Features of the Rodless Ultra Low Aspect Ratio Tokamak

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INTRODUCTION

The replacement of the conventional metal centre-post in spherical tokamaks (STs) for a plasma centre-post (PCP, the TF current carrier) is the ideal scenario for a ST reactor.

Experiments using PCP are currently being conducted via Proto-Sphera device[1].

A simple rodless ultra low aspect-ratio tokamak (RULART) using a PCP ECR-assisted screw-pinch with an external solenoid has been recently proposed, aiming to be the most compact RULART[1].

In that proposal, the solenoid provided the stabilizing field for the PCP and the seed toroidal electrical field for the tokamak start-up plasma, which, after evolving, will further stabilize the PCP, acting as stabilizing closed conducting surface.

That RULART will require relative low TF, and the compactness (high ratio of plasma-vessel volume) may provide passive stabilization against external kink and tilt modes or vertical instability, and possibly easier the access to L-H mode transition (because of small gap volume for neutral gas). This may avoid the need of inboard gas injection for setting H-mode as observed in the ultra-low aspect ratio tokamak (ULART) Pegasus[3].

THE FORMATION OF PCP ECR-ASSISTED SCREW PINCH

It is presented here a preliminary study of a very simple PCP highly suitable and synergetic to an ULART experiment. The initial phase of the PCP formation is shown in figure 1.

The initial field for the PCP is created by a pair of solenoid coils positioned on the top and bottom of the vacuum vessel. The solenoid geometry and currents can be easily prescribed to allow the ECR power to be absorbed to form an initial vertical column with a waist in the centre, as seem in figure 1.

The PCP here is basically a vertical plasma column formed by ECR limited by 2 bias metal ring-type plates which are placed on top and bottom inside of the vacuum vessel.

A vertical current through the PCP can be driven and stably sustained by a bias voltage applied between those plates.

This current creates the total toroidal field needed for sustaining an ULART plasma which in turn can be maintained by other conventional CD schemes such as RF or via a simple and reliable Coaxial Helicity Injection(CHI) system[4,5].

