

**Towards the completion of the CEA Contributions
to the Broader Approach Projects**

J.-C.Vallet¹, S.Chel², R.Gondé¹, F.Robin³, W. Abdel-Maksoud²,O.Baulaigue¹, N.Bazin², B.Bolzon², Ph.Brédy², N.Chauvin², J.David⁵, P.Decool¹,G.Disset², H. Dzitko^{2*}, L.Genini², S.Gharafi¹, R.Gobin², F.Gougnaud², Ch.Hoa⁴, V.Lamaison¹, J.Marroncle², Ch.Mayri², J.Noé³, B.Renard².

¹CEA, DRF/ IRFM, F-13108 St-Paul-lez-Durance, France.

²CEA, DRF/IRFU, F-91191 Gif /Yvette, France.

Email : jean-claude.vallet@cea.fr

³CEA, DRF/DIR, F-91191 Gif sur Yvette, France.

⁴CEA, DRF/ INAC, F-38054 Grenoble, France.

⁵CEA, DEN/DPIE, F-13108 St-Paul-lez-Durance, France.

*Now at F4E.

The CEA contributions to the Broader Approach projects, IFERC, IFMIF [1] and JT-60SA [2] which included the deliveries of components and services are now approaching completion. For IFERC, the supercomputer Helios, provided by CEA, will perform in the end 2016 its last runs after 5 years of operation with a very high availability and utilization rate. For IFMIF, the CEA contributions include the deliveries and the commissioning of the prototype injector, of the beam diagnostics and beam control system which are now ready at Rokkasho and the prototype of the high energy SRF LINAC for which the manufacturing and delivery of most components will be completed end 2016. For JT-60SA, the first TF coils have been produced, tested at the cold test facility at CEA Saclay and delivered to Naka. The JT-60SA cryogenic system is now commissioned at Naka. The five superconducting magnet power supplies, in charge of CEA, have performed successfully the factory acceptance tests. They were delivered at Naka mid-2016 and their installation was completed mid-September 2016. The first units of the mechanical structures of the JT-60SA magnetic field system, Outer Intercoil Structures and Gravity Supports were also delivered. This report synthesizes the achieved performances for all of these manufactured components and starts to draw the manufacturing and operation feedbacks gained by CEA in association with its industrial sub-contractors.

I) Status of the CEA contribution to IFERC-CSC

I-a) Helios status and upgrade

The IFERC objectives are to promote DEMO Design R&D Activities, ITER Remote Experimentation, and to implement, from January 2012 to December 2016, a Supercomputer Simulation Centre (CSC) for: large scale simulation activities for fusion plasma experimental data analysis, ITER scenarios and performance simulations and DEMO Design. The IFERC centre, located at Rokkasho, Japan, is hosting the various IFERC facilities including the CSC. CEA provided the PetaFlops Class “Helios” supercomputer, the associated peripheral equipment and services for 5 years of operation including maintenance. According to schedule, the Helios supercomputer, designed and assembled by Bull Company, entered into operation in January 2012. Helios has a classical architecture with, at the time, 4410 compute nodes federated by a fat-tree InfiniBand network. Each node contains 16 cores (2 Intel Sandy-Bridge processors with 8 cores each). The total computing power was 1.237 PFlop/s Linpack which yield a 12th place in the June 2012 Top 500 list. It was the largest supercomputer dedicated to a single scientific community. In order to prepare codes to the most promising architectures of future supercomputers two upgrades of Helios were performed. A first upgrade took place in 2014with the addition of 180 nodes based on

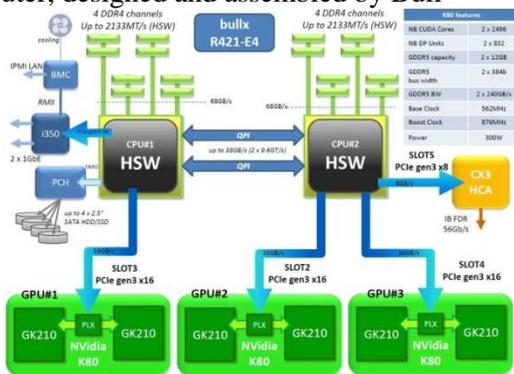


Fig.1 NVidia K80 GPU node Architecture.

