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Cooperative effort between Consorcio European Spallation Source – Bilbao and Oak Ridge National Laboratory Spallation Neutron Source for manufacturing and testing of the JEMA-designed modulator system

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Research Accelerator Division
Neutron Sciences Directorate

CRADA Final Report

COOPERATIVE EFFORT BETWEEN CONSORCIO EUROPEAN SPALLATION SOURCE – BILBAO AND OAK RIDGE NATIONAL LABORATORY SPALLATION NEUTRON SOURCE FOR MANUFACTURING AND TESTING OF THE JEMA-DESIGNED MODULATOR SYSTEM

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I. Abstract

The JEMA modulator was originally developed for the European Spallation Source (ESS) when Spain was under consideration as a location for the ESS facility. Discussions ensued and the Spallation Neutron Source Research Accelerator Division agreed to form a collaboration with ESS-Bilbao (ESS-B) consortium to provide services for specifying the requirements for a version of the modulator capable of operating twelve 550 kW klystrons, monitoring the technical progress on the contract with JEMA, installing and commissioning the modulator at SNS, and performing a 30 day full power test. This work was recently completed, and this report discusses those activities with primary emphasis on the installation and testing activities.

II. Objectives

a. Pre-CRADA Activities
   i. Specify the system requirements necessary to support operation of twelve 700 kW 805 MHz klystrons in parallel. This operating level was chosen to support the proposed Power Upgrade Project under consideration at the time the collaboration was established. A statement of work and specification was drafted for the modulator and approved by both parties of the collaboration[1].
   ii. Conduct a final design review of the JEMA modulator system at Oak Ridge National Laboratory utilizing external and internal experts. This review was held on June 2, 2010. The reviewers included David E. Anderson, Craig Burkhart (SLAC), Vladimir Peplov, Ken Rust, Robert Saethre and Dennis Solley. An internal report was generated and disseminated to JEMA, ESS-Bilbao consortium and review committee members[2].
   iii. Participate in factory acceptance testing at JEMA in San Sebastián, Spain, to verify all requirements were met. Factory acceptance testing was performed during November/December 2011 in Spain on a similar modulator[3]. Factory acceptance testing of the SNS-designed modulator was performed later but the unit was not ready for testing at the time of the visit.

b. CRADA Activities
   i. Install infrastructure in Building 8320 to support full average power testing of the JEMA modulator, including
      1. Electrical utility feeds
      2. Deionized water connections for system cooling up to 40 gallons per minute
      3. Controls and signal cables to interface the modulator to the klystron load(s), timing system and the SNS Test Network
      4. Concrete pad and switch gear for exterior utility feed
   ii. Provide a suitable klystron or beam stick load for the modulator. Note: Installation of the originally proposed beam stick load would have caused delays

[1] SNS Document Number 104010200-SW0007, "SNS High Voltage Pulsed Power Supply Statement of Work (SOW) and Specification", July 2009.
[2] "Summary of Comments and Recommendations from JEMA Review held at ORNL Spallation Neutron Source on June 2, 2010", June 2010.
[3] JEMA Document Number 20802, "Test Report for Factory Tests on the Long Pulse Klystron Modulator", March 2012.

to other SNS programs and exceeded projected costs so a mutual decision was reached with ESS-B to utilize a 5.0 MW klystron operating at expanded pulse widths to dissipate sufficient average power to fully test the modulator.

iii. Provide controls interface support for remote display and operation of the modulator and associated subsystems.

iv. Using assistance from JEMA, install the modulator and connect all the interfaces.

v. Procure any additional safety equipment such that the JEMA modulator would comply with OSHA, DoE, NFPA-70E and ORNL safety requirements and standards. This required

  1. Modification of the internal hardware to provide locations for measuring voltages for LOTO purposes,
  2. Adding provisions for shorting and safeing capacitor systems and
  3. Adding a CO2 fire suppression system sufficient to extinguish any fires that may result from modulator operation.

vi. Using assistance from JEMA, conduct initial turn-on testing and commissioning of the modulator.

vii. Perform a 30 day test at full average power or a mutually agreed upon average power level. For the purposes of this test an operating level of 90 kV, 38 A, 3.5 ms pulse and 60 Hz was selected. This results in approximately 720 kW of average power.

viii. Generate a report of the testing results – this CRADA report fulfills that requirement.

ix. Either return the modulator at the end of the test period or extend the terms of the loan to extend the testing activities. Deadlines associated with the importation terms require the unit to be shipped back to Spain on or before February 6, 2017.

