Final Technical Report 2012

The Maryland Centrifugal Experiment (MCX): Centrifugal Confinement and Velocity Shear Stabilization of Plasmas in Shaped Open Magnetic Systems

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Overview:
The Maryland Centrifugal Experiment (MCX) Project has investigated the concepts of centrifugal plasma confinement and stabilization of instabilities by velocity shear. The basic requirement is supersonic plasma rotation about a shaped, open magnetic field. MHD stability and classical confinement theory show that the supersonically rotating centrifugal confinement scheme is scalable to fusion conditions and features several advantages. In addition, an understanding of the physics of supersonic rotation, parallel confinement, and velocity shear stabilization should have broad applications in general fusion science.

The magnetic configuration of MCX is a long solenoid with axisymmetric mirror end-fields with mirror field up to 2T and mirror ratio of 1-20. A solid core runs down the axis and acts as the high voltage electrode. Biasing of the core drives $\mathbf{E}\times\mathbf{B}$ azimuthal rotation; the high voltage is provided by a 20 kV capacitor bank. The centrifugal force from the rotation is predicted to confine plasma to the solenoidal portion and velocity-shear is predicted to suppress MHD interchanges as well as drift type modes. MCX is an extremely versatile device, allowing studies for a wide range of parameters; it is a unique facility in the fusion community.

The experiment has yielded supersonic rotating plasmas in routine operation (ion thermal Mach number $M_s \sim 1\text{-}2.5$) with densities in the range 0.8–8 10^{20} m^{-3}, Doppler broadening ion temperatures of about 40eV, and almost complete ionization over much of the plasma. Plasma rotation was consistent with $\mathbf{ExB}/B^2$. The plasma is grossly stable for up to ~1000's of MHD flute instability times, with no major disruptions observed, lending support to the velocity shear stabilization paradigm. Momentum confinement times of more than 200μs were observed and the Alfven Mach number was in the range 0.1-0.8.

Overall Milestones:
In an overall view, the MCX Project attained three primary goals that were set out at the start of the project. First, supersonic rotation at Mach number upto 2.5 was obtained. This was a required primary goal. Second, turbulence from flute interchange modes was found considerably reduced from conventional. This reduction was correlated with shear in the rotation and the reduction was by significant factor than what is expected from MHD interchange modes. Third, plasma pressure was contained along the field, as evidenced by density drops of x10 from the center to the mirror throats, via interferometric measurements. All three milestones reached would constitute a *sine qua non* if this concept were to be viable as a fusion energy experiment. MCX is a unique facility for the study of velocity shear and the effects on stability and has great flexibility.

Progress in the final reporting period:

In this most recent contract period, there were some new results:

- Centrifugal confinement has been unambiguously confirmed for higher mirror ratios, using our two interferometers and an axial array of diamagnetic loops. The axial decrease of plasma density is dramatic and in agreement with MHD Grad-Shafranov theory.
- Magnetic fluctuations in the plasma edge provide strong if indirect support of the paradigm of velocity shear stabilization. The dominant power is measured to be in the low m modes, fully consistent with linear and nonlinear velocity shear theory and simulation. Observed mode propagation velocity is consistent with convecting structures rotating at a speed commensurate with the plasma rotation from Doppler spectrometer data, and in agreement with simulation. The field strength fluctuation is about 1%, indicative of low level turbulence.
- An extensive study of velocity limits at varying applied voltage, magnetic field strength, and mirror ratio has been conducted. It establishes a hard limit at the Alfven speed, in agreement with MHD theory, and a softer limit at the so-called Alfven Critical Ionization Velocity (CIV). Various techniques (gas puffing, high voltage) were attempted to exceed this limit.
- Our new 16 chord H_α emission array has measured radial profiles of neutral hydrogen which are strongly peaked at the plasma edge and much lower at plasma center.
- Radial profiles of angular velocity from Carbon lines are now routinely measured, confirming earlier results. Parabolic type profiles in different charge states are seen, consistent with ExB rotation; the velocity shear is found to exceed the theoretical stability criterion. These measurements have been extended to different axial locations

Diagnostics: MCX has successfully deployed diagnostics in support of the experimental campaigns. Apart from current and voltage monitors, and standard Doppler spectroscopy, we have operational two independent 3.39 micron IR laser interferometers which can be located at different axial locations providing time resolved line averaged density; an axial array of diamagnetic loops is operational, as are axial and azimuthal arrays of magnetic pickup loops; a 16 chord H_α detector array has been developed and yields neutral hydrogen profile information; and analysis of RGA gives the time history of neutral pressure. Initial results with edge Langmuir probes have been obtained.

