Features of the high field ultra-low aspect ratio tokamak

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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 (Iₚ) can be sustained by a fixed toroidal magnetic fields (Bₜ)[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 Pₜ scales as ~ε(kβₜ⁰Bₜ)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 βₜ the normalised plasma beta. The maximum k, βₜ increase as the aspect ratio (Rₒ/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, $P_T \sim \varepsilon(k\beta_0 B_T)^4$ 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 $A=1.1$, $k=2$, $\delta=0.8$, $B(R_o)=0.1T$ (0.4T max.), $I_p=0.5MA$ (2MA, max.), $n_e(0)\sim1x10^{20}m^{-3}$, $T_e(0)\sim0.5$-1keV, and discharge duration $\tau_d\sim100ms$. 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, $I_p=0.5MA$, $B(R_o)=0.1T$, $R_o=0.51m$, $a=0.47m$, $A=1.1$, $k=2$, $\delta=0.8$, $q\psi(\text{Peng})=22$, $T_e/T_i = 263/486eV$ (scaled from ref.9),
the following final values can be reached for short period (~ms): $I_p=1.0\text{MA}, \ B(R_o)=0.61\text{T}, \ R_o=0.33\text{m}, \ a=0.28\text{m}, \ A=1.2, \ k=1.6, \ \delta=0.1, \ q_\phi(Peng)=12, \ T_e/T_i=1.9/3.4\text{keV}, \ n_e(0)\sim2.8\times10^{20}\text{m}^{-3}$. Notice this compression could be extended up to values of $q_\phi(Peng)=2$, 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.

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**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]

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**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].

<table>
<thead>
<tr>
<th>Toroidal Current [A]</th>
<th>5.029E+05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Centroid [m]</td>
<td>0.364 0.000</td>
</tr>
<tr>
<td>Magnetic Axis [m]</td>
<td>0.599 0.000</td>
</tr>
<tr>
<td>Elongation</td>
<td>2.31</td>
</tr>
<tr>
<td>Triangularity</td>
<td>0.70</td>
</tr>
<tr>
<td>$q_{0,95,a}$</td>
<td>1.07 6.46 14.68</td>
</tr>
<tr>
<td>Peak Pressure [Pa]</td>
<td>1.806E+03</td>
</tr>
<tr>
<td>Stored Energy [J]</td>
<td>2.228E+03</td>
</tr>
<tr>
<td>$&lt;\text{Beta}_{pol}&gt;$ [%]</td>
<td>7.97</td>
</tr>
<tr>
<td>$&lt;\text{Beta}_{tor}&gt;$ [%]</td>
<td>8.63</td>
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<tr>
<td>Toroidal flux [Wb]</td>
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<tr>
<td>Magnetic Energy [J]</td>
<td>1.688E+03</td>
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<tr>
<td>Magnetic Helicity [J-m]</td>
<td>5.699E+02</td>
</tr>
</tbody>
</table>
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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References

[10] Private communication with Dr. M. R. Cianciola.