PILOT HYBRID EXPERIMENT WITH REVERSED FIELD PINCH AS NEUTRON SOURCE AND DOUBLE FISSION TEST BEDS: AN INNOVATIVE STAGE APPROACH TOWARDS A FULL POWER FUSION-FISSION HYBRID REACTOR

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A novel approach to fusion-fission hybrid reactors (FFHR) has been proposed in recent years, regarding the fusion core for high energy neutron production, based on a Reversed Field Pinch (RFP) [1] [2] [3]. The authors specify that these studies are only based on calculations and computer simulations and any experimental activity involving nuclear fuel management is not planned.

Main advantages of this configuration in a reactor perspectives with respect to the currently prevailing ones are: the internal toroidal field is self-generated by the current flowing in the plasma, allowing the use of “light” room temperature toroidal field coils rated for hundreds of milliTesla; no intrinsic current limit exists, so that increasing the plasma current, the ignition could be achievable by ohmic heating only, avoiding the use of additional heating systems; the configuration is not prone to disruption. In principle it could be also avoided the need of a divertor, so further simplifying the machine design.

However, till now, a price has to be paid in terms of a partly chaotic character of the magnetic field leading to a poorer plasma confinement. Fortunately, advancements in RFP confinement have suggested modifications to the RFX-mod experiment (the largest RFP machine in operation) which are expected to decrease magnetic chaos and to improve significantly confinement. These enhancements are underway and the restart of the machine is foreseen in the next year.

In order to cover the gap between the present status of the RFP as a fusion core and the knowledge necessary in designing the fission subcritical reactor with respect to the full power FFHR, a pilot FFHR based on a RFP operating with an energy gain Q near one has been conceived and the feasibility studies are underway [4].

It is considered to exploit the full machine capability with the double swing operation. Being up to now at a level principle with reduced experimental assessment a current drive technique (called Oscillating Field Current Drive) to maintain stationary the RFP operation, a continuous pulsed operation is considered for the pilot in which the set-up and flat-top of the plasma current is maintained with a loop voltage induced by the magnetizing flux variation only.

The gaps to be covered by the pilot can be summarized into three groups of issues, in which some examples are given:

— Plasma physics: the large extrapolation between the present day RFP performances to larger devices and higher plasma currents (e.g. ion temperature increase, loop voltage reduction, Quasi Single Helicity persistency, MHD modes reduction), ion and fast-ion confinement;
— Fusion reactor technology: plasma-wall interaction, MHD modes control, heat and particle/helium exhaust, AC losses in the superconducting magnetizing/equilibrium coils, fatigue in materials due to the pulsed operation;
— Fission reactor and nuclear aspects: nuclear waste transmutation, nuclear energy production with low level of actinides, limits of nuclear materials, alpha particle behaviour.

Based on the available scaling laws derived from the experimental results of RFX-mod and considering the expected performance improvements, the main dimensions and expected performances of the fusion core are summarized in Table 1.

TABLE 1. MAIN DATA OF THE PILOT RFP FFHR

Major plasma radius [m]	4
Minor plasma radius [m]	0.8
Max plasma current [MA]	12
Electron/ion temperature [keV]	9.4
Input ohmic power [MW]	60
Fusion power [MW] (n/n_G=0.3)	55
14.1 MeV neutron flux [10^{12} $cm^{-2}s^{-1}$]	15
Continuous duty cycle [s]	11 ON/19 OFF

The dimensions are the result of the trade-off among cost limitation, level of plasma current and flat-top duration vs. the machine stored Volt-seconds, power and neutron flux levels on the first wall and the available nuclear materials.

In order to minimize the investment cost, to maintain some grade of flexibility during the pilot exploitation and to limit the time for the start of operation progressing simultaneously with experiments and machine enhancements, a three-stage approach has been identified in which the plant, built in a nuclear site, is gradually upgraded taking into account the acquired scientific and technological knowledge during the previous stage.

The three stage approach is summarized in Fig. 1. Stages 1 and 2 are operated only with H or D in order to prevent the activation of the machine and the need of the Remote Handling, which will be necessary in Stage 3 when D-T fuel will be used.

Phase 1 is mainly addressed to deepen the study of the RFP physics issues expanding the present operating space in a larger device at higher plasma current. The torus (i.e. the inner machine including vessel, shell, copper toroidal field winding and saddle coils for MHD control) is designed to remain the same in all the three stages; only the first wall could be replaced in the Phase 3 in order to take into account the effect of the neutron irradiation on the materials. The magnetizing/equilibrium coils, made with room temperature copper in order to limit the cost and the complication of superconductors and cryo-systems, occupy approximately the same volume foreseen in the final superconducting coil layout of Phase 2 and 3 in order to allow the easy coil interchange. The machine Volt-seconds are reduced with respect to the Phase 2 and 3 and, consequently, the maximum plasma current will be reduced to about 8 MA, a level sufficient to gain confidence on the open physics issues and to allow the step forward towards the Phase 2.

Phase 2 is mainly addressed to find solutions to the main technological issues of the RFP fusion reactor. The previous magnetizing copper coils will be replaced by superconducting ones allowing increased machine Volt-seconds and to reach the maximum plasma current and flat-top duration with the continuous pulsed operation. The size of the new magnetizing/equilibrium coils is such as to guarantee the space to host the neutron shield and the blanket in the subsequent Phase 3. The improvement of some plant systems and the implementation of new ones (e.g. power supplies, cryogenic, cooling) are required during this phase. A positive result in the assessment of the technological issues opens the door to the next phase.

