Physics and Engineering Design of ESTELL Quasi-Axisymmetric Stellarator

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Introduction

The Evolutive Stellarator of Lorraine, ESTELL, is a quasi-axisymmetric stellarator to be built at the University of Lorraine. Its main objectives are i) to study confinement and turbulence properties in quasi-axisymmetric stellarator configuration and ii) to train young scientists and engineers in an academic environment on a flexible and well-diagnosed device enabling fundamental investigations in plasma physics. Since the original project proposed in 2011 [1], depicted in Fig. 1, some significant modifications of the design have been decided in order to improve the confinement properties of ESTELL while keeping the budget at the same moderate level of founding (12M€ for the construction phase). In this contribution, we present the main modifications to the project and their impact on the research to be conducted in ESTELL.

ESTELL objectives and requirements

Quasi-axisymmetric stellarators (QAS), i.e. stellarators with |B| symmetric in the toroidal (Boozer) direction, would have neoclassical transport very similar to that of tokamaks while keeping intrinsic advantages of stellarators, such as the absence of disruptions. Little is known about the properties of turbulent transport in such a configuration, but it can be noted that the negative global shear, which tends to be stabilizing for curvature-driven modes, is expected to improve confinement [2]. The potential benefits of QAS could make them serious candidates for a fusion power plant, but first their confinement properties have to be experimentally investigated and compared to those of tokamaks and other optimized stellarator configurations. Several QAS have been projected (CHS-qa in Japan, NCSX and now QUASAR in the US) but none has been completed. ESTELL would be a more modest device but is designed to offer sufficient performance for answering important questions related to QA confinement properties by characterizing plasma equilibrium, self-generated pressure-driven plasma current and neoclassical transport as well as the consequences of QA violations. For moderate technological and financial costs, ESTELL should demonstrate good confinement properties up to $< \beta > = 0.5$ % and 1 T magnetic field. In addition, its design includes enough flexibility to enable plasma shaping, a wide range of operation and future upgrades. Due to its medium size, flexibility and accessibility, ESTELL will be well suited to test innovative concepts at lower risk and cost than in large-scale devices. Fundamental plasma physics studies will mainly focus on i) turbulence and turbulent transport at $\rho^{*}\sim 10^{-2}$, ii) RF heating and related RF sheath physics, iii) 3D magnetic reconnection and iv) innovative diagnostics.

Device engineering design

Technical complexity is certainly the largest disadvantage of stellarators compared to tokamaks. The key idea behind ESTELL's design is to enable the exploration of QAS confinement properties at minimum technical and financial risks. The most critical issue of optimized stellarators is the accurate realization and the long-term integrity of the modular coils. The efficient confinement of high- β plasmas requires sufficient rotational transform ι, which is obtained by increasing the number of toroidal periods N and results in complex coils (and vessel) shapes, especially for compact devices. Since achieving high- β performance is not the purpose of ESTELL, we selected $N = 2$ which allows for a relatively simple coil set exhibiting low curvatures and comfortable clearance between adjacent coils.

In the original project, water-cooled copper coils were envisaged in order to enable almost stationary operation required for some fundamental studies of plasma-surface interactions. A reference configuration with 10 coils per period, demonstrating efficient confinement properties up to $<\beta> = 0.5$ % at $B = 0.5$T was chosen [1]. It was also shown that an alternative configuration with 12 coils per period would reduce the effective ripple and reduce the diffusive transport by a factor of two[3], but such a configuration turned out to be significantly more complicated to realize from a technical point of view, as long as large water-cooled coils were required.

In 2014 a decision was taken to abandon the possibility of stationary operation in order to lower the operational cost of the device. A new set of 12 slim coils per period has been designed, which should significantly improve the neoclassical confinement. The nominal coil current at full magnetic field $B = 1$T will be 320kA per coil, enabling a duty cycle of 1 pulse

(1s flat top) every 10 minutes without water cooling. The minimum curvature radius of the coil set is about 23cm, and the smallest clearance between two adjacent coils is 4cm. The design provides enough accessibility for installing 60 ports dedicated to various diagnostics and auxiliary systems, and enabling future upgrades. The 24 coils consist of 6 sets of 4 identical coils assembled in symmetric positions (Fig. 2). Identical coils will share the same power supply. Adjusting the current delivered by these 6 different power supplies will offer enough flexibility to enable basic plasma shaping required for investigating the consequences of QA violation as well as for studying 3D magnetic reconnection. Advanced plasma shaping would require additional coils which would not fit in the current budget, but attention will be paid in the final design phase to keep the possibility of installing such coils in future.

The second critical component after the modular coils is the assembly of structures supporting the coils and the vacuum vessel. The stainless steel vacuum vessel itself will not be significantly modified compared to the original project (except for the location of most of the 60 ports), but the structure supporting the coils will have to endure significantly enhanced mechanical and thermal stresses. A new design of the stellarator assembly will be made in the forthcoming months, once the evaluation of these stresses is completed.

