INNOVATIVE AND EFFICIENT PLASMA MAGNETIC CONFINEMENT METHOD BASED ON AN OVERLOOKED HISTORICAL DISCOVERY

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1. SUMMARY

A method to confine plasmas based on a novel type of pinch was discovered and published in the late 1970s by two European physicists, Owen Storey and Laurent Cairó, building on an earlier discovery by American astrophysicist Eugene Parker [1]. They proved that when a supersonically-flowing plasma is confined by a magnetic field parallel to the flow, a secondary magnetic field discovered by Parker can emerge under certain conditions, reinforcing the confinement and thereby reducing the requirement for the external magnetic field. The resulting overall confining field is concentrated within the thin static boundary layer between the plasma and the external field, while the bulk plasma remains both field-free and current-free. Storey and Cairó suggested that this might be applicable to fusion and proposed a conceptual device exploiting it [2][3]. Confinement in such a device would be intrinsically MHD-stable and more energetically efficient than that of most devices currently under investigation. In this presentation, we briefly review the historical background and present recent numerical simulation work carried out to demonstrate the validity and efficiency of this magnetic confinement method.

2. THE HISTORICAL DISCOVERY

While investigating a simplified model of the flow of the solar wind around Earth's magnetic field in the late 1960s, Eugene Parker discovered theoretically that where the solar wind is parallel to the magnetic field, a secondary magnetic field arises in the dayside boundary layer between the plasma and the field. At supersonic flow velocities, the secondary field exceeds the magnetospheric field. The boundary layer cannot be in equilibrium, so it disintegrates [1].

Reviewing Parker's work in the late 1970s, European physicists Owen Storey and Laurent Cairó determined the conditions required for the effect to emerge. Moreover they showed that if a supersonically flowing plasma is confined by a magnetic field, rather than the reverse, then the boundary layer can remain in equilibrium, and the effect discovered by Parker would reinforce the confinement. At the interface (the "boundary layer") between the flowing plasma and the external magnetic field, the ions create a strong current, which in turn produces an internal magnetic field, leading to a net pinching effect. The bulk plasma remains field-free and current-free, confined by what they called a "boundary-layer pinch".

Storey and Cairó proposed a toroidal device they called the Plasma Storage Ring (PSR), with a stationary confining magnetic field and the plasma flowing supersonically along the minor axis of the torus [3], as shown schematically in Figure 1 below. Its key features are:

- the bulk of the plasma remains field-free and current-free,
- the system is intrinsically MHD-stable (by Teller's criterion),
- the confining currents are in the boundary layer only,
- the system has a high global beta (see Figure 2).

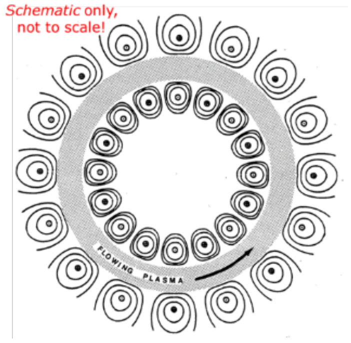

Figure 1 - Plasma Storage Ring concept

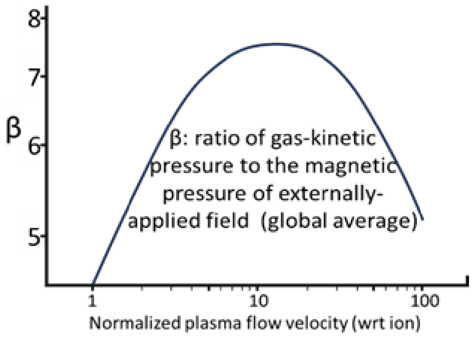

Figure 2 - Variation of global β vs. plasma flow velocity

3. RECENT RESULTS AND ON-GOING WORK

Working since 2020 with one of the original scientists, our research group initially aims to:

- Verify the reality of Parker's Effect, i.e. the emergence of a secondary magnetic field stronger than the external one, under specific circumstances, by numerical simulation and/ or by hardware experiment.
- Characterise the confinement, stability, bulk flow velocity, plasma density and temperature, and the external requirements to maintain them.

An initial numerical simulation investigated the rate of particle loss through the cusps of a stationary picket-fence using a Monte-Carlo simulation with 100,000 particles and a range of particle flow velocities. The results, illustrated in Figure 3 below, show that the confinement becomes excellent at velocities of the order of Mach 5 with reference to the particle thermal speed. In a related series of simulations, we confirmed that the loss of momentum and of energy in the flow direction can be counteracted by superimposing a time-dependent electric field.

To follow-up, we have been developing a full simulation model of a PSR module using the open-source software framework Gkeyll [4] which uses continuum (Eulerian) methods, discretising the distributions over a grid and solving the partial differential equations by finite differences. An example output from these simulations is shown in Figure 4. We have run into difficulties implementing the simulation, not all of which we have overcome yet. These relate to the compatibility of different elements of the software and the fast-evolving High-Performance Computing hardware, to the coordinate system, the initialisation, and to the numerical complexity of simulating different phenomena at vastly different spatial scales causing excessive run times.

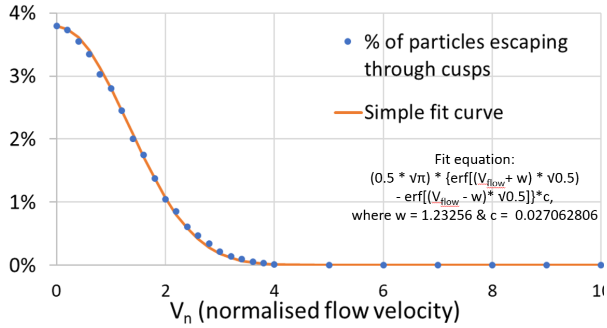

Figure 3 - Numerical simulation of particle loss rate vs. plasma flow velocity

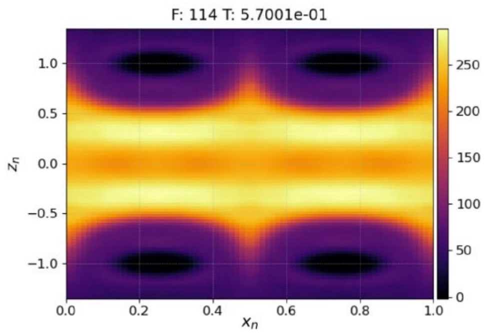

Figure 4 - Ion density within spatial domain in a 2-cell module of stationary picket-fence

3. POTENTIAL IMPACT

In designing a prototype fusion energy plant, the global beta is a key factor in deciding what type of reactor to use. A spherical tokamak is roughly ten times better than a classical one in that respect, and a reactor exploiting Parker's effect might offer another tenfold improvement. It has the potential to be topologically simpler than a tokamak, with a large aspect ratio further simplifying the engineering and maintenance, and with the stability of a stellerator. A demonstration of the reality of this effect and of the possibility of such a device, based on the proposed workflow, could redirect fusion technology onto a cheaper and shorter path to the goal of a fusion plant supplying secure, equitable and environmentally sustainable electricity.

Some related research is currently going on at several locations worldwide – e.g. [5] and [6]. However, none of those projects, to our knowledge, makes use of Parker's effect, nor are their protagonists even aware of its potential. This, therefore, is a timely topic and opportunity, with possible transformative and far-reaching consequences.

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