Intel Xeon Phi co-processors (at the same time 90 nodes similar to the ones of the initial configuration were also added). A second upgrade took place in early 2016 with the addition of 6 nodes based on NVidia K80 GPU, each node including 2 Intel Xeon Processors and 3 NVidia K80 GPU (Fig.1). The peak performance added to Helios with this second upgrade is 36 Tflops leading to an aggregate peak performance of 2.02 Pflops.

I-b) Experience on accelerated nodes

With the continued goal of using the (now) two kind of accelerators (Intel Xeon Phi and NVidia K80) for preparing fusion code for next accelerated computer architecture, work has continued to support training of advanced users, specific porting and tuning of mini-apps of chosen codes (Gysela, MIPS) with help of specialists from supercomputer (Bull/Atos) and processor (Intel) vendors, substantiated as close collaboration for enhancing and real-enabling their high edge products. Complementary to training sessions into Europe and Japan, two joint-Europe-Japan workshop were organized in “Maison de la Simulation” in Saclay with international assistance from experts in 2014 and 2015, with up to 40 people in 2015, and one more currently organized for last 2016 quarter. The Intel Xeon Phi partition specific resource usage reached up to 40%/50%, during both 2015 and first half of 2016 years, with some production-quality runs for extended periods, while background porting/testing undertake the shallow level at 10%-20% as background. With respect to the other kind of accelerator architecture (GPU) just installed, people from different European Fusion centres were also able to check suitability and performance of their locally developed codes on this latest generation (before Pascal architecture). On the whole code developers can envisage serenely the good usage of new generation of architecture available as future EUROfusion computer coming end 2016 and 2017.

I-c) Utilisation of Helios and results

Helios is currently used by more than 120 Japanese scientists and about 300 European scientists. Almost all the users of the CSC are remote, even those in Japan. For the conventional (not accelerated) nodes, allotment of computing resources to user’s project is mostly done by peer review, instituted in a joint setup, the Standing Committee (StC), a small amount of computing resources being distributed separately. Increasingly, researchers from Europe collaborate to Japanese projects and vice-versa. With current utilisation of the computer around 90% and reaching regularly 95%, made possible by a continuous optimisation of the scheduling on Helios and the very high availability of Helios (fig.2), the total resources available for StC allocation is around 35 million nodes-hours (Mnodeh) per year. The chosen metrics result from the choice of allocating nodes (16 cores) exclusively to a job which is the most efficient setup for large runs. From the 3rd cycle (fig.3) a “plateau” is reached for proposal number and job characteristics. It corresponds to a mean project allotment of 0.3 Mnodeh (mean size of 0.8 Mnodeh for a proposal).

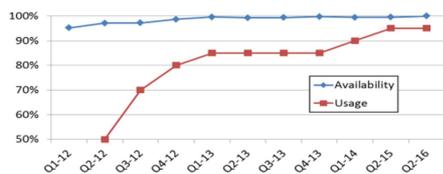


Fig.2: Usage and availability of Helios.

Helios Supercomputer	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
Compute period from-to	Apr 2012 Oct 2012	Nov 2012 Oct 2013	Nov 2013 Oct 2014	Nov 2014 Oct 2015	Nov 2015 Dec 2016
Number of received proposals	62	82	122	126	121
Total proposal asking (Mnodeh)	65,8	70,6	102,7	107,0	96,9
Average asking (Mnodeh)	1,1	0,9	0,8	0,8	0,8
Overasking vs resource	1,8	2,0	2,9	3,0	2,3

Fig.3 : Cycle characteristics.

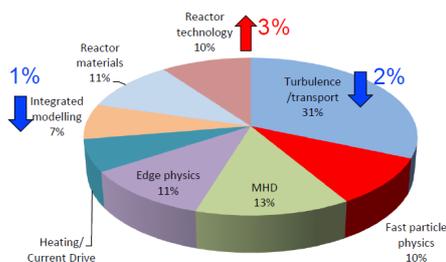


Fig.4: Partition of proposals per category (5th cycle) and trend from previous cycle.

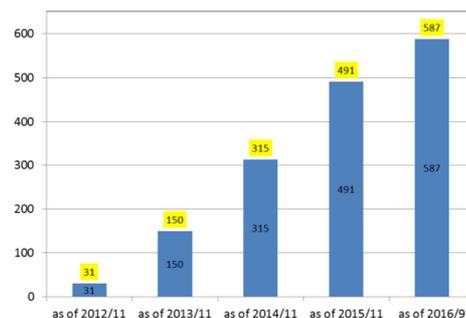


Fig.5: Number of peer reviewed papers issued.

