UCLA Tokamak Program Close out Report

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(Research from 1976 to 2006, DOE investment about $50k)

1.0 Brief history of experimental fusion research at UCLA.

This program at UCLA, like fusion research in general, went on much too long. The initial expectation was to move forward to energy production type machines in 5 years. This did not happen even after 30 years. The big miss was studying the science of small scale devices at the national level that never had a chance to produce self sustained fusion. Plasma devices of any size at a University are, of course, useful for thesis work. Such were the case of "small" tokamaks. In addition, we concentrated on low field tokamaks to reduce the cost.

The Electric Tokamak (ET) was the end of a series of small machines built under the direction of the PI (Taylor). In the beginning, the UCLA tokamak research program was the outgrowth of operating tokamaks at MIT in the early 1970's (Alcator, Rector, Versator tokamaks). Most of this history can be found on the WEb by Googling <device and institution> .

The UCLA fusion program was initiated by installing two tokamaks (Microtor, Macrotor) in the late 1970's. These were classified as "university tokamaks" due to their low cost and modest performance (Te < 1 KV). They were appropriate for student training and some research.

1.1 Microtor R=40cm:

The research contribution from Microtor was focused on impurity control [2] and diagnostic development, aside from student education. ICRF heating was also explored with unsatisfactory results. We in fact expected this outcome on a small machine but the results were below our expectations. This was due to the RF reducing confinement by disturbing the particle.

1.2 Macrotor R=1.5m:

The focus on Macrotor was on understanding plasma rotation driven by radial current using biased electrodes and in reducing ion sputtering. With the arrival of Stewart Zweben [4] both machines were explored for the physics of anomalous transport using insertable magnetic and electric probes. The first ever force poloidal rotation and bifurcation was obtained on Macrotor. H-mode was obtained but not explored. We were studying the reduction of ion sputtering of the walls. Reduction of sputtering was achieved, which meant better plasma particle confinement by radial potentials [5]. As in the later discovered H-mode, theoretically this resulted in no significant ion heat loss, hence in a modest improvement (<2) in global energy confinement. This was not measured due to lack of the required instrumentation.

The modified ion transport phenomenon went unexplained until more extensive neoclassical theory was developed by Shaing and more experiments were conducted in the CCT tokamak a decade later.

1.3 CCT R=1.5m:

Macrotor was shut down due to its low aspect ratio (A=2), which made the UCLA theorist and Pat Diamond nervous. The aspect ratio of CCT was increased to 3.3. CCT was the most extensively studies tokamak for H-mode like bifurcation physics using insertable probes. It had very rugged toroidal field coils. They were donated by Bob Ellis from the Princeton ATC tokamak.

Originally, it was built to explore Continuous Current; its payoff was in understanding rotation [6] and some of the ingredients of anomalous transport. Again, the RF experiments failed both on physics and technology.

2.0 Low Curvature Tokamaks at UCLA R=5m:

Alcator scaling, our own experience and transport theory speculations all indicated that higher aspect ratio and larger tokamaks would result in less anomalous transport even at low magnetic fields. The energy confinement times of the previous UCLA devices were in the ten millisecond range. A large tokamak was expected to improve the confinement times.

2.1The Electric Tokamak R=5m, an introduction:

The Electric Tokamak was conceived to increase the confinement time to the second range by size alone and it was sold as a possible second stability tokamak (Cowley).

