{j=1}^2 a_{ij}(x_0^j - x_a^j) = v_{\parallel 0} f_B(\mathbf{x}_0) \frac{\partial f_A}{\partial x^i} + \left(v_{\perp 0}^2 + 2v_{\parallel 0}^2 + \frac{4ef_{\Phi}(\mathbf{x}_0)}{mf_B^2(\mathbf{x}_0)} \right) \frac{f_B(\mathbf{x}_0)}{2\alpha} \frac{\partial f_B}{\partial x^i} - \frac{e}{m\alpha} \frac{\partial f_{\Phi}}{\partial x^i}. \quad (9)$$

The spatial particle trajectories, $\mathcal{H} = 0$, are then continuous piecewise second order curves. Due to continuous interpolation of all functions of the coordinates in Eq. (1), orbits are continuous also in the velocity space where preferable variables are $(v_{\perp}, v_{\parallel})$. Those are more convenient for modelling of collisions and of anomalous transport, both required in transport simulations. A parametric (time-dependent) form of orbit segments is obtained from the equations of motion (4), which are further simplified by ignoring the Larmor radius correction, $h_{\parallel}^* \rightarrow 1$ and by replacing R with a constant \bar{R} being the radial coordinate of the center of mass of a given triangle,

$$\dot{x}^i = \frac{(-1)^i}{\bar{R}} \sum_{j=1}^2 a_{ij} (x^j - x_a^j). \quad (10)$$

This approximation does not affect the orbit shape. Depending on the sign of the determinant $D = \det(a_{ij})$, orbits are either ellipses ($D > 0$) or hyperbolas $D < 0$, respectively given by

$$\begin{aligned} x^i &= x_a^i + x_c^i \cos(\omega \Delta t) + x_s^i \sin(\omega \Delta t), & D > 0, \\ x^i &= x_a^i + x_c^i \cosh(\omega \Delta t) + x_s^i \sinh(\omega \Delta t), & D < 0, \end{aligned} \quad (11)$$

where Δt is the integration time step,

$$\omega = \frac{|D|^{1/2}}{\bar{R}}, \quad x_c^i = x_0^i - x_a^i, \quad x_s^i = \frac{(-1)^i}{|D|^{1/2}} \sum_{j=1}^2 a_{3-i,j} x_c^j. \quad (12)$$

The numerical implementation of this integrator is quite straightforward: One follows the test particle for the time step Δt (usually determined by collisions or anomalous transport) using Eqs. (11) and modifies its velocities $(v_{\perp}, v_{\parallel})$ according to the conservation laws (1).

If Δt exceeds the time to reach a boundary of the triangle, one stops the trajectory at this point of intersection. Its coordinates, \mathbf{x}_b , satisfy a quadratic equation, and the corresponding time can be found from (11) for $\mathbf{x} = \mathbf{x}_b$. Then one follows the particle in the next triangle using the point of intersection as a new starting point \mathbf{x}_0 and its local velocities as new $v_{\perp 0}$ and $v_{\parallel 0}$.

