The Centrifugally-Confined Mirror as a Pathway to Fusion

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Topical area: MFE

Goals

The goal of this initiative is to test the viability of an unconventional and underexplored alternative path to fusion, namely a Centrifugal Mirror[1-5]. If proven to have sufficiently good confinement properties:

- Centrifugal Mirrors have a simple, axisymmetric, magnetic geometry, dramatically lowering the cost of construction and maintenance, due to the lack of coils that are topologically linked with the vacuum vessel.
- Centrifugal Mirrors have no driven current. This eliminates disruptions, simplifies the path to long-pulse and steady-state operation, and removes the need for complex current drive systems.
- In addition, Centrifugal Mirrors are projected to have a very low recirculating power fraction, as they do not need driven current or an injected hot-ion population to operate.

These possible upsides are sufficiently exciting to support the renewal of an experimental programme dedicated to establishing if Centrifugal Mirrors could provide a viable path to fusion. The proposed university-scale experiment would have the following core goals:

- To demonstrate high-Mach-number (M ~ 6) operation, with a low neutral fraction and low impurity concentration.
- To demonstrate the confinement of high-ion-temperature (T_i >= 1 keV) plasmas for multiple confinement times.
- To demonstrate long-pulse operation into the quasi-steady-state regime (i.e. limited only by coil cooling constraints).

If these goals are achieved, it would be possible for a subsequent upgrade to achieve fusion-relevant T_i ~ 10 keV operation. Furthermore, the parameters are chosen such that if all the foregoing goals are achieved on the same discharge, this upgraded experiment would have a DT-equivalent Q of 5.

Description of the Initiative

It is recognized that axisymmetric mirrors, while a very attractive geometry for fusion, have poor plasma confinement due to two key physical processes[1]:

1. Parallel end losses, which limit confinement times to an ion-ion collision time.
2. The MHD interchange instability, which, if not stabilised, leads to pressure collapse on Alfvenic timescales.

In an axisymmetric mirror rotating azimuthally at supersonic speeds, the radial centrifugal force closes the loss cone, radically improving parallel confinement.[1-5] In addition, the concomitant velocity shear can stabilize the interchange mode[6-8], resulting in a quiescent, MHD-stable plasma.

Furthermore, the large velocity shear should provide strong stabilisation of the microinstabilities that limit tokamak and stellarator confinement. Preliminary theoretical explorations suggest that classical collisional confinement levels are achievable. With the proposed hypersonic rotation velocities, the parallel confinement is also reduced to this level.[4]

Despite having had less research on them than more popular confinement concepts, Centrifugal Mirrors exhibit promising experimental and theoretical results that this proposal will build upon.

<u>Previous Experiment:</u> The Maryland Centrifugal Experiment (MCX)[5] was configured to test some of the above concepts. Operated from 2003-2011 under the auspices of the DoE Innovative Confinement Concepts program, it was very successful.

Key results from MCX include:

- Routine operation at sonic Mach numbers of 2.5-3. [5-10]
- Sustained, quiescent, confined plasmas for many confinement times, without disruption [5-10].
- Velocity shear was measured which far exceeded the stabilization condition for the ideal interchange mode [9-14] .
- Small magnetic fluctuations were observed, consistent with modelling for the achieved Mach number [10-12]
- Finally, density drops of up to factors of 12, from midplane to mirror throats, were measured, consistent with (axial) centrifugal confinement [14,15].

<u>Theoretical Predictions:</u> Modelling capabilities that were developed for, and validated on, MCX have been used to make predictions for fusion-relevant devices. Important predictions are that

[1] These are not insurmountable, and other proposals exist for overcoming these limitations. See, e.g. [Ryutov,....]. However of these designs only the GDT at Novosibirsk is as well-developed as the Centrifugal Mirror.

- MHD simulations of rapidly rotating mirror configurations show that, if high-Mach-number operation ($M>4$) can be achieved, the interchange mode is completely stabilised, with no residual fluctuations [8,16].
- Equilibrium and transport studies suggest that parallel heat losses can be reduced to the point whereby transport is dominated mainly by perpendicular losses on the rotating field lines.[4]

Theoretical and experimental work on tokamaks shows that the velocity shear present in a Centrifugal Mirror would far exceed that required to stabilise microturbulence. However, as no theoretical studies at such large velocity shear have been performed, the goal is to demonstrate this experimentally.

<u>Experimental Operating Point:</u> Based on a 0-D transport model, parameters are chosen so as to run at T=1keV, with a maximum of 50kW of steady-state auxiliary heating. Operation is limited by requiring the Alfven Mach number to remain below unity. At these conditions, with neutral burn-through, it is anticipated that transport losses will be classical.

Density is chosen to be 10^19/m^3 to decrease the Alfven Mach number and to permit complete ionization of the plasma in a relatively short startup phase.

The proposed upgraded second stage experiment would operate at 10keV and explore higher-field and higher-density operation.

<u>Key questions:</u> The system as described above shows potential as a fusion device. This white paper describes a possible initiative towards resolving the remaining questions surrounding this concept

1. Is the cross-field transport really reduced to classical levels, or is some level of turbulent transport driven by the rotation itself?
2. Can the required Mach numbers be achieved? MCX was unable to achieve sustained Mach numbers significantly above 3 [5-10].
3. Can the insulating end plates, which insulate the rotating field lines from the vacuum vessel, withstand the large electric fields?