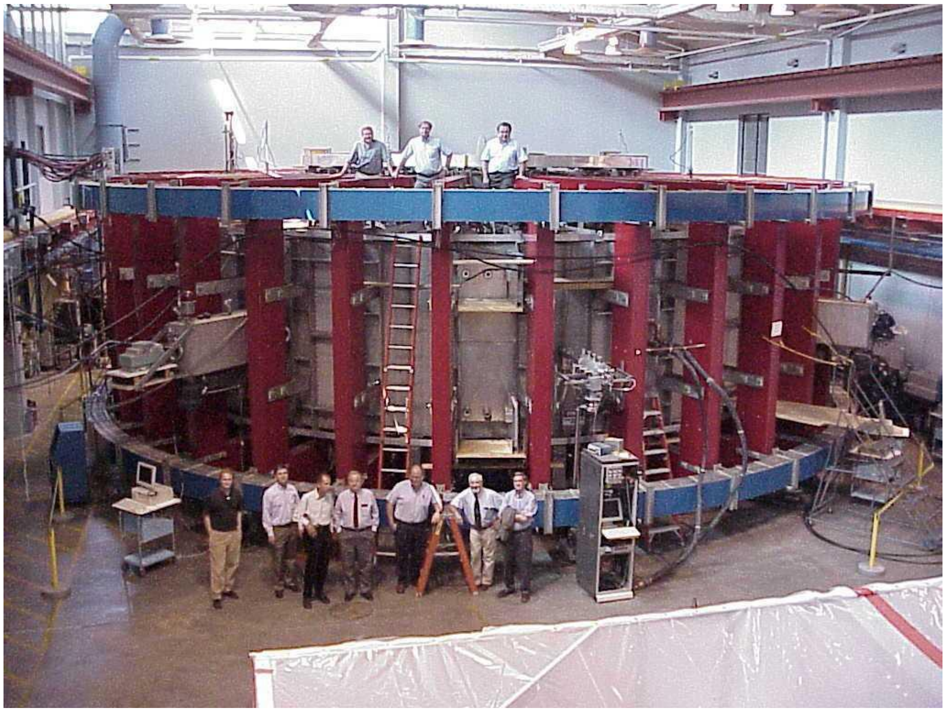

Fig. 1. The Electric Tokamak under review by DOE and Committee (about 2000).

With University funding of the Science and Technology Research Building (STRB), it became possible to assemble such a large tokamak at UCLA with the use of cranes. The magnets were operated from a 50 MW substation in Westwood. The ET device was funded in 1998 but some of its components were under testing for years. The ET tokamak became the "default tokamak" at UCLA after the migration of Bob Conn and Neville Luhman. Fusion was under a political strain in the Engineering department after the fission group went into exile. The ET tokamak was considered politically safe but it was transferred to the Physics Department where there was only a mild "anti tokamak" undercurrent, not enough to kill the funding of ET or exile its PI.

The PI was made happy through gaining access to a huge facility designed for Bob Conn's more ambitious plans, which in fact could not be funded due to declining budgets at DOE. For Bob Conn, there was also an ITER hosting issue. Conn lost landing of ITER design to UCLA. Eventually this would be followed with more financial and program management disasters in Washington. Nevertheless, by the end the first decade of 2000's the ITER program was well established politically but had some serious consequences for the domestic fusion research program that persist to the date of this writing.

By the 2010's, the ICC program that supported ET has declined at it was only able to give out awards with a yearly funding level, ranging from **$40K to $952K.**
http://www.iccworkshops.org/icc2010/FES%20ICC%20Meeting%20Presentation.pdf

Under such condition ET could no longer be funded and operated and was closed in 2006. The PI also retired at the same time. The ET tokamak is still under vacuum (2013) and is used for student education with a low temperature (non-tokamak) toroidal plasma in it.

Thankfully, the ET program achieved very significant results from 2000-2006, including large energy (0.5 sec) and particle confinement times (>> 1 sec).

3.0 Summary of the ET Tokamak program.

The "electric" designation was derived from Tomas Stix [1] theoretical discovery of "Magnito Electric Confinement". Our previous experiments with H-mode rotation indicated that this was a good guess.

3.1 Program goal

The major political goal of the program was researching access to second stability. Steve Cowley at UCLA was a key theorist in getting the program funded at the political level. At the experimental level good confinement, access for reasonable "heat ability" and "current drive" were the necessary ingredients of the proposed program.

Little did we know that the controllability of the central beta would become last thing *not* solved before the program was terminated. However, we were lucky enough to understand the nature of the physics of a serious particle pinch phenomenon discovered by Stix and elaborated further by Shaing.

Interestingly, the physics of this so called "electric pinch" (our term) became derivable from previous results on Macrotor and CCT relating to plasma poloidal rotation. The basics of this all relates to neoclassical ion banana transport in radial electric fields where the electron particle transport remains turbulent. However, the electron particle transport cannot overpower what the ions are forced to do in following neoclassical banana orbits. This dichotomy of transport between electron and ion particles is an undefeatable experimental fact. Simulation to date, and leading turbulence theories, have not been able to reproduce the physics of such a dichotomy in particle motion, at this time (2013). This resolution would be needed for the design of the control system of a fusion reactor.