The oversubscription, still very high, is slightly lower for the 5th cycle mostly due to the larger amount of computer time available for this cycle. The repartition of the computing resource (fig.4) is still largely dominated by plasma turbulence computation, which has been historically the most compute-hungry discipline. However, reactor technology is getting a larger share of resource with an increase of 3% between the 4th and the 5th cycle. Along with computation volume, another scientific relevant criterion is the number of peer reviewed papers issued. As shown (fig.5), in each yearly cycle around 150 papers are issued by the European and Japanese researchers. As of September 2016 with the 5th cycle not finished, 587 peer reviewed papers have been issued since the beginning of Helios.

I-d) End of operation of the CSC

Helios will be shut down in the end of December 2016 after providing during 5 years a world-class computing resource to the European and Japanese fusion community, fully in accordance with the objective of the CSC. A final report summarizing the lessons learnt in terms of highly successful joint implementation of a large scale computing centre and the outstanding contribution of Helios to advancement of fusion studies will be produced in early 2017. After the closing of the CSC, the European and Japanese fusion users will carry on their research on different systems, Marconi-Fusion in CINECA for the European side (EUROfusion), before, hopefully, a future new joint supercomputer is decided based on the excellent experience of the CSC.

II) Status of the CEA contribution to IFMIF-EVEDA

II-a) Scope of CEA contributions

In the frame of the IFMIF-EVEDA project, CEA is strongly committed in both the design and validation activities of the IFMIF accelerator facility, sharing the work with the Implementing Agencies (Fusion for Energy, Quantum and radiological Science and Technology agency) and contributing European Institutes (CIEMAT, INFN and SCK•CEN). Other challenging facilities of the high flux 14-MeV-neutron source IFMIF, the lithium target and the test cells, were studied and validated by other contributors within the same EVEDA phase, and the design activities were completed in 2014 with the delivery of the engineering design report [3]. The IFMIF accelerator facility comprises 2 identical linacs, each accelerating a cw 125-mA deuteron beam at the final energy of 40 MeV. A total beam power of 2x5MW is required to produce the high flux of neutrons $\sim 10^{17}$ n/s through break-up interactions of the D⁺ beam with the Li target. CEA was involved in the design study of several sub-systems of the IFMIF accelerator facility (Injector, 40 MeV SRF Linac, HEBT, beam diagnostics), and participated in beam dynamics studies and cost assessment.

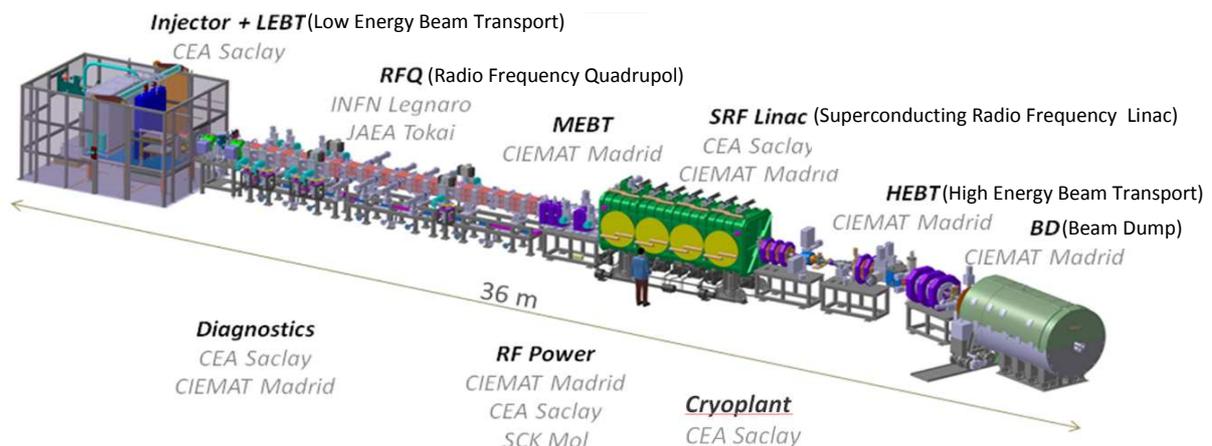


Fig.6: General layout of the Linear IFMIF/EVEDA prototype accelerator (LIPAc).

