The concept of the compact ultra-low aspect ratio tokamak CULART

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Introduction

The concept of the low aspect ratio tokamak (LART) also called spherical tokamak (ST) has been originally conceived as a potential more efficient path for a magnetic fusion reactor relative to the high aspect ratio tokamak (conventional tokamaks). This is because of the higher toroidal beta limit, which is the result of higher MHD stability provided by this unique geometry, where higher plasmas currents (I_p) can be sustained by relatively low toroidal magnetic fields (B_T) [1]. Research in LARTs (or STs) has been conducted for more than three decades all over the world.

While the ST geometry naturally leads to a more compact and modular reactor, improvements in size and cost may not be realized because of physics and engineering relative constraints, such as how to handle a higher fusion power density (particularly related to plasma exhaust to the divertor), higher neutron wall loading, critical neutron shielding of the toroidal field centre-stack even when a solenoid is not envisaged, which in turn imposes an additional constraint to external current-drive schemes.

The high neutron wall load and the modular configuration, however, make the ST the most suitable candidate for a Fusion National Science Facility (FNSF) [2], whose activities could guide both ST [3] and conventional tokamak reactor design studies alike.

Fusion power density P_f scales as $\varepsilon(k\beta_N B_T)^4$ for a fixed bootstrap current fraction [2]. Here ε is the inverse of aspect ratio, that is, a/Ro (a and Ro are the plasma minor and major radius), k is the plasma elongation and β_N the normalized plasma beta. The maximum k and β_N increase as the aspect ratio (R_o/a) are reduced [2], so these parameters will be maximum for a ULART (ultra-LART) extreme geometry device, but as a trade-off with engineering constraints to increase B_T. Independently, higher values of B_T are also very important for the thermal energy confinement ($\tau_{th,e}$) scaling as seen in H-mode in MAST [4] and H and L-modes in NSTX [5].

Therefore, operation at high B_T became a trend for the upgrades in large devices such as NSTX-U and MAST-U, and the basic physics of ULART was left for devices such as PEGASUS.

The CULART Experiment

A medium-size Compact device with an Ultra-Low Aspect Ratio Tokamak plasma (CULART) has been recently proposed [6]. The major objective of CULART is twofold. First, to explore very high toroidal beta (VHTB) limits (~100%) via passive stabilization under relatively low-medium toroidal field (TF) at ULAR geometries. Secondly, as a proof-of-concept, to use, at least initially, these VHTB plasmas as a target for applying the combined minor and major radius adiabatic compression (AC) technique aiming for attaining the equivalent of 1MW of D-T fusion power with relatively high energy or power amplification (Q factor).

This might be one of the potential pathway scenarios for an ultra-compact pulsed neutron source based on the ST concept with the lowest cost. The major characteristics of typical VHB CULART target plasmas are: R_o=0.51m, a=0.47m, aspect ratio A=1.10, k=2, $\delta\approx$0.8, $B(R_o)$=0.1T (0.4T max), I_p=0.5MA (2MA max), $n_e(0)\sim 1\text{x}10^{20}\text{m}^{-3}$, $T_e(0)\sim$1keV, and discharge duration $\tau_d\sim$100ms.

The CULART design incorporates present-day technology without using superconducting coils and with the advantage of operating in ohmic heating regimes exclusively for the target plasmas.

Major engineering aspects of CULART proposal need to be addressed that enable both regular steady-state-like tokamak operation as well as pulsed AC experiments while addressing technical difficulties such as the minimization of errors fields in the compressed plasma caused by eddy currents [7]; the minimization of the soak-through penetration time ($\tau_{s\text{-}th}$) by design; the need of fast (~0.1ms) real-time plasma position control/feedback system and programmable PSU for the magnet coils.

The vacuum vessel is spherical and will be made of SS or INCONEL® 625. This alloy has excellent mechanical properties at high temperature (≤ 500 °C) and has high electrical resistance (~50% higher than conventional SS, thus reducing $\tau_{s\text{-}th}$ by the same factor). It is, however, more expensive and more easily nuclear activated by neutron irradiation. Equally spaced corrugated bellows are also an option for reducing the total vessel resistivity.

The central stack will be a pure copper rod (~91mm diameter) covered by a thin sleeve of tungsten acting as a thermal shield (~2mm) and as a plasma limiter. The rod will be cooled via de-ionized water or cryogenic liquids. The rod should operate at high currents such as ~1MA for ~150ms in ordinary-mode of operation or in ≤1s duty cycle (depending on the engineering constraints) in cycled-mode of operation. i.e., AC (~3ms, I_p=0.5→1.6MA) followed by a thermalization time of α-particle (~60ms at I_p=1.6MA) and decompression (≤937ms, I_p=1.6→0.5MA).