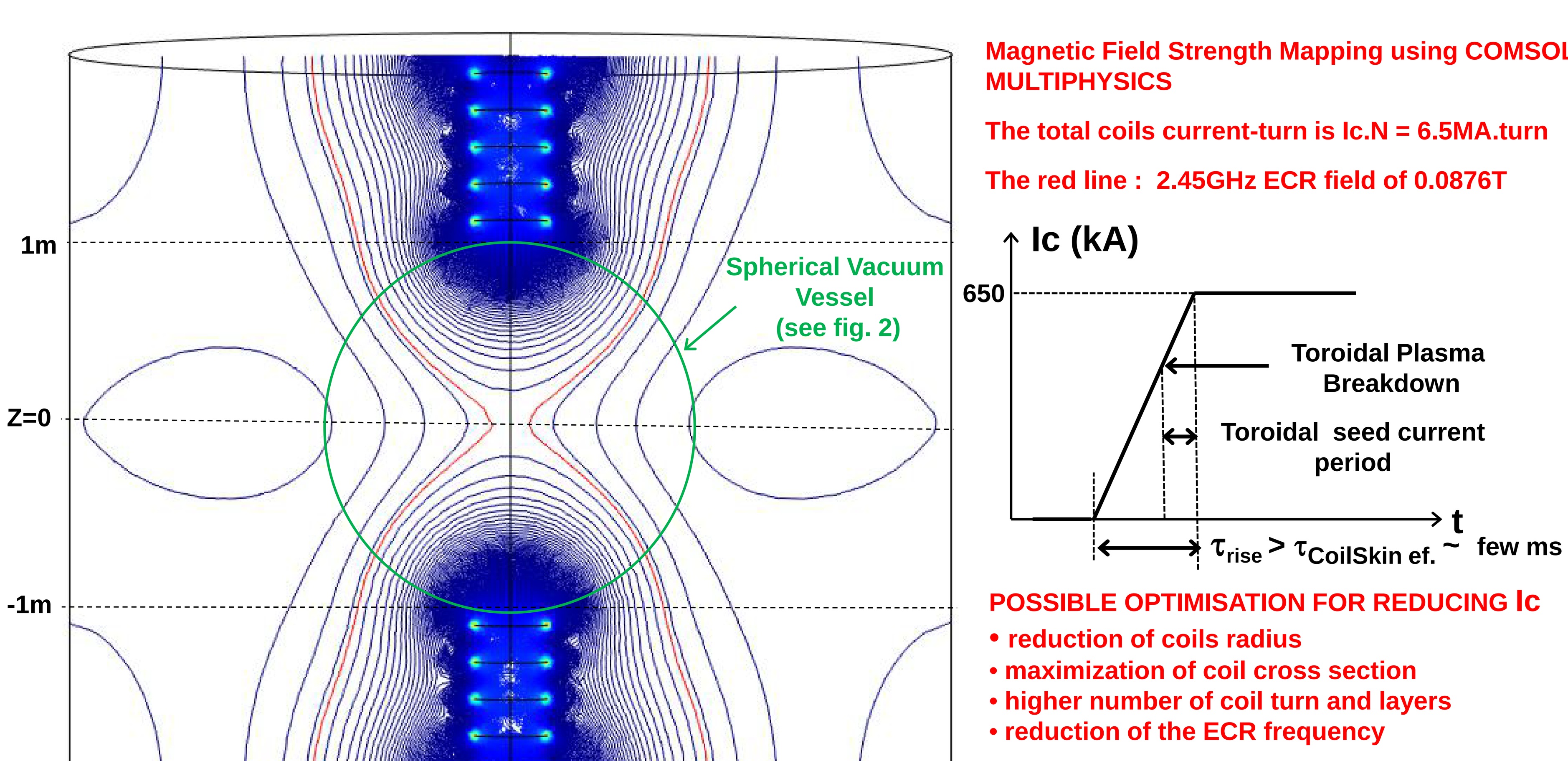

Fig. 1 PCP formation

THE STABILITY OF PCP ECR-ASSISTED SCREW PINCH

As the bias voltage is set the vertical ECR waist PCP column contracts.

The PCP during this phase has a natural hollowed current profile (skin current conducting cylinder in which can also act as a close fitting carrying current conductor) and can stabilize the PCP column itself.

The radius of the PCP during this phase varies from $R_{sp} \approx 0.71$m at the biased plates to $R_{sp} \approx 0.10$m at the waist at the vessel midplane.

Assuming an average value of $\langle R_{sp} \rangle \approx 0.41$m and a T_e(ECR) $\approx$ 10eV, the resistivity diffusion time for reaching a flat current profile is $\tau_R \approx$ 9ms, which sufficient long for starting the tokamak plasma.

Furthermore, the spatial average magnetic field provided by solenoids is $\langle B_{sol} \rangle \approx 1.4$T, which allows a PCP current of $I_{sp} \approx 5.3$MA, using $\langle R_{sp} \rangle \approx 0.41$m , and $L_{sp} \approx 1.4$m (PCP length) for reaching q=1 (PCP kink instability limit). Since in practice I_{sp} << 5.3MA (100kA might be the technical limit), the PCP will be highly stable regardless even the uncertainties related to the evaluation of τ_R.

The ECR resonance position related to the PCP will vanish when the much large PF coil currents are activated for maintaining the ULART plasma.

However, after the ULART plasma is formed this will further stabilize the PCP plasma in subsequent phases (acting as a close conducting current plasma shell) during the plasma start-up/ramping and flat top phases, so steady state can be achieved providing conventional CD is available. An schematic view of the RULART is shown in fig.2.

In addition, the time variation of the magnetic flux from the double external solenoid can be adjusted for providing a seed plasma current for the ULART.