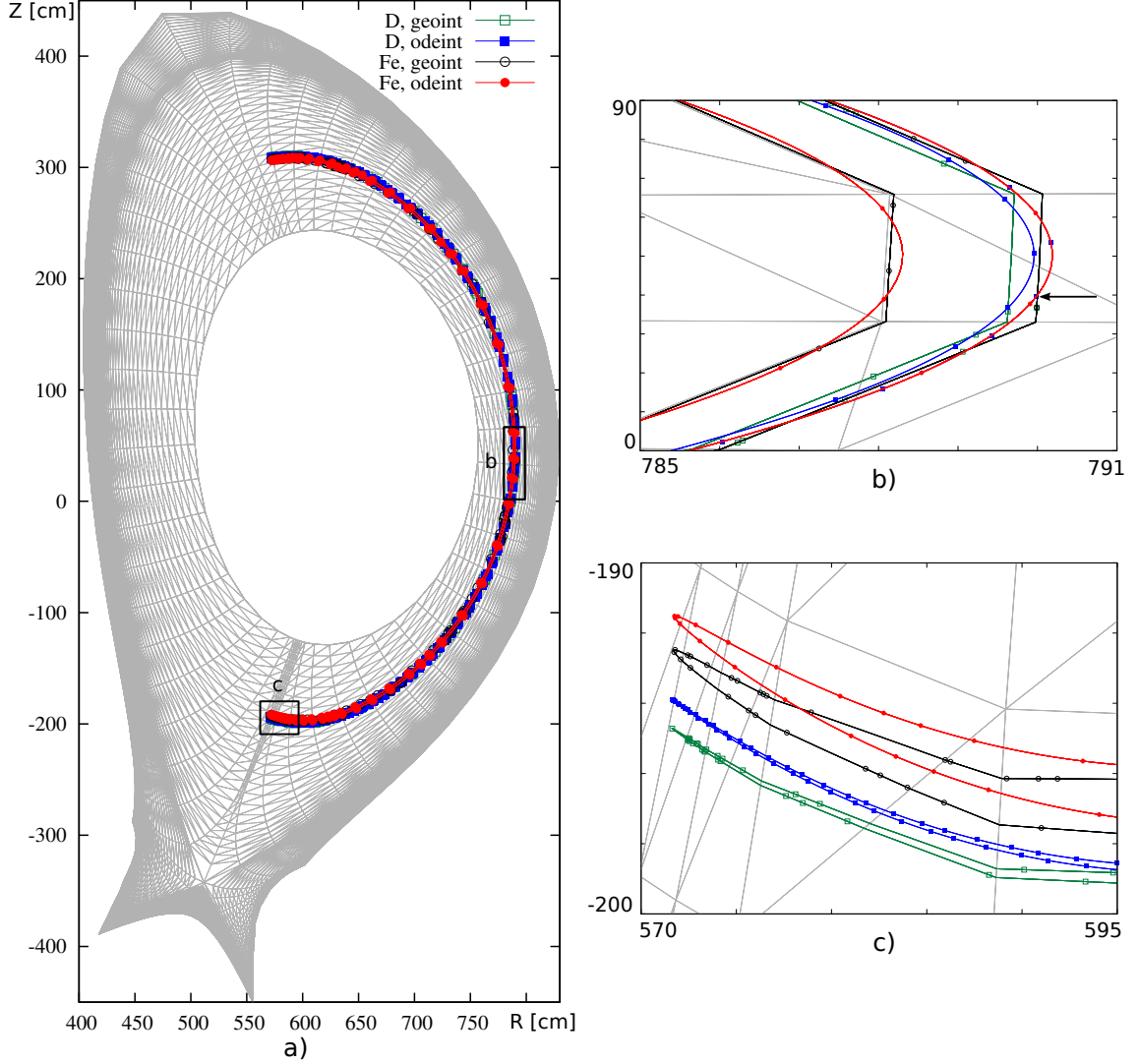


FIG. 1: a) – Geometry of an ITER-like configuration and example orbits (squares – D ions; circles – Fe ions; open symbols – geometrical integrator from Sec. II; filled symbols – *odeint*⁹). b) and c) – magnification of the pertinent zones in a). The arrow points to the starting point of all four trajectories depicted.

III. BENCHMARKING

We now compare the results obtained by the geometrical integrator derived in the previous section and a conventional adaptive ODE integrator, *odeint* (Ref. 9). The magnetic configuration we use is ITER-like (the same had been used in Ref. 4) with zero electric field everywhere.

The triangular mesh required for the geometrical integrator has been produced from an nearly orthogonal field-aligned quadrangular mesh used for fluid modelling by the B2 code¹⁰. The *odeint*⁹ solver has been employed here for the full 3D system of guiding center equations⁷ in the covariant representation¹¹ for cylindrical coordinates. A very accurate divergence-free representation of the magnetic field based on 2D spline interpolation (5th order) of the poloidal flux function has been used for this integrator, which acts as a reference case’.