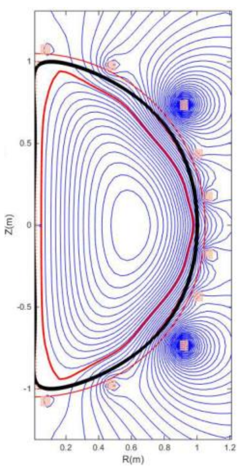
The plasma in the first phase of operation is expected to be naturally diverted (ND) and poloidally insulated from the vessel by a thin (~ 20mm) tungsten (W) semi-spherical limiters.

No internal poloidal field (PF) coils or solenoid will exist by design. This helps the compactness due to plasma-vessel proximity, it leads to wall stabilization as previously envisaged in the RULART proposal device [8], while also potentializes easier H-mode (small edge neutral source), which has already been observed in Pegasus ohmic, ND plasmas, using inboard gas fuelling [9].

The major source of initial heating is provided by I_p generated from local helicity injection (LHI). This technique was invented and has been successfully used in the Pegasus experiment in several regimes [10, 11] generating up to 250kA via 2 LHIs at high field side, 180° apart in the toroidal direction, at the bottom of that device [11]. Other schemes of heating and CD such as via NBI, RF (e.g. EC, EBW) in combination with transient Coaxial/Local Helicity Injection (CHI/LHI) techniques will also be considered, as all have been successfully demonstrated in STs.

Equilibrium

Initial equilibrium simulations from 2-D free-boundary FIESTA code have been performed with the objective to reproduce the re-constructed equilibrium of the world record VHTB obtained with the Pegasus device (β_T~60% with constant B_T) [10]. This equilibrium required a minimum of 7 parameters of Lao's polynomial representation [12], which we also adopted. Without full optimization, all features of Pegasus VHTB plasma could be reproduced, as seen in fig.1.



I_p = 500kA
I_{rod} = 250kA
$B_T(R_o)$=0.0973T
R_o = 0.514m
a = 0.4644m
A ≡ R_o/a =1.106
k = 2.03
δ = 0.762
q(a) ≈ 25
li(2) = 0.313
β_p = 0.398
$\beta_T(R_o)$ = 45.4%
$\beta_N(R_o)$ = 4.11

Fig.1- Free-boundary equilibrium simulation from the FIESTA Code showing the plasma cross-section, preliminary PF coil set, and the magnetic flux surface. A table with the major final equilibrium parameters is also presented.

Confinement

The expected thermal energy confinement time for CULART is calculated using NSTX L-mode scaling law [5] and the equilibrium parameters from figure 1. Values of ~13ms were obtained. This means that the compression time can really be $\leq$ 3ms, without many technical difficulties.

The relative power for L-H transition in CULART plasma is about 4-17 times higher than predicted by ITER scaling P(ITPA04) which includes some dependence of the low aspect ratio. More important, this value is close to, but higher on average, than the observed relative power for L-H transition from Pegasus to respect this ITER scaling low (i.e., 3.8 times). Therefore, it is very likely CULART plasmas will naturally operate in H-mode regime.

Adiabatic Compression

By applying the AC technique over the VHTB of fig.1, that is, I_p = 0.5MA, $B(R_o)$ = 0.1T, R_o = 0.51m, a = 0.47m, A = 1.1, k = 2, $\delta \approx 0.8$, $q_\Psi(98\%)$ = 25 [q_Ψ(Peng) = 22], T_e/T_i =263/486eV (scaled from ref.10), $n_e(0)$~$0.15\text{x}10^{20}\text{m}^{-3}$[10], the following final values can be reached: I_p=1.6MA, $B(R_o)$=2.4T, R_o=0.16m, a=0.10m, A=1.6, k=1.6, $\delta\approx0.2$, $q_\Psi(98\%) \equiv 25$ [q_Ψ(Peng) = 1.8], T_e/T_i=4.6/8.0keV, $n_e(0)$~$1.0\text{x}10^{21}\text{m}^{-3}$. These values produce the equivalent of 1MW of D-T fusion power with a neutron flux of 3.6×10^{17}n/s.

Conclusion

Progress on CULART modeling has been presented and engineering issues highlighted. Combined adiabatic compression in minor and major radii presents a potentially very effective way for increasing ion and electron temperatures as well as the density while retaining very low aspect ratio and current stability. The future tasks are: FIESTA simulations of the prior (refining it) and compressed plasmas, analysis of linear-stability calculations from D-CON code linked to FIESTA or CHEARS codes for prior and compressed plasmas, soak-through calculations, etc.

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