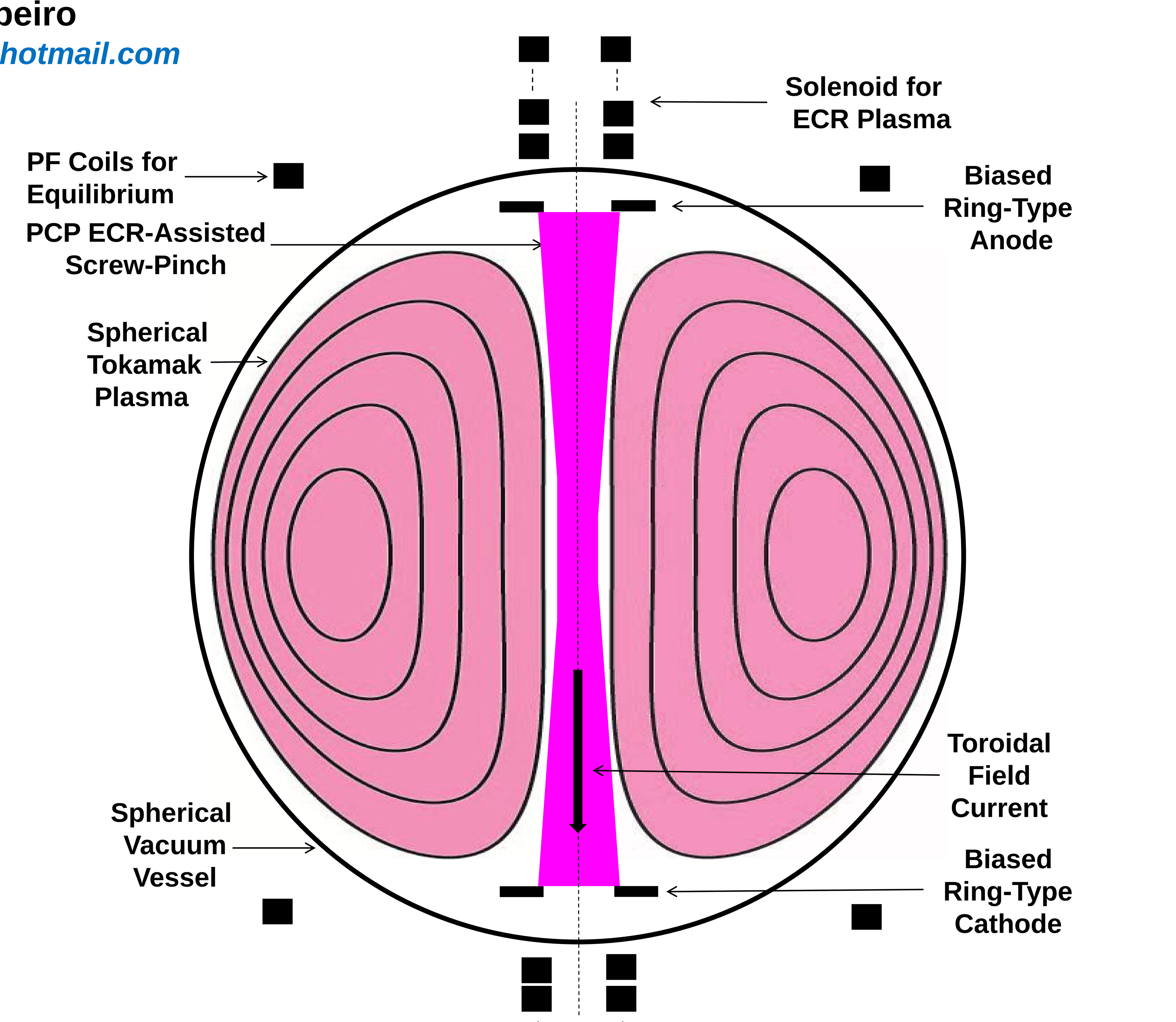

Fig.2 Schematic view of the RULART
The toroidal field coils are not shown.

RULART HELIUM PLASMAS for p-11B REACTIONS STUDIES

This is envisaged via pairs of proton (p) and boron (^{11}B) ion beams, whose sources can be arranged in several ways, such as at vessel horizontal mid-plane (VHMP) or placed symmetrically (top & bottom) to respect the VHMP, at the HFS, with a quasi-vertical line-of-sight (sufficiently for the beams miss the sources of each other, while allowing a near maximum relative velocities, thus reactivity).

The p-^{11}B reactions should occur at HFS close to the PCP surface ($R_{sp} \approx 0.1$m). Some of the born α-particles should cross the PCP and might be dragged by the He$^+$ ion current flow (higher momentum exchange) towards the cathode but, unlikely this ion flow, will not bend towards the cathode but escape ($v_\alpha >> v_{i\text{-}drift}$) directly into a direct electricity converter placed behind of it.

The energy of a fraction of α-particles which fail to the reach the convertor won´t be confined since their gyro-radius at born is about ~1.1m ($\geq$ 2a + 2R_{sp} = 1.0m) using the maximum local magnetic field B=0.22T (from I_{sp}=100kA and I_p=200kA). They will reach and heat evenly the vessel directly with a time-of-flight is about 0.1μs ($v_\alpha \approx 1 \times 10^7$m/s, 2a + 2$R_{sp} \approx$ 1.0m). A small fraction may still slowdown into the plasma depending of the temperature and density.

The p-^{11}B reaction has a maximum cross section (~0.9x10^{-24} cm^2) with energies of 600–700 keV [6]. Using 650keV as an centre value any combination of boron (E_B) or proton(E_p) beam energy such as E_B+ E_p= 650keV is possible. Assuming no losses such as from space charge effects and intra-beam scattering, 1MW (from the total 8.7MeV from the beams) is possible to be achieved, leading to ~10^{18} p-^{11}B reactions per second. The beams are from compact (~3m loop length) storage collider rings fed by RFQ (radio- frequency quadrupole) accelerators[7].

For a helium tokamak plasma of I_p=200kA, a=0.42m, R_o=0.52m, elongation k$\approx$2, T_e~1keV, the dissipated ohmic power is about 0.54MW. Therefore, it is likely that the effect 1MW from the p and B beams should be easily measured in this plasma and thus in the vessel as heating (directly from the α-particles or indirectly from the plasma via thermal and particle diffusion).

CONCLUSION

A highly MHD stable plasma central post-PCP ECR-assisted screw-pinch scheme has been proposed aiming to create the total toroidal field for initiating and sustaining a second plasma with ultra-low aspect ratio geometry.

This later plasma can further stabilize the PCP by acting as a close conducting current plasma shell during all phases of tokamak operation, so steady state can synergistically be achieved, providing conventional spherical tokamak current drive schemes are applied.

Preliminary analysis of potential use of the RULART operation in helium plasmas with proton and boron beams is presented. A proper calculation is needed to address what the fraction of α-particles would slows down and heat the electrons and then the ions, what fraction heats the vessel directly, and finally what fraction could be directly converted to electricity.

Scaling of RULART size, temperature (via auxiliary heating) and PCP current is favorable for this concept, which may play a role as a relative low temperature (few keV) compact low field energy drainer for the α-particles.

This might be a potential hybrid direct-steam cycle conversion reactor scheme, nearly aneutronic, and with no ash or particle retention problems, as opposed to any conventional D-T thermal reaction proposals.

A proof-of-principle of cheap PCP ECR-assisted (or even the full RULART) experiment can be made in half scale (spherical vessel of 0.5m radius) to respect of the present proposal.

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