As an example, a few collisionless trajectories calculated by the geometrical integrator for trapped deuterium and iron ions are presented in Fig. 1 together with pertinent orbits from the reference case. In addition, the used triangular mesh is also shown. All orbits almost coincide in the overview figure (a), but the magnification of the zones (b) and (c) shows a noticeable difference in some details of the trajectories, especially in the region of the banana tips shown in (c). This shift is related to the crude representation of the field-related values, Eq. (6), on the mesh. The integrator preserves all constants of motion exactly, therefore, an initial error introduced by a linear interpolation at the start point (arrow in Fig. 1, b) propagates along the whole trajectory. Indeed, if one starts the trajectories near the corner of a cell (where this error vanishes), the shift between the banana tips vanishes, too. It should be noted that the B2 mesh is optimized to represent the hydrodynamical plasma parameters. For transport studies, this interpolation can be essentially improved without suffering from larger costs.

However, the crucial point is how, if at all, these differences affect the overall transport properties of the system. To check this, we add collisions to our model according to Ref. 5. Test particles are started at the same point as before, but with random, evenly distributed pitch parameters $v_{\parallel 0}(v_{\perp 0}^2 + v_{\parallel 0}^2)^{-1/2}$, and are followed for 10 collisional times τ_{coll} . During this process, the time evolution of the poloidal flux at the particle location is stored. The variance of the poloidal flux deviation $\langle(\psi - \psi_0)^2\rangle$ (ψ_0 is the flux at the start point) serves as a measure of the neoclassical radial diffusion coefficient of the system. The results of the

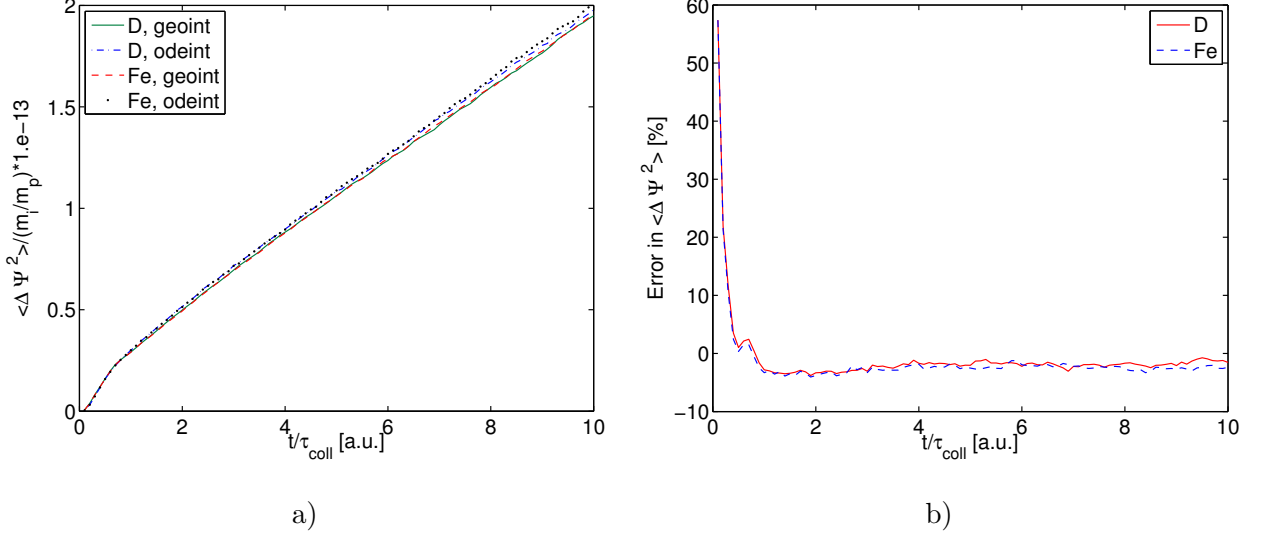


FIG. 2: a) – Variance of the poloidal flux deviation $\langle(\psi - \psi_0)^2\rangle$ normalized to the mass ratio as a function of normalized time: solid line – D, geometrical integrator, dash-dot line – D, conventional integrator, dash line – Fe, geometrical integrator, dotted line – Fe, conventional integrator. b) – the relative error of the variance, $(\langle(\psi - \psi_0)^2\rangle_{geoint} - \langle(\psi - \psi_0)^2\rangle_{odeint})/\langle(\psi - \psi_0)^2\rangle_{odeint}$ in percent: solid line – D, dash line – Fe.

