LETTERS TO THE EDITOR

COMMENTS ON "ION DEFOCUSING IN MULTICUSP PLASMA CONFINEMENT SYSTEMS"

T. J. Dolan recently[1] suggested that the nonsphericity of the B fields in Polywell™-type multipole magnetic systems for electron confinement[2,3] inherently would greatly defocus ions circulating through the system. The purpose of this letter to the editor is to explain how and why this notion is in error and to amplify some aspects of the overall concept.

The correct physics of this system had already been discussed in letters from each of us to Dr. Dolan, who had kindly sent his proposed letter[1] to us for comment, and by facsimile copy to the editor of *Fusion Technology*. We quote from one of these letters [material in ( ) added for clarification]:

"Dear Tom: Thanks for your submitted 'letter' to Fus. Tech. (But) I fear that somehow you have missed the point of the whole electric potential geometry and flow scheme (of the Polywell™).

(1) Ions approaching the edge (from the core at radius r_c) reach lower and lower energies by 'climbing' up the potential 'hill' along some quasi-radial path.

(2) At the edge they collisionally *isotropize* (see Rosenberg & Krall article from Physics of Fluids; copy enclosed)[4] and will return as random input at *a few eV* (their injection energy).

(3) If the 'edge' is *inside* the physical edge (radius) sufficiently, the returning ions will *not* lose their convergence by in-falling $\boldsymbol{V} \times \boldsymbol{B}$ (forces).

So far, we think that we see ways/means/radii-of-operation (i.e., injection) that can give us convergence ratios of $\langle r_c \rangle = (r_c/R) \leq 0.0033$ or so.

The defocusing is *not* by 'reflection from the convex boundary,' as your note states, but rather by $\boldsymbol{V} \times \boldsymbol{B}$ integrated over (r); $\int \boldsymbol{V}(r) \times \boldsymbol{B}(r)\, dr$ from $r = r_{injection}$ to $r = r_c$, as the ions return to the core from their 'edge' isotropic 'injection' radius.

I hope this helps."

Unfortunately, it did not seem to "help," thus necessitating *this* letter! We wish to elaborate:

1. It is important to recognize that the ions are at very low energy in the edge region, having lost their large central kinetic energy to the confining electrostatic potential well on their outbound journey. Because of this, edge collisionality is so high that isotropization occurs *in a single pass*, thus removing all "memory" of transverse momenta added in each preceding pass. The only way an ion can acquire increasing transverse momentum (and thus continually defocus) is by core Maxwellianization and energy upscattering, which will spread the "edge" region and reduce the isotropization effect. But, this requires that the ions "live" in the machine for a time longer than is required to achieve a fusion rate sufficient to yield large net power and gain. If losses due to various physics effects are not enough to limit ion lifetime, then this can be controlled by a simple "limiter" analogous to (but very much less stressed and heated than) those used in tokamaks.

2. Dr. Dolan's drawing (Ref. 1, Fig. 2) errs in showing ion motion as linear paths reflecting from an inward-curved electrostatic boundary. Anent his assertion that equipotential surfaces will follow the mod-B surfaces, this is not at all evident since most of the electrons are *not* bound to field lines. And, given the diamagnetic electron flow and high-beta operation essential to the concept, the B fields will be pushed out to their maximum extent (well beyond that suggested in Ref. 1, Fig. 1b) as limited by magnetohydrodynamic stability. In actual fact, the ion motion from the core will result from a combination of both $\boldsymbol{V} \times \boldsymbol{B}$ and $e\nabla\phi$ forces, and the ion paths will be curved as they approach the edge. As previously described,[3] the ion injection "edge" radius must be *inside* the physical boundary of the system, precisely to avoid large-scale $\boldsymbol{V} \times \boldsymbol{B}$ deflections. Under such conditions, the ions will tend to follow "lines of steepest $e\nabla\phi$ descent" as they return from collisional isotropization at the "edge" to the core. These maximum gradient lines are always radial at the core and normal to the equipotential surfaces at the "boundary."

3. Some months ago (March 1993) (Ref. 5), we showed that these systems lose gross power gain (G_{gt}) only slowly with increasing convergence ratio $\langle r_c \rangle$; $G_{gr} \propto \langle r_c \rangle^{0.25}$. Thus, *even though the core will not spread*, the maintenance of small $\langle r_c \rangle$ turns out to be of only minor consequence to system performance.

We hope that these few remarks will dispel (at least some of) the confusion that seems to becloud understanding of the ion flow in these systems.

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2. R. W. BUSSARD, "Some Physics Considerations of Magnetic Inertial-Electrostatic Confinement: A New Concept for Spherical Converging-Flow Fusion," *Fusion Technol.*, **19**, 273 (1991).

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4. M. ROSENBERG and N. A. KRALL, "The Effect of Collisions in Maintaining a Non-Maxwellian Plasma Distribution in a Spherically-Convergent Ion Focus," *Phys. Fluids B*, **4**, *7*, 1788 (July 1992).

5. R. W. BUSSARD and L. W. JAMESON, "Inertial-Electrostatic-Fusion (IEF) from D to ^{3}He: A Strategy for Practical Fusion Development," *Proc. 2nd Wisconsin Symp. Helium-3 and Fusion Power*, Madison, Wisconsin, July 19–21, 1993.

RESPONSE TO "COMMENTS ON 'ION DEFOCUSING IN MULTICUSP PLASMA CONFINEMENT SYSTEMS'"

My response to Ref. 1 comprises the following points upon which perhaps the authors of Ref. 1 and I can agree:

1. The degree of focusing is related to the sphericity of the electrostatic equipotential surfaces.

2. Surfaces at small radii probably have fairly good sphericity.

3. Multidimensional computations would be needed to define the shapes of the equipotential surfaces.

In summary, we have differing expectations about the results of such computations.

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REFERENCES

1. R. W. BUSSARD and N. A. KRALL, "Comments on 'Ion Defocusing in Multicusp Plasma Confinement Systems,'" *Fusion Technol.*, **25**, 228 (Mar. 1993).