Phase 3 is intended to operate the machine with D-T and, to this goal, a nuclear shield is added and inserted between the inner machine torus and the superconducting magnetizing/equilibrium coils (see Fig. 1). Additional systems e.g. for tritium management and the remote handling need to be provided in this phase. Fast neutrons produced by D-T fusion reactions with an expected flus of 1.5 10^{13} $cm^{-2}s^{-1}$ are used to drive the subcritical fission blanket. Fission blankets have two main purposes:

- To investigate fuel burn up in a RFP based hybrid system;
- To evaluate the power production in a subcritical blanket (verifying also the actinidies balance in a system driven by a 14.1 MeV neutron source).

Another important focus of this model is to study the Lithium fertilization in order to increase the necessary fusion Tritium fuel production by using the modified neutron spectrum emerging from the fission blanket. For this purpose, in this work, a Tritium breeding region will be dedicated to observe and evaluate the Tritium production.

This approach allows maintaining and reusing almost the whole equipment, plant systems and diagnostics from one phase to the next, so minimizing the costs and adapting the design of the new components on the basis of the gained previous experience.

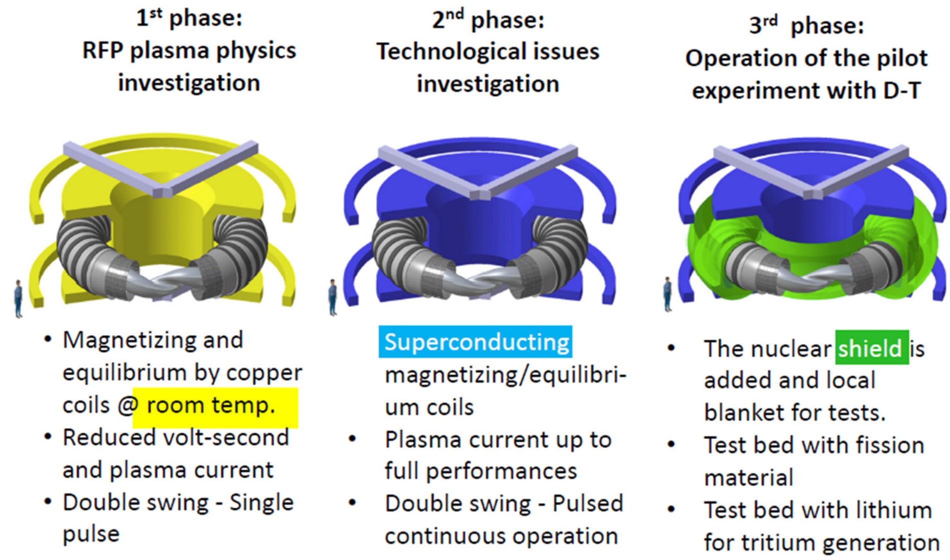

FIG. 1. Phases of the three stage approach of the pilot RFP FFHR.

Studies are underway on a preliminary design of the pilot in order to verify its feasibility [5]. The use of superconductors in a RFP reactor, although mandatory in the magnetizing/equilibrium coils, could represent an issue due to their limitations in the allowed magnetic field derivative, which is quite high during the initial plasma current phase of the RFP operation. On this purpose, a new concept is proposed based on a double coil system: the first made with superconductors and the other with conventional copper coils; such solution allows to guarantee the high loop voltage of plasma start-up but limiting the magnetic field derivative in the superconductor to less than 2 T/s. The resulting section of the machine is shown in Fig. 2.

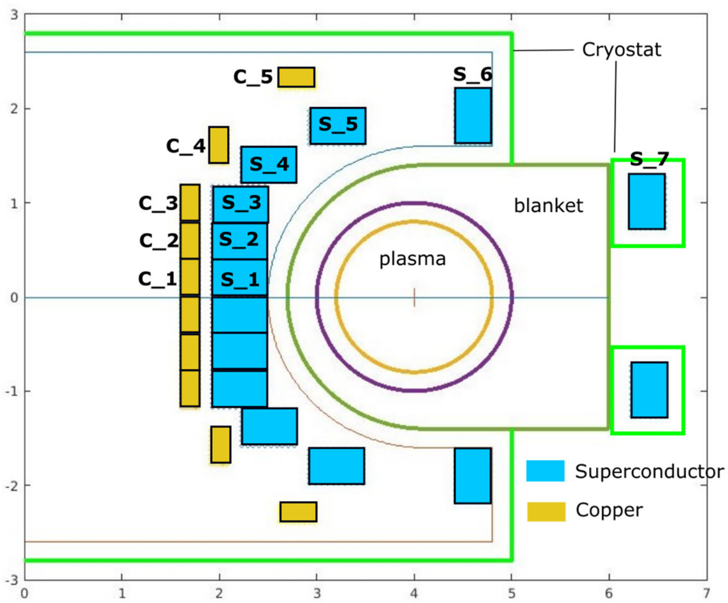

FIG. 2. Section of the pilot RFP FFHR with the double magnetizing/equilibrium system..

With the layout of Fig. 2, where large space is available for the blanket, the total stored Volt-seconds in the pre-magnetization phase are 150 Vs, which can guarantee the desired plasma current and the flat-top duration.

Studies are in progress to derive a preliminary design of the fusion and fission components, checking the nuclear aspects and performing a further step in the electromagnetic and mechanical design of the pilot machine.

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