As the IFMIF accelerator shall reach unprecedented performances, a prototype of its low-energy part (fig.6) is being developed, for which CEA developed and fabricated several sub-systems: deuteron

injector consisting of the ECR source and the Low Energy Beam Transport Line, LEBT, most of the components of the SRF-Linac including superconducting accelerating cavities, RF couplers, frequency tuners as well as cryogenic circuits, magnetic shielding and instrumentation; wide range of beam diagnostics as profile monitors (IPM, SEM-grid), current monitors (ACCT, DCCT) and Beam Loss monitors. Besides these prototype accelerator components, CEA delivered the cryoplant, RF power amplifiers and other standard equipment. CEA is also involved in the beam dynamics studies as well as installation and commissioning with beam of accelerator sub-systems at Rokkasho site.

II-b) On-going activities

The remaining activities of the teams involved are mainly dedicated to the fabrication of the components of the 5 MeV–9 MeV section of the accelerator, their installation at Rokkasho and the commissioning which will be conducted by successive phases, each involving more accelerator components before the overall ramp up to final beam power. The objective is to demonstrate the capability of this 9 MeV D+ full scale prototype accelerator and to devise methods for mastering high current beams at low energy where the space-charge phenomena may lead to beam characteristics degradation and therefore to beam losses. Commissioning phase has been extended by 30 months, with a completion expected by end 2019.

II-c) Status of the SRF-Linac

The SRF-Linac is a full-scale and operational cryomodule for accelerating D+ beams from 5 to 9 MeV. The cryomodule [4] is a horizontal vacuum tank of ~6 m long which includes: 8 accelerating superconducting half wave resonators (HWRs), working in cw at 175 MHz and at 4.45 K, 8 Power Couplers providing 70 kW to the cavities, and 8 Solenoid Packages, developed by CIEMAT, focusing the beam. Once the performances with beam will be experimentally demonstrated at Rokkasho, the cryomodule design will be used as a reference for the IFMIF SRF-Linac.

During these last two years, most of activities were dedicated to the manufacturing of series components [5]. Pre-series HWR cavity has been delivered and prepared according to the process for superconducting RF cavities (chemical etching, high pressure ultra-pure water rinsing in clean room (fig.7), assembly of ancillaries in clean room). Though first tests at cryogenic temperature of 4.4 K were limited due to vacuum leaks, the quality factor Q_0 at low field was measured at $1.3e9$, accelerating field E_{acc} of 8 MV/m was reached, and no field emission has been observed ensuring of the good quality of the cavity preparation. The cavity is back to the manufacturer for undergoing a heat treatment



Fig.7: pre-series cavity preparation: chemical etching (left) and high pressure rinsing (right).

preventing from performance degradation due to slow cool-down before being welded to the helium tank. New tests in vertical and dedicated horizontal cryostat will then be performed. In parallel, the fabrication of the series cavities is progressing, notwithstanding some issues during the qualification of Nb / NbTi welding and full penetration welds. It is worth noticing that the mandatory application form of the cavities has been formally approved by the Japanese certification agency KHK on March 2016. Manufacturing of the power couplers has been delayed due to the poor quality of copper plating of some RF conductors and leaks on bellows connecting the couplers to the cryomodule. Remedies are under investigation and all couplers should be delivered by end of 2016.

The manufacturing of the other components of the cryomodule is in progress too. Most of factory acceptance tests and delivery of components are planned within this year, and early 2017 for the support frame, magnetic shield, cryopiping and phase separator. The Sathori test bench dedicated to

characterization of a jacketed and fully dressed cavity with coupler and tuning system is ready for use (fig.8). In such a test bench, the elementary components of the SRF-Linac will be characterized in depth, in an environment equivalent to the nominal operation, i.e. nominal RF power source, working point around 4.4 K, and HWR, coupler and tuner tested in the same position as in the cryomodule. The RF, thermal and mechanical behavior of a cavity with its coupler and tuning system will be assessed at least 15 months before the first RF test of the fully assembled cryomodule, allowing correction in case of problems. Due to risk related to overseas transport, the assembly of the cryomodule will be performed in a dedicated infrastructure to be built by QST in the DEMO Joint Research Building at Rokkasho. CEA prepared the sequences of assembly for Fusion of Energy in charge of the assembly.