The experimental goals outlined at the start of this white paper have been chosen to both demonstrate fusion-relevant plasmas and to resolve these outstanding questions.

Programmatic Benefit

The advantages of the Centrifugal Mirror as a confinement system have been outlined at the beginning of this white paper. It addresses several gaps that previous reports have highlighted as issues with the current tokamak research program (disruptions, steady-state operation, recirculating power). It may also provide a route to a high-power volumetric neutron source, which is identified as being key to the future of the program whichever confinement concept is ultimately adopted.
Any fusion-relevant plasma experiment entails a rich set of opportunities to train staff in the intricacies of high-temperature plasma diagnostics. With a simpler magnetic geometry than most

confinement experiments, validation of theoretical and numerical tools may also be possible more easily than in tokamak experiments.

The lack of new experiments where students will be able to have an actual impact and see short-term results is currently an impediment to hiring the highest calibre of students. Hence, experiments in this general area (given the fusion focus, the early stage of development and relatively unexplored physics, including inertial forces and velocity shear) would have a large positive impact on fusion science at universities. This is key to maintaining the scientific quality of the programme going forward.

US Leadership and Global Context

Except for the Ixion experiment[1] (50's), and related experiments in Sweden[2] in the 60's, supersonic centrifugal confinement is relatively unexplored. US experiments at UMD and UTexas both ended between 2010 and 2012.

The US, historically, maintained a world-class mirror research program. It has also funded novel confinement strategies to a larger extent than the European or Japanese programmes. However, with the loss of the Livermore mirror programme in the 1980s and Innovative Confinement Concepts programme in the 2010s, the US has ceded its leadership role in this area. The most exciting mirror experiments today are being carried out on the GDT experiment in Novosibirsk and the Gamma-10 device in Japan.

The confinement achieved in GDT, whilst impressive, could be surpassed by a well-designed Centrifugal Mirror. This initiative proposes such a device. This would allow the US to regain its preeminence in mirror research, without duplicating the research performed on the GDT.

Timeline of the Initiative

This initiative is both timely and easily accessible with current technology. Given availability of funds, we estimate that a detailed design study for this experiment would take only a few months, and construction could begin within a year.

[Build it in a year?]

After construction, commissioning and operating of the experiment towards the initial goals of the initiative will take 12-18 months. If these experiments are successful, upgrading the experiment to operate at higher fields and higher temperatures will follow.

Even on this timeline, it is not unreasonable to expect the effective-Q ~ 5 scenario to be studied experimentally in under 5 years from commencement of the initiative.

Science and Technology Readiness

In order to demonstrate the confinement goals set out above, a copper-coil machine would be sufficient. The technology for operating copper-coil devices at high field is well understood. While is is not regularly used in fusion, the technology for driving the large (>10MV/m) electric fields that supply the supersonic rotation is also standard. The insulting end-caps are the only novel part of this experiment; smaller alumina insulators were procured commercially for MCX, and we anticipate no problem in having larger insulator fabricated.

Community Preparedness

The experimental community has long experience with cylindrically-symmetric plasmas, such as LAPD and [...]. Diagnostics for high-temperature fusion-relevant plasmas are well understood in the proposed aneutronic environment.

Theory support for this experiment would require little extra preparedness. For the initial design study, the existing 0D tools, alongside MHD equilibrium tools that were developed for analysing MCX will be sufficient.

For more detailed analysis, kinetic tools will be required. The theory and modelling community have a wide variety of state-of-the-art tools for simulating plasmas including velocity shear for understanding tokamak discharges. Extending current gyrokinetic flux-tube codes to study turbulent transport in a Centrifugal Mirror can proceed in parallel to the design and construction phases. Similarly, tools for providing a kinetic equilibrium model will be developed on this timescale.

Equipment/Facility Design Details

Configuration:

The magnetic configuration is a simple axisymmetric mirror, with 4T fields in the mirror throat and 1T fields in the central cell. These fields are produced by water-cooled copper coils. A scaled-up version of the MCX vacuum vessel, with improved neutral handling capability, including the possibility of glow-discarge cleaning and baking will be required. The design of this vacuum vessel includes a central conducting rod, electrically insulated from the rest of the vacuum vessel, that is used to rotate the plasma. This necessitates biasing the axial core with respect to the vessel wall. This bias is generated by high-performance capacitor banks, which will be required to supply >10MV voltages with sufficient stored energy in the bank to enable long-pulse operation. The termination of the rotating field lines occurs on a high-quality insulating end plate. The end-caps for MCX were manufactured from alumina and we anticipate that ribbed alumina will also be sufficient for this experiment. If required, fused quartz would provide a higher breakdown voltage. In order to facilitate experimentation, the design will permit the removal of the insulating plates and central rod. Driving the high-field copper coils and attendant cooling systems will require megawatt-class power handling systems.

Cost Range

Construction of the next step device would be possible for between 2-4 Million USD.
Continued operation of the device, including staff to analyse data and perform theoretical support work, would cost <??> / year.

Cross-Cutting Connections

Workforce development, Measurement & Diagnostic, Theory & Computation.

Advocates of This Initiative

Prof T. M. Antonsen
Prof J. F. Drake
Prof W. Dorland

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