3.2 Machine design

ET was the largest tokamak in the world up until 2013 and eclipsed the confinement time of all existing tokamaks built to date albeit at a very low magnetic field (0.3 Tesla). The name of the device was derived from "Magneto Electric" confinement ideas of Tomas Stix and the physics was validated in the CCT H-mode research, which for configuration physics had followed

Shang’s calculations [7], as mentioned above. At the same time CCT and ET did not follow anybody’s theories for behavior of the electron transport in any regime. It also appears that this understanding may not be needed in fusion reactors in contrast with the ion channel physics.

In the ET regime the ions become “enhanced neoclassical” and the electrons remained anomalous, as always. The orbits of the electrons are scattered radially by soft scale EM turbulence. Whereas the ion orbits tend to follow “orbit averaged trajectories”. The “average” needs to be based on the full gyro orbit and catastrophic magnetic turbulence need to be avoided.

If electrons did the same, we could have small ignited tokamaks at low cost. However, such a device would not produce energy in the market due to its small size and to a related technology overhead. It is unfortunate that Transport Task Force never emphasized the understanding of this dichotomy. The “miss” is that the anomalous electron transport need not be “cured”. Based on our experimental results, and the attachable theories, both the success and the failure of ITER program can be predicted from the ET results with existing mathematical tools.

The ET device produced 5 second long pulses but at end of the program we failed to enter the second stability region due to lack of funding needed for configuration control at high beta. We asked for a modest support of $3M/year. The control of the current profile became too expensive and the program could not be funded in the ICC budget at this level. The ICC program itself was destined to expire about the same time (2002-2006).

3.4 Summary of the ET physics results:

Despite of the ET program’s short existence, we have come to understand the nature of electron and ion transport and the related confinement in ET [10,11]. The electrons were seen to rattle around in small fluctuating electric/magnetic fields while mostly circulating around the tokamak and deviating from the magnetic guiding centers. Ions were not bothered by such micro fields and manage to follow neoclassical guiding centers, provided by the magneto/electric configuration. This is only possible, of course, in the absence of large scale MHD magnetic turbulence. The MHD turbulence seems to be avoidable in tokamaks, unless they are exposed to high power injection.

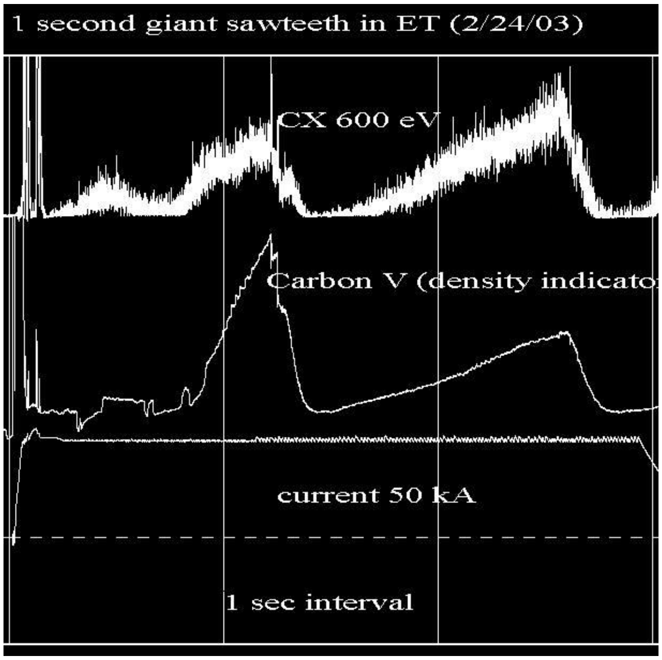

Fig. 2. Mass accumulation problem. No control found over this phenomena.

4.0 ITER predictions and comments:

Based on our experience at UCLA with small and large tokamaks for 40 years (1976-2006) we would predict that the cost of controlling a fusion reactor will put fusion outside the rage of competition for economic energy production. However, ITER needs to be tried and possibly simplified. The complexity of holding a plasma channel together in any device for sustained operation is going to be nearly impossible for a number of reasons. It is regrettable that the US fusion program lost a lot of money in building small devices around the country (including TFTR). These became irrelevant devices since they could not solve the energy confinement problem in the electron channel on theoretical and experimental basis, including using higher magnetic fields.