Fig.8: Sathori cryostat connected to cryogenic lines through Cryholab at CEA/Saclay.

II-d) Status of the cryoplant

The cryoplant dedicated to the cooling of the superconducting resonators and solenoids of the cryomodule is being manufactured by Air Liquide Advanced Technologies (AL-AT) under a contract placed by CEA. The cryoplant falls under the Japanese Refrigeration Ordinance according to High Pressure Gas Safety Law, and it has been agreed that ASME is considered as reference for design, manufacturing and inspection. Some specific requirements were added for the reservoirs. Factory acceptance tests of the cold box, compressor unit, and oil removal system were passed in January 2016, and these components were delivered at Rokkasho site on April 2016. Installation is on-going and will last until the end of 2016. The first tests of the cryoplant are scheduled for February 2017.

II-e) CEA participation to Installation and Commissioning Activities

Commissioning of the injector started in November 2014 with proton beams which are appropriate for preliminary tests. In the last two years, the injector has been operated with both H⁺ and D⁺ beams and characterized in depth [5, 6, 7, 8]. In December 2015, a D⁺ beam of 112 mA (a world record!) has been transported with a normalized RMS emittance of 0.23 π .mm.mrad both measured at the Beam Stop (BS) at the very end of the LEBT. Fine tunings of the injector parameters were performed at 20% duty cycle, and measured fraction ratio of D⁺ was very high providing evidence of the good optimization of the injector design for deuteron beams. The emittance measured at the BS for current around 110 mA is still under control at 50% duty cycle (see Table 1), but emittance growth was noticed at higher currents due to space charge. The commissioning is going on at high duty cycles, the goal being to reach 100% while controlling the emittance. The beam monitors developed by CEA [9] are on Rokkasho site. Some were partially integrated on beam transfer lines at CIEMAT premises before shipment to Japan in order to carefully check the interfaces and assembly sequences. Installation at Rokkasho is now in progress and mechanical, electrical, vacuum checks are scheduled for fall 2016 with the goal to start the 5MeV commissioning phase of the LIPAc in early 2017. The last 9 MeV commissioning phase should start in 2018 with the objective to qualify the accelerator components, to tune the accelerator in cw operation up to 1 MW of beam power, as well as to operate this prototype accelerator for long runs at the highest performances.

Duty cycle [%]	20	50
Extracted current [mA]	150	158
BS current [mA]	112	108
Norm. ϵ [π mm.mrad]	0.23	0.31
D ⁺ / D ₂ ⁺ / D ₃ ⁺ ratio [%]	92/5/ 3	not measured

Table 1: optimized beam parameters at different duty cycles.

III) Status of the CEA contribution to JT-60SA

III-a) Status of manufacturing and activities

For the CEA contribution to JT-60SA, and after solving the last technical issues, 2015, was the year of completion of the industrial processes engaged by the CEA with its industrial sub-contractors that led to the delivery of the first components.

At Belfort, in the Alstom/GE premises, five, over 10, Toroidal Field, TF, coils [10, 11] were completed and delivered to CEA-Saclay for cryogenic testing. The TF coils have a D shape geometry with height, width and weight of 7.5m, 4.5m and 19.7t respectively (fig.9). When cooled at 4.5K, they can carry a current of 25.7kA under a maximum magnetic field of 5.65T. Now, the five remaining coils are all engaged at different manufacturing steps along the manufacturing line and the two firsts were already delivered to Naka after having been cold tested and assembled with their Outer Inter Coil Structures (OIS) at CEA/Saclay.

At Saint-Romans, in the SDMS premises, the first four, over 18, OIS, were completed and delivered to the pre-assembly facility at CEA/Saclay to be assembled with the related TF coil before shipment to Japan (fig.9). The manufacturing of the 14 remaining OIS is on-going according to the schedule. When assembled, with insulated bolted plates, the 18 OIS form an outer structure, encircling the TF magnet. This structure shall withstand the electromagnetic loads during plasma operations.

At Tarbes, in the Alsylom premises, the manufacturing of the 18 Gravity Supports (GS), were completed (fig.10) and shipped to Naka. The GS are articulated structures, using 3 spherical bearings each, aiming at sustaining the weight of the whole magnet system, seismic events, plasma disruptions as well as the thermal gradient between the TF coil at 4.5K and the cryostat base at ~240K.