In order to achieve $\langle\beta\rangle = 0.5\ \%$ at maximum magnetic field B = 1T, 1MW of ECR heating power will be available. It is also planned that ESTELL will be equipped with at least one ICRH system but the expected total ICRH power will be more modest.

Finally, to deal with the expected heat fluxes it is likely that the vacuum chamber will be equipped with CFC limiters. Although the chamber cross-section is large enough to host a divertor, its installation should certainly be left to a device upgrade, due to the larger technical complexity (and substantially higher cost) of this configuration.

Major radius <R>	1.4 m
Aspect ratio	5
Maximum magnetic field	1T
Rotational transform (axis)	0.21
Pulse duration (flat top)	1s

Tab. 1. Summary of main parameters of ESTELL

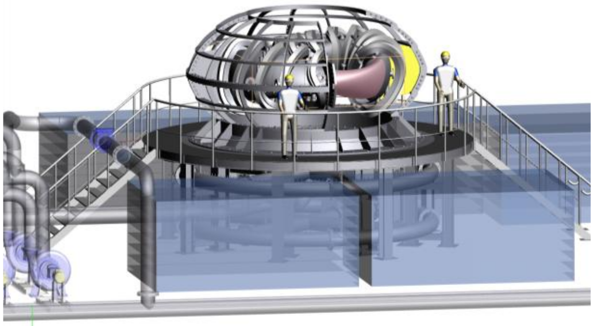

Fig. 1. Conceptual design of ESTELL before the cancellation of stationary operation in 2014.

Prospects

ESTELL has entered the final detailed design phase, which is expected to last for one year. Its construction is expected to start in 2015 provided the founding is obtained on schedule.

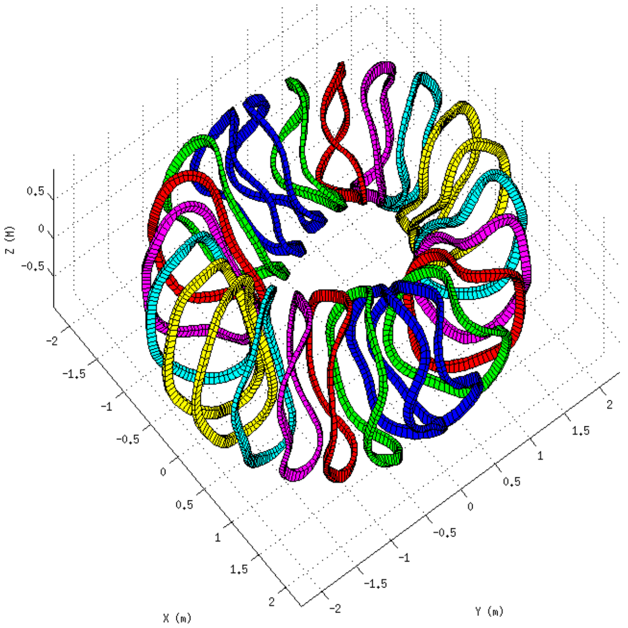

Fig. 2. Schematic drawing of the new coil set. Coils with the same color are identical.

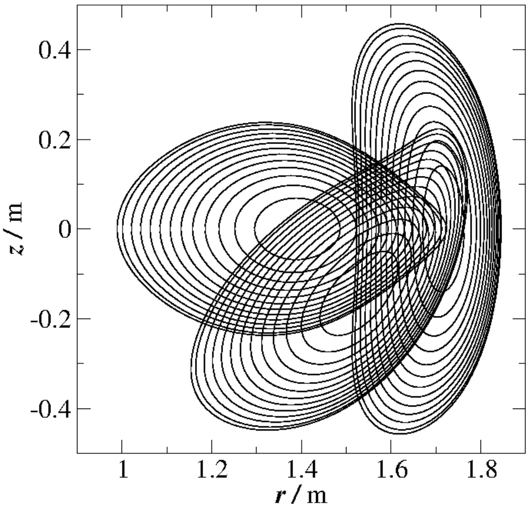

Fig. 3. Toroidal cuts of the free boundary equilibrium (VMEC calculations) at <β>=0%, for the 24 coils configuration.

References

[1] F. Brochard and the ESTELL Team, « ESTELL, a quasiaxisymmetric stellarator », Stellarator News 134 (2011).

[2] P. Helander, C.D. Beidler, T.M. Bird, M. Drevlak, Y. Feng, R. Hatzky, F. Jenko, R. Kleiber, J.H.E. Proll, Y. Turkin and P. Xanthopoulos, « Stellarator and tokamak plasmas: a comparison », Plasm Phys. Control. Fusion 54, 124009 (2012).

[3] M. Drevlak, F. Brochard, P. Helander, J. Kisslinger, M. Mikhailov, C. Nührenberg, J. Nührenberg, Y. Turkin, « ESTELL : a quasi-toroidally symmetric stellarator », Contrib. Plasma Phys. 53, 459-468 (2013).