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Fast Ion Orbits in Spherical Tokamaks

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Abstract:

In a spherical tokamak, the $1/R$ variation of the toroidal field is extreme, and for a given value of the safety factor a relatively low average toroidal field can be used, together with large plasma current and large plasma minor radius and elongation. The poloidal and toroidal fields are then of similar size. In consequence, the orbits of fast ions depart considerably from the guiding center orbits because of gyromotion in the small magnetic fields in the low field side.

In a typical spherical tokamak equilibrium, the poloidal field is of the same order as the toroidal field. For example, a typical prediction for a USTX (University Spherical Tokamak Experiment) [1] plasma is described in Table 1. Shown in Fig. 1 is the magnitude of the magnetic fields along the plasma equator. It is clear that the poloidal field is larger than the toroidal field in the low field side.

$R_0(\text{m})$	=0.700	$B_{\Phi 0}(\text{T})$	= 0.50	$I_p(\text{MA})$	= 1.00
$a_p(\text{m})$	=0.489	$\beta_{\Phi}(\%)$	= 18.20	$\beta_{\theta}(\%)$	= 40.60
A	=1.43	$R_{\text{axis}}(\text{m})$	= 0.816	$R_c(\text{m})$	= 0.756
κ	=1.66	δ	= 0.125	l_i	= 0.641
q_{axis}	=0.95	q_{95}	= 3.20	q_{out}	= 4.33

Table. 1: Typical parameters of a USTX plasma.

Typically, estimates of banana widths are made with the formula $\rho_b = v_{\perp}/(ZeB_p/m)$, (B_p is the local poloidal field), while estimates of the Larmor radius are given by $\rho_L = v_{\perp}/(ZeB/m)$ (B is the total magnetic field, sometimes the toroidal field B_t is used instead). When B and B_p are similar, $\rho_b \sim \rho_L$ and the particle orbits make considerable excursions around their guiding centers. The projection of the Larmor radius on the (R, Z) plane gives an indication of how large a departure there will be between a guiding center orbit and a particle orbit. This is given by

$$\rho_{L\theta} = \frac{|(\mathbf{V}_{\phi} \times \mathbf{B}_{\theta} + \mathbf{V}_{\theta} \times \mathbf{B}_{\phi})|}{ZeB^2/m},$$

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here the subindex ϕ indicates the toroidal direction and θ the projection of a vector in the (R,Z) plane (non toroidal, rather than poloidal in the strict sense).

Fig. 2: Magnitude of magnetic fields along the equator.

A numerical code was written to solve the particle orbit equations (see Appendix), without the guiding center approximation. The equations of motion are solved with a leap-frog scheme, toroidal momentum conservation is used to compute the toroidal velocity as a function of the local poloidal flux. Conservation of energy is not used in solving the equations, but it is used as a check for accuracy. Conservation of the adiabatic moment is a property of the guiding center equations, so it is not applicable to an orbit code.

In Fig. 2 are shown two different orbits, as well as the flux contours. The first one shows a circulating ion, its orbit being barely perturbed by gyromotion. In the second one, a deeply trapped ion, the effect of gyromotion is very visible, producing large departures from the average orbit. The orbits in Fig. 2 are not typical: they are extreme (passing and trapped).

Spherical tokamaks, as a concept, rely heavily on non-inductive current drive. Neutral beam injection is a candidate current drive source. Calculations of neutral beam deposition, slowing down and current drive are based on guiding center approximations. The main purpose of this note is to point out that such calculations may not be accurate enough: gyromotion needs to be taken into account when computing the loss cone for fast ions, in particular if collisions are being simulated.

Fig. 3. Orbits of 60 keV H ions in a 1. MA, .5 Tesla plasma (corresponding to Figs. 1-2).
a) initial position $R = 1.0$ m, $Z = 0.$, purely toroidal initial velocity, co, passing, $v_{||}/v = .88$.
b) initial position $R = 1.0$ m, $Z = 0.$, purely vertical initial velocity, trapped, $v_{||}/v = -.47$.

Appendix: Particle orbit code

A particle orbit code, ORBIT was developed to trace trajectories from known poloidal and toroidal fields. The equations of motion for V_R and V_Z (the radial and vertical velocities in a cylindrical coordinate system (R, Z, ϕ)) are solved with a centered leap-frog scheme (based on a code provided by M. L. Sloan). Conservation of toroidal momentum is used to compute the toroidal velocity as a function of the poloidal flux and the particle's position. Energy conservation is not used for the orbit calculation, but as a check for computational accuracy.

A separate subroutine, PSIFUN, reads an input file and produces as output the poloidal flux and the fields at a point. In the particular implementation of the code used

here, the equilibrium was simulated with our local version of the EFIT^{1,2} code, and the output file fort.30 was read. In that case the input file, orb.inp, contains the following information:

```
'fort.30'          ! name of efrit output file to be used by psifun
1. 1.              ! Z(charge), A (mass)
.005               ! delta0, time step
3 2                ! iban(# banana bounces), itor(# toroidal circuits)
0.50 .00 0.0       ! starting point of ion, in m, radians (R,Z,Phi)
40.e3              ! ion energy, in eV
-0.0 0.0 1.0       ! Vr,Vz,Vphi, normalized by v_thermal
0.0e3              ! Electric field, in V/m (assumed to be a function of  $\Psi$ )
500                ! Number of plotted points for code to stop
```

The code is written in FORTRAN, plotting is done with NCAR. The codes are available for general use in the IBM RISC workstations. Potential users should consult with the author before copying the code. Other implementations allow the use of generalized analytical equilibria of the Solov'ev type to describe the flux surfaces, as described in [2].

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References:

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- [2] S. B. Zheng, A. J. Wootton, E. R. Solano, "A tokamak equilibrium with arbitrary aspect ratio", Fusion Research Center Report #475, The University of Texas at Austin.