At Lasarte-Oria, in the JEMA premises, the five superconducting magnet power supplies, one for the TF coils and four for four Equilibrium Field, EF, Coils were manufactured and successfully passed the set of full power factory acceptance tests (fig.11). The installation at Naka was completed by mid-september 2016. The final on site acceptance tests are scheduled for the first half of 2017.



Fig.9: the 1st validated TF coil during assembly with its OIS at CEA/Saclay.

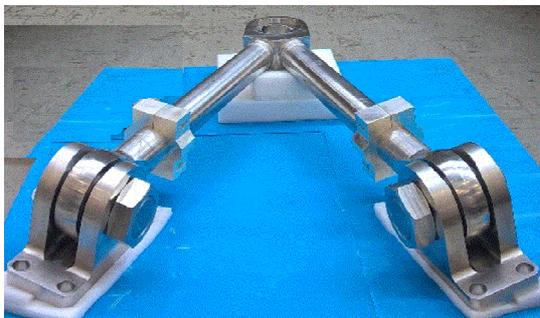


Fig.10: One of the 18 Gravity Supports.



Fig.11: The EF power supplies during installation at Naka. (EF4 & EF5 in front of the picture EF2 & EF3 on the back)

At Saclay, in 2015, the Cold Test Facility was completed (fig.12) and fully commissioned [12]. The nominal performances in terms of current intensity, cryogenic power, cooling and warming speeds as well as in terms of operation safety were demonstrated. From February to September 2016, the tests of the six first coils, over 20, were successfully completed. In particular nominal current (25,7kA) and nominal current sharing temperature ($T_{CS} \sim 7.5K$) [13] were recorded, demonstrating the quality of the TF coils design and manufacturing [14,15].

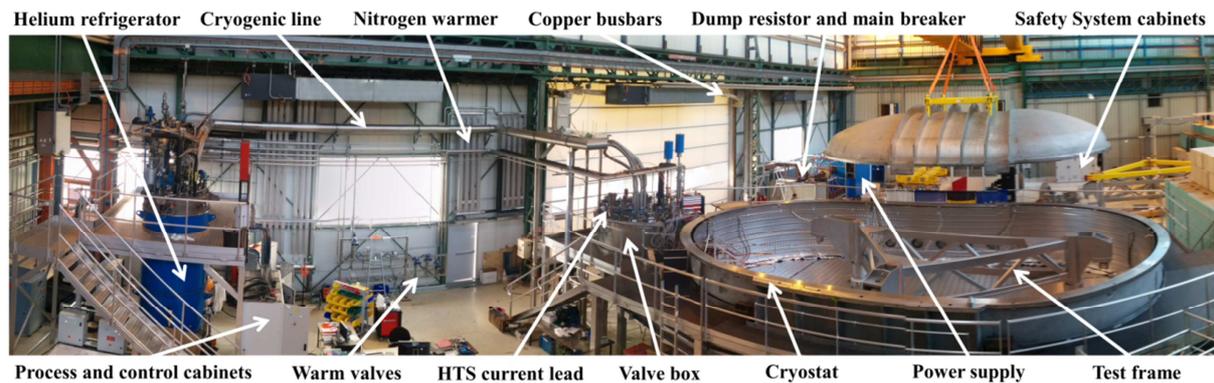


Fig.12: view of the cold test facility

At Naka, in 2015, the Cryogenic System for JT-60SA, manufactured at Sassenage, in the Air Liquide Advanced Technologies, ALAT, premises, was installed (fig.13) and pre-commissioned [16]. Beginning of 2016, the commissioning activities have started. The final acceptance tests were completed in September 2016 demonstrating a full compliance of the plant with the specifications (9.5kW equivalent at 4.5K). The cryogenic system is aiming at providing the refrigeration powers required at the various temperatures 80K, 50K, 4.4K and 3.7K for thermal shields, HTS current leads, superconducting magnets and cryogenic pumps respectively, according to the different operation modes of JT-60SA.



Fig.13: Composite view of the cryogenic system installed at Naka (ORS: Oil Removal System)

III-b) First feedback elements

From a management point of view, the main lessons learnt are that the effective quality management system set up for the control of the industrial productions has helped to reach without significant deviation the specified performances of the components. This quality management system has included quality assurance procedures, tight requirements and documentation follow-up, interfaces monitoring, mock-up development for critical industrial processes, extensive testing and manufacturing control.

