Features of the high field ultra-low aspect ratio tokamak

C. Ribeiro[1], J. J. E. Herrera-Velázquez[2], F. Ganoa-Castellanos[2]

[1] *Laboratório de Física de Plasmas e Fusão, Instituto de Matemática, Estatística e Física, Universidade Federal do Rio Grande, Rio Grande do Sul, Brazil*

(celso_ribeiro@hotmail.com)

[2] *Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico*

Introduction

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

STs geometry leads naturally to a more compact and modular reactor. However, this might not be necessarily a small, and thus a cheaper device in the first place because of similar but enhanced 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 load, 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.

However, the high neutron wall load and the modular configuration 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 $\sim\varepsilon(k\beta_N B_T)^4$ for a fixed bootstrap current fraction[2]. Here ε is the inverse of aspect ratio, that is, a/R_o (a and R_o are the plasma minor and major radius), k is the plasma elongation and β_N the normalised plasma beta. The maximum k, β_N increase as the aspect ratio (R_o/a) is reduced[2], so these parameters will be maximum for an ULART (ultra-LART) extreme geometry device, but as a trade-off with engineering constrains 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 fair trend for steady-state STs operation in the upgrading of larges devices such as NSTX and MAST, and the understand of the basic physics of ULART was left for devices such as PEGASUS.

The High Field Ultra Low Aspect Ratio Tokamak (HF-ULART)

The basic features of the medium-size high field ultra-low aspect ratio tokamak (HF-ULART) have been recently proposed[6]. The major objective is to explore very high beta scenarios under the minimum toroidal field as a target plasma, and then explore higher pressure values using the combined minor and major radius adiabatic compression (AC) technique. The final configuration will be under medium-high B_T for a short period (few to tens of milli-seconds prior to decompression). Therefore, $P_f \sim \varepsilon(k\beta_N B_T)^4$ could be fully optimized for all 4 parameters and $\tau_{th,e}$ could also increase in such time interval. This might be a potential path scenario for an ultra-compact pulsed neutron source based on the ST concept.

The major characteristics of a typical HF-ULART target plasma (prior-AC) are: R_o=0.51m, a=0.47m, aspect ratio A=1.1, k=2, $\delta\approx0.8$, $B(R_o)$=0.1T (0.4T max.), I_p=0.5MA (2MA, max.), $n_e(0)\sim1\times10^{20}m^{-3}$, $T_e(0)\sim0.5$-1keV, and discharge duration $\tau_d\sim100$ms. The vessel is spherical, made of SS, and insulated from the natural diverted (ND) plasma by thin (2 cm) tungsten (W) or SS semi-spherical limiters. The central stack is made of cooper protected by a thin (~2mm) W sleeve. No internal PF coils or solenoid are envisaged. This helps the compactness due to the close plasma-vessel fitting, capitalizing of wall stabilization as previously envisaged in the RULART proposal[7], while also potentializes easier H-mode (small edge neutral source volume), which has already been observed in Pegasus ohmic H-mode ND plasmas, using inboard gas fuelling[8]. The major source of initial heating is provided by I_p generated from RF (e.g. EC/EBW) in combination with transient Coaxial/Local Helicity Injection (CHI/LHI) techniques, as both have been successfully demonstrated in STs.

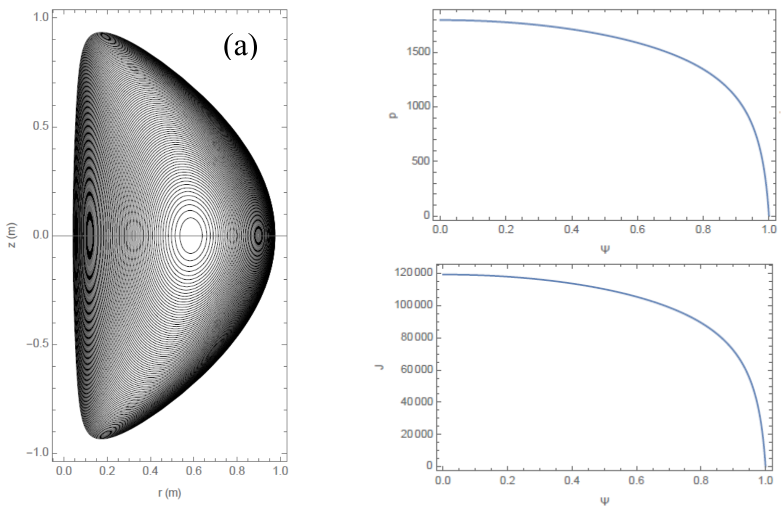
Adiabatic Compression in HF-ULART

By applying the AC technique over a very high beta plasma, that is, I_p=0.5MA, $B(R_o)$=0.1T, R_o=0.51m, a=0.47m, A=1.1, k=2, $\delta\approx0.8$, q_Ψ(Peng)=22, T_e/T_i =263/486eV (scaled from ref.9),