Theoretical support

The experimental campaigns were continually tested against theoretical propositions. In particular, nonlinear simulations using the fluid dissipative MHD code at the University of Maryland have already provided much insight and support of the magnetic fluctuation data, in the context of residual interchange turbulence in the presence of velocity shear. This effort was extended to cylindrical and then mirror geometries.

Recent Reports and Publications

1) Sub-Alfvenic velocity limits in magnetohydrodynamic rotating plasmas. *Physics of Plasmas 17 052503 (2010)*
C. Teodorescu, R. Clary, R. F. Ellis, A.B. Hassam, C. A. Romero-Talamas and W.C. Young.

2) Low Dimensional Model for the Fluctuations observed in the Maryland Centrifugal Excperiment. *International Symposium of Waves, Coherent Structures and Turbulence in Plasmas, 2010* American Institute of Physics 978-0-7354-0865-4/10
P.N.Guzdar, I. Uzun-Kaymak, A.B.Hassam, C. Teodorescu, R.F. Ellis, R.Clary, C.Romero-Talamas, and W. Young

3) Isorotation and differential rotation in a magnetic mirror with imposed ExB rotation. *Physics of Plasmas 19, 072501 (2012).* C.A. Romero-Talamas, R.C. Elton, W.C. Young, R. Reid and R.F. Ellis.

4) Experimental study on the velocity limits of magnetized rotating plasmas. *Physics of Plasmas 15 042504 (2008).* C. Teodorescu, R. Clary, R.F. Ellis, A.B. Hassam, R. Lunsford

5) Diamagnetism of rotating plasma. W.C. Young, A.B. Hassam, C.A. Romero-Talamas, R.F.Ellis and C. Teodorescu.
Physics of Plasmas 18, 112505 (2011)

6) Analysis and modeling of edge fluctuations and transport mechanism in the Maryland Centrifugal Experiment. I.U.Uzun-Kaymak, P.N. Guzdar, R. Clary, R.F.Ellis, A.B. Hassam and C. Teodorescu. *Physics of Plasmas 15, 112308 (2008)*

7) 100 eV electron temperatures in the Maryland centrifugal experiment observed using electron Bernstein emission. R.R. Reid, C.A. Romero-Talamas, W.C.Young, R.F.Ellis, and A.B.Hassam. *Physics of Plasmas 21, 063305 (2014)*

8) Confinement of Plasma along Shaped Open Magnetic Fields from the Centrifugal Force of Supersonic Plasma Rotation. C. Teodorescu, W.C.Young, G.W. Swan, R.F.Ellis, A.B.Hassam, and C.A.ROmero-Talamas. *Phys. Rev. Lett. 105, 085003 (2010)*

9) Charge and mass considerations for plasma velocity measurements in rotating plasmas. C.A. Romero-Talamas, R.C.Elton, W.C. Young, R. Reid, R.F.Ellis, A.B. Hassam. *Journal of Fusion Energy, 29, 6, 543-547 (2010)*

Associated PhD Students, PostDocs, and Collaborators

PhD Theses Completed

Remington Reid, *Microwave emission and electron temperature in the Maryland Centrifugal Experiment* (2013)
William Young, *Diamagnetism of a supersonic rotating magnetized plasma (2012)*
Jupiter Bagaipo, *Nonlinear stability of ideal MHD interchange modes (*2011) (theory)
Ryan Clary, *Halpha and Neutral Density Scaling in the Maryland Centrifugal Experiment*,(2009)
Robert Lunsford, *Parametric Limitations on Discharge Performance in the Maryland Centrifugal Experiment*, (2006)
Sarah Messer, *Supersonic Rotation on MCX,* (2004)
S. W. Ng, PhD thesis, *Plasma-Neutral Equilibrium in Centrifugally Confined Plasma* (2007) (on theory grant)
Y-M. Huang, *MHD Equilibrium and Stability of Centrifugally Confined Plasma,* PhD thesis (2006) (on theory grant)

Research Scientist

Carlos Romero-Talamas, 2009-

Research Associates

Andrew Case, 2003-2006
Deepak Gupta, 2003-2005
Catalin Teodorescu, 2003-2009
Seung Ho Choi, 2006-2008
Ilker Uzun-Kaymak, 2006-2008

Collaborators

Douglas Witherspoon, Andrew Case and SarahMesser, HyperV Technologies
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