On the technical level, for TF coils and associated GS and OIS structures, welding procedures and controls have let open some issues to be solved at the manufacturing level. Meet the requirement of the ASME BPVC, in particular at cryogenic temperature (4K), and perform a robust inspection of the stainless steel welds, was a challenge. This was especially true for the GS for which the difficulty to find a filler metal not brittle at cryogenic temperature and the late analysis of alternative procedures have prevented the use of Electron Beam, EB, welding for upper welds, which would have greatly simplified the welds preparation, welding and control. This has imposed to the manufacturer the development of dedicated procedures and qualifications and of very sophisticated UltraSonic, US, control able to 100% guarantee the stainless steel welds quality. Fortunately the manufacturing of the

GS was far from the critical path. As a lesson learnt, extensive use of EB welding, as finally proposed by the OIS manufacturer has to be favored when possible for such components. For TIG/MAG welding, the development of semi-automatic procedures assisted by welding robots, as developed for the TF cover welding, is also interesting for saving time and ensuring zero defect. On the five TF coils already produced by GE and 100% controlled by US no defect was recorded on the cover welds. However the shrinkage associated to TIG/MAG welds needs also to be more anticipated as partially done for the TF covers welds [11]. The stress relief qualification of such heavily welded components was found as an open question that would require more fundamental developments.

For the Cold Test Facility, the great robustness of the design based on the W7X feedback as well as the great versatility of the control system allowed during the commissioning to reach the specified performances. The reliability of the magnet safety system allowed a safe operation of the TF coil and a safe management of the quench tests and fast discharges.

The pre-assembly activities as well as the TF cold testing implying a lot of handling activities of the TF coils OIS structures are critical activities conducted by well trained and experienced team. The safety for the goods and the personal was a concern shared by the CEA teams and managed according to CEA rules. For pre-assembly the handling procedures were first validated using a TF mock up.

For the Cryogenic System, the tendering procedure chosen (competitive dialog) while time consuming (~1 year) was very efficient for selecting the most reliable technical offer built jointly by CEA and each bidder. For installation of this very large cryogenic unit, interfaces management between components and buildings managed by QST was critical and the system of interface sheets setup by CEA with ALAT and QST was very useful to limit the issues. A close collaboration between stakeholders was the key of the success for this procurement. European teams worked in Japan for 20 months (6 for installation and 14 for commissioning) out of the 48 months of contract, with only 2 months slippage. The compliance of the acceptance tests was undoubtedly linked to the operation performance assessed at CEA Grenoble on the HELIOS test facility [17], which has allowed the development of a robust scheme for the pulsed heat load management, one of the most challenging feature ever tested and validated on a cryogenic system. Dynamic modelling of the system by CEA [18] was also a development which could support the industrials during design stage and commissioning of cryogenic systems for future fusion devices in order to limit risk on critical components and to save time during commissioning.

For Power Supplies, the set of full power factory tests performed allowed to verify the compliance of the products with the specifications and to limit or anticipate the corrective actions to be conducted in Japan. Some discrepancies, such as overheating of power components (DC interface reactors and thyristors fuses) or control accuracy underperformances were identified well before the installation phase. Some of them were easily solved before shipment to Japan or during the installation at Naka. Some fine tuning of the control systems remain to be done during the final on site acceptance tests.

Summary

The CEA contribution to the Broader Approach project is now nearing completion. This program allowed the CEA teams and their industrial partners to make significant progress in the production and management of such components associating high technologies and large scales. At IFERC, the Helios computer has perfectly fulfilled its mission both in technical terms and by being a means for federating research activities between Europe and Japan. At IFMIF the main components are either now installed at Rokkasho or near to be delivered. Runs at 5MeV are scheduled early 2017 and at 9 MeV during 2018. For JT-60SA, the completion of the cryogenic system will be achieved mid of October 2016. The TF coils testing and assembly deliveries are progressing according to the schedule. The end of the installation of the power supplies is expected to mid-September 2016 and the final acceptance test scheduled by mid-2017. Most of the final performance measurements are expected to be available beginning of 2017, opening the time for developing a full feedback analysis.

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