In ET we have gained good electron energy confinement due to the large size of the device. The confinement exceeded our proposed value by a factor 3 and reached 1 second in the core, 0.3 second globally, in ohmic plasmas. This result mostly followed an improved “Alcator Scaling” where confinement depended mostly on the volume of a device and not its cross section nor its magnetic field. This scaling landed far from the expectation of classical (neoclassical) theory. This trend was disappointing for a fledgling fusion program but proved to be not deleterious for a useful reactor where size is required to keep the neutron fluxes at technologically reasonably low level, while producing electricity above 1 GWe per installation. ITER is expected to come close to such desirable levels of energy production due to its size which is somewhat larger than the size of ET in major radius 6/5 m, in minor radius a 2/1 m and most significantly, in magnetic field 5/0.3 Tesla. The major cost of ITER is related to its large magnetic field. The ET program was designed to reduce the required large field for a reactor by exploring the second stability regime but we failed to validate the achievability of such a regime due to costs and time. The ET program had only a 3 year happy exploration time after it was built. By all standards, this was shamefully too short. A minimum of 10 years would have been required. It is likely that the Iraq war and the promise of an improve oil supply from the Middle East put fusion support on the back burner. Now with improved fracking in the homeland, the cost of energy supply looks fair for a long time. Fusion, which was a cold war baby, is likely to experience low levels of funding which will put it outside of the interest of new generation of physicist and engineers as a carrier or curiosity objective. This should not be considered either good or bad. The exciting days of fusion science exploration are naturally behind us.

ITER provides us with the right scale and knowledge to take fusion from the table top to a technology arena. The control of the DT plasma operations in JET and in TFTR has been dismal. Hopefully this will be correctable in ITER. Nevertheless, our results on the electric pinch indicate it otherwise.

5.0 Additional thoughts on closing of the 30 year UCLA tokamak program.

The research program was closed on July 31, 2006. It was a beginning of the closure of a series of Innovative Confinement Concept programs, which by 2013 reached the Alcator program at MIT. After a reconsideration Alcator was re-funded. The support for fusion research has experienced a continued decline since about the late 80's, when it became clear that the confinement physics was resistant to significant improvements and the program found refuge in "Science" exploration instead in "Energy" development. A modest improvement was found in energy confinement in the H-mode operation but the improvement never eclipsed a factor 2. In desperation, the H-mode was exploited politically to keep the hope for achieving needed confinement alive. At the same time it was realized that an H-mode, in which particle confinement was increased to undesirable levels, relative to energy confinement times, would in fact be deleterious to the operability of an energy producing reactor.[8]

In the early 2002 the US has rejoined the ITER program, which was in a rather questionable state for decades. But again we were faced with very difficult decisions in a hopeless fusion program. Finding some hope in implementing a very costly "next step" on a world shared budget became a messiah. By the time of this report (2013) the US fusion research program had been largely converted to ITER support.

In contrast, the purpose of the Electric Tokamak at UCLA was to provide a low cost path to explore problem areas in extending (1) energy confinement times, (2) improving our understanding of particle transport physics, (3) reducing the magnetic field requirement by entering second stability regimes, and (4) to reduce the cost of building and operating large tokamaks.

Not everything worked out according to our wishes. Items (3) and (4) were missed. The major reason for the failure of (3) was found to be in the tendency of the plasma mass to accumulate around the magnetic axis of the plasma, which is at the "center" of the tokamak channel. This accumulation is in fact akin to the particle build up in the H-mode. This in fact is related to achieving "neo-classical" ion confinement but no direct electron confinement.

In the case of ET this mass buildup up resulted in a high central plasma pressure (beta) without the evolution of a needed poloidal current profile to balance its effects by magnetics. We were not given the time to implement the needed current profile control. We were in the process of doing this but the project did not receive a favorable review. A desired onsite review for such a monumental project was not implemented by DOE by choice. Instead, a paper based review process was used by DOE and our project was considered "too ambitious".

The fact the ET was the largest tokamak was held against the sanity of the project. We needed to be funded at $3M/year and not at the limit of the ICC program of $1.3/year. Therefore, funding issues were a major factor in the early close out of the ET program. We had a 3 year diagnostic time. In general, a 10 year diagnostic time would have been a better investment.

The PI is grateful to the 30 year overall support from DOE, UCLA and the staff, in particular to Zoltan Lucky for technical and administrative support and for Anne Davis and Chuck Finfgeld of DOE for providing funds and guidance.

6.0 References

Note: Most of our results have been published in Nuclear Fusion in connection with IAEA conferences and in the Physical Review Letters more than 50 articles.

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