1. Final project report for DOE Grant No. DE-FG02-02ER54690
2. Principal Investigator: Thomas Sunn Pedersen, Columbia University
Graduate students supported on this grant: J. P. Kremer, Q. R. Marksteiner
Title: The Columbia Non-neutral Torus

3. Executive summary
During the duration of this grant, I designed, built, and operated the Columbia Non-neutral Torus, the world's lowest aspect ratio stellarator, and arguably, the world's simplest stellarator. This demonstrates the ease and robustness of the chosen stellarator design and allowed us to commence the investigation of the physics of non-neutral plasmas confined on magnetic surfaces. These plasmas are unique in many ways and had not previously been studied in a stellarator. Our first results showed that it is possible to confine and study a relatively cold pure electron plasma in a stellarator. We confirmed that the plasma is stable, and that the plasma is reasonably well confined in a stellarator configuration. These results were published in Physics of Plasmas (2006) and Physical Review Letters (2006). They enabled the existing program which is resolving the underlying transport processes in a classical stellarator with intense self-electric fields and enable the next phase of operation, electron-positron plasma physics.
During the period of this grant, two students were trained in experimental plasma physics and both received their PhD degrees shortly after the grant terminated. One student is now employed in the financial services industry, the other is a postdoctoral associate at Los Alamos National Laboratory.

4. Comparison of goals and achievements
The chief goals were to build and begin operation of the Columbia Non-neutral Torus. These goals were achieved in the third year of funding. The development of diagnostic methods and the confirmation of stable equilibria were also achieved during the grant period. In summary, the main scientific goals were all met. The main educational goals were also met, as the experiment became the training ground not only for the two aforementioned graduate students but also for a number of undergraduate students. Several of these have gone on to graduate school, some in plasma physics, others in related areas. We have had significant outreach activity, including visits to nearby elementary schools (PS 163 in Manhattan), and high school students and high school teachers volunteering in the laboratory.

5. Most of the funding period was spent during design and construction. The main expectations were that the chosen linked-circular-coil design would be relatively easy and inexpensive and should be relatively error field resilient. As for the ease and cost, the experiment was built on time and on schedule, confirming the expectations. Numerical simulations were developed that suggested that the error field resilience, for an optimally chosen angle, was even larger than originally expected. This was indirectly confirmed by the fact that field line mapping showed a very large volume of good magnetic surfaces despite known coil misalignments and paramagnetic materials on the vacuum chamber.

One physics expectation was that the plasma would be able to reside in a macroscopically stable equilibrium. This was confirmed experimentally. Another expectation was that the confinement of these plasmas would be very good, perhaps even thousands of seconds. The experimental reality was that the confinement time at most was 20 msec, large by many standards, and indicative of the aforementioned macroscopic stability, but it was much lower than expected. One reason for the discrepancy was quickly identified: the presence of internal rods perturbed the plasma to the extent that it was responsible for most of the transport at low neutral pressures. At higher neutral pressures, the confinement was largely limited by electron-neutral collisions, which had a surprisingly deleterious effect on the confinement. This was an early indication of bad orbits. In order to understand this lower than expected confinement time, studies were performed, varying the number of rods, the plasma density, the magnetic field strength, and the neutral pressure in an effort to gain an understanding of the underlying transport processes. The conclusion of that research was not reached until after this grant expired, but a lot of the ground work was performed towards the end of the grant period.

6. Products

a) Publications:

Experimental demonstration of a compact stellarator magnetic trap using four circular coils, T. Sunn Pedersen, J.P. Kremer, R.G. Lefrancois, Q. Marksteiner, X. Sarasola, and N. Ahmad, Phys. Plasmas 13, p. 012502 (2006)

Experimental confirmation of stable, small-Debye-length, pure-electron-plasma equilibria in a stellarator, J.P. Kremer, T. Sunn Pedersen, R.G. Lefrancois, and Q. Marksteiner, Physical Review Letters 97, p. 095003 (2006)

First studies of pure electron plasmas in the Columbia Non-neutral Torus, J.W. Berkery, T. Sunn Pedersen, J.P. Kremer, R.G. Lefrancois, Q.R. Marksteiner, A.H. Boozer, H.E. Mynick, N. Pomphrey, W. Reiersen, F. Dahlgren, H. Himura, and X. Sarasola, Non-neutral Plasma Workshop, Aarhus, Denmark, 2006, AIP Conference Proceedings 862, p. 62-70

Construction and initial operation of the Columbia Non-neutral Torus, T. Sunn Pedersen, J.P. Kremer, R.G. Lefrancois, Q. Marksteiner, N. Pomphrey, W. Reiersen, F. Dahlgren, and X. Sarasola, Fusion Science and Technology 50, p. 372 (2006)

Columbia Non-neutral Torus completes construction and starts operation, T. Sunn Pedersen, Stellarator News 97, p. 1 (2005)

First non-neutral plasmas in the CNT stellarator, T. Sunn Pedersen, Stellarator News 99, p. 3 (2005)

The Columbia Non-neutral Torus: A new experiment to confine non-neutral and positron-electron plasmas in a stellarator, T. Sunn Pedersen, A.H. Boozer, J.P. Kremer, R. Lefrancois, F. Dahlgren, N. Pomphrey, W. Reiersen, and W. Dorland, Fusion Science and Technology 46, p. 200 (2004)

Confinement of plasmas of arbitrary neutrality in a stellarator, T. Sunn Pedersen, A.H. Boozer, J.P. Kremer, and R. Lefrancois, Phys. Plasmas 11, p. 2377 (2004)

Stability of pure electron plasmas on magnetic surfaces, A.H. Boozer, Phys. Plasmas 11, p. 4709 (2004)

2003

Prospects for the creation of positron-electron plasmas in a non-neutral stellarator, T. Sunn Pedersen, A.H. Boozer, W. Dorland, J.P. Kremer, and R. Schmitt, Journal of Physics B 36, p. 1029 (2003)
Confinement of non-neutral plasmas in the Columbia Non-neutral Torus, T. Sunn Pedersen, A. H. Boozer, and J. P. Kremer, Non-neutral Plasma Workshop, Santa Fe, NM, 2003, AIP Conference Proceedings 692, p. 302
The status of the design and construction of the Columbia Non-neutral Torus, J.P. Kremer, T. Sunn Pedersen, N. Pomphrey, W. Reiersen, and F. Dahlgren, Non-neutral Plasma Workshop, Santa Fe, NM, 2003, AIP Conference Proceedings 692, p. 320

6.b
A website for the CNT experiment was created, including general information about the experiment, a list of publications, list of collaborators and students, etc. It can be found at www.apam.columbia.edu/CNT