$n_e(0)$~$0.15x10^{20}m^{-3}$[9], the following final values can be reached for short period (~ms): I_p=1.0MA, $B(R_o)$=0.61T, R_o=0.33m, a=0.28m, A=1.2, k=1.6, δ≈0.1, q_Ψ(Peng)=12, T_e/T_i=1.9/3.4keV, $n_e(0)$~$2.8x10^{20}m^{-3}$. Notice this compression could be extended up to values of q_Ψ(Peng)=2, when MHD external kink stability could play a role, while the pressure-driven modes could also be important. Proper analysis of these limits should be performance. Such reduction in geometry could lead to much higher temperature and densities.

Equilibrium

Preliminary simulations on fixed-boundary equilibrium by the 3-D VMEC[10] and the 2-D PSI-Tri[11] are shown in fig.1 and fig.2, respectively. Initial equilibrium simulations from 2-D free-boundary FIESTA code are presented in fig.3.



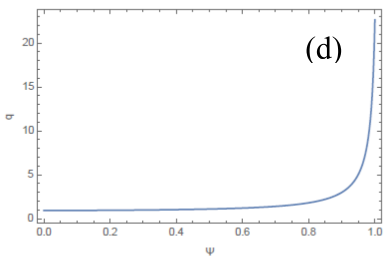
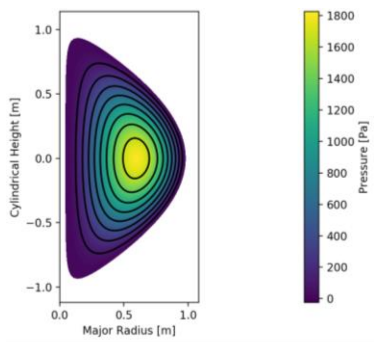
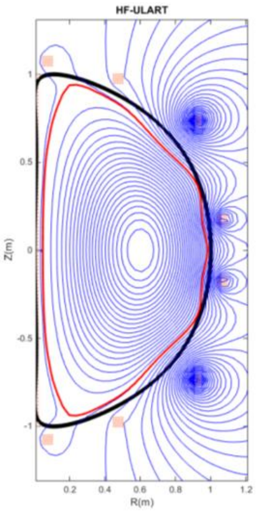


Fig.1- Fixed-boundary equilibrium simulation from the 3D VMEC Code showing the plasma cross-section (a) and the plasma (b), current (c) and safety factor (d) profiles as function of the normalized flux coordinate[10]



Toroidal Current [A]	= 5.029E+05
Current Centroid [m]	= 0.364 0.000
Magnetic Axis [m]	= 0.599 0.000
Elongation	= 2.31
Triangularity	= 0.70
q_0, q_95, q_a	= 1.07 6.46 14.68
Peak Pressure [Pa]	= 1.806E+03
Stored Energy [J]	= 2.228E+03
<Beta_pol> [%]	= 7.97
<Beta_tor> [%]	= 8.65
Diamagnetic flux [Wb]	= 4.091E-02
Toroidal flux [Wb]	= 2.858E-01
Magnetic Energy [J]	= 1.689E+03
Magnetic Helicity [J-m]	= 5.699E+02

Fig.2- Fixed-boundary equilibrium simulation from the 2D PSI-Tri Code showing the plasma cross-section and pressure scale and a table with the final equilibrium parameters[11].



Ip	0.5	MA
Irod	0.25	MA
U	1.33	KJ
Rin	0.0481	m
Rout	0.982	m
V	3.62	m^3
R0	0.603	m
A	1.1	
κ	2.01	
δ	0.6	
B0	0.243	T
q0	0.816	
q95	4.37	
li(2)	0.883	
β P	0.0361	
β N	0.579	%
β T	6.38	%

Fig.3- 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 are also presented.

Conclusion

Progress on HF-ULART modelling has been presented. Combined adiabatic compression in minor and major radius seems a very effective way for increasing ion and electron temperatures and also to increase the density, while retaining very low aspect ratio and current stability. Further compression can be envisaged and will be guided initially by linear-stability calculations from D-CON code linked to the output of the fixed and free-boundary equilibrium simulations, whose preliminary results have been presented in this work.

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