Monte Carlo computations of this variance (normalized to the mass ratio for D and Fe), obtained with help of the geometrical integrator and of the reference case integrator are presented as functions of time in Fig 2, a). Again, the curves almost coincide. To emphasize the difference, we plot the relative error, $(\langle(\psi - \psi_0)^2\rangle_{geoint} - \langle(\psi - \psi_0)^2\rangle_{odeint})/\langle(\psi - \psi_0)^2\rangle_{odeint}$ in percent, see Fig 2, b). A significant relative difference is present only at the start of the trajectories, $t \leq \tau_{coll}$, where the change of ψ due to collisions is small compared to the orbit width and thus is of no importance. After one collision time the difference converges to an acceptable value of a few percent. As it was mentioned above, this value can be reduced further by optimization of the mesh.

The estimation of the relative numerical efficiency of the integrators is a subtle matter: The systems which are solved are not quite the same. Moreover, the CPU time ratio strongly depends on details of the implementation of both integrators, even on the realization of the compiler intrinsic functions (see Eq. (11)). One can estimate the overall effect of our effort by a rule of thumb comparing the computing times for calculations pertinent to Fig 2 where, of course, the CPU time spent on collisions was excluded from the measurement. For the same statistical error, one gains a factor of ten when using the geometrical integrator. This

value would be even higher if one compares the efficiency for a self-consistent transport problem, like the one described in Ref. 4. A frequently used tool in transport studies is a so-called track length estimator (see, e.g., the textbook Ref. 12), where the knowledge of the dwell time of each particle per cell is required. This means, that when using a conventional integrator also the computations of any intersection of trajectories with cell boundaries are required. To find all these intersection points makes the usage of the conventional integrator even more expensive, because those points are already automatically obtained when using the geometrical integrator.

Another aspect is the quality of the fields entering Eq. (2). The magnetic field used in these test calculations had been represented very accurately and is smooth, and the electric field was set to zero – this allows us to use a high-order adaptive integrator, at least for purposes of this test. However, in a realistic case the electric field should be calculated self-consistently. This electric field is represented piecewisely by constants within mesh cells and, therefore, it is discontinuous at cell boundaries. In addition, this field has a significant numerical noise in case of Monte Carlo modelling and cannot be represented by smooth dependencies in the whole space. This makes the usage of high-order numerical schemes problematic and would require filtering of the statistically obtained electric field. This might introduce artifacts and introduces further CPU expenses. However, the low-order representation of all field-related values in Eq. (6) allows one to use the noisy field quantities directly within the geometrical integrator.

IV. SUMMARY

The semi-analytical geometrical integrator described here has roughly an order of magnitude higher efficiency as a conventional method for guiding center orbit integration. Essentially this is due to the fact that all analytical results employed by this integrator are expressed in terms of elementary functions, which are intrinsic functions of FORTRAN compilers with a pertinent CPU cost of the order of a single algebraic operation. In transport modelling, the efficiency of this geometrical integrator is even higher because the track length estimator frequently used for the evaluation of fluid parameter distributions does not require any additional search of orbit intersections with the given mesh. These data are obtained by the geometrical integrator as a by-product of orbit tracing. The integrator has been already

employed in 2D kinetic transport modelling in a tokamak⁴ and can also be applied for the modelling of kinetic effects in combination with 2D fluid and neutral transport codes.

V. ACKNOWLEDGMENTS

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