III. Government furnished equipment and/or infrastructure

  a. Exterior transformer pad for ABB transformer unit
  b. Switchgear to control 13.8 kV power to transformer
  c. 805 MHz, 5.0 MW klystron to serve as a high average power load
  d. Deionized water system to cool modulator electronics
  e. Cabling infrastructure for power, controls, timing, external interlocks, etc.
  f. CO2 fire suppression system

IV. ORNL Expenditures by fiscal year, including materials, subcontract, labor, other direct costs and overhead. Engineering and technician effort to support installation, design, commissioning, testing, operation and maintenance not included.

FY2012: $69k
FY2013: $205k
FY2014: $76k
FY2015: $217k
FY2016: $18k
TOTAL: $585k

V. Benefits to DOE Office of Science-Basic Energy Sciences

The Department of Energy's (DOE) Office of Science (SC) - Basic Energy Sciences (BES) supports basic research in accelerator physics and x-ray and neutron detectors. Accelerator research is the corner stone for the development of new technologies that will improve the performance of light sources and neutron spallation facilities. This research explores new areas of science and technology that will facilitate the construction of next generation accelerator-based user facilities. This research interacts with BES scientific research that employs particle accelerators as the drivers for light sources and spallation neutron sources. This research interacts with BES scientific research that employs synchrotron and neutron sources.

Modulator technology is a critical component of accelerator construction and operation. Modulator systems represent a significant cost associated with accelerator construction. Modulators can also account for a significant amount of downtime during operation of the accelerator and must operate with maximum reliability. Testing the subject modulator will demonstrate system reliability and identify key components and/or subsystems which cause downtime, a useful parameter to quantify for this modulator and modern solid-state based modulators in general.

UT-Battelle, as the management and operating contract for DOE's Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL), and the European Spallation Source-Bilbao Consortium (ESS-B) have a common interest in the development of various technologies which support the design and construction of next generation pulsed neutron sources. UT-Battelle and ESS-B understand that the sharing of related development tasks allows the most efficient use of resources.

VI. Technical Discussion

Executive Summary

The JEMA modulator was tested at ORNL into a single 5.0 MW klystron for 30 days. To achieve average power levels that were representative of the design parameters, the modulator was operated with 3.5 – 4.0 ms pulses at 60 Hz (duty cycle 0.24) at an output voltage of 90 kV. Significant time was spent by ORNL personnel installing the necessary infrastructure to support the test and modifying the modulator to be consistent with DOE-HDBK-1092-2013 requirements. During operation, several technical issues were uncovered, primarily in the HV Modules, Inverter and Controls section of the modulator. Utilizing assistance from JEMA engineers, these issues were resolved. Resolution took considerable time, but near the end of the testing program the modulator was operating reliably. If this modulator is intended to be used elsewhere, some additional improvements can be made that should further improve the reliability.

Elaboration

The modulator arrived at ORNL in early 2014. Installation of the infrastructure took place in 2 phases. The first phase provided infrastructure associated with the 1500 kVA ABB 13.8 kV:407 V transformer. Since no suitable switchgear existed, it was also necessary to procure a metal-enclosed switchgear from industry. Additionally, cablebus to route power into building 8320 and ultimately to the modulator was required. Finally, services of a subcontractor had to be secured to perform the installation.[4]

The second phase consisted of internal interface wiring for power, load connection, controls, timing and interlocks and deionized cooling water. To permit future expansion and permit operation of the JEMA modulator with other loads, the scope was expanded to build this possibility into the design change request. Based on a history of smoke-generating events in other SNS High Voltage Converter Modulator systems and the large volume of capacitors and plastics in the JEMA modulator, a decision was made to install a CO2 fire suppression system in the JEMA modulator. A Design Change Notice[5] was created to specify the scope of work, and services of a subcontractor were secured. This work was completed near the end of fiscal year 2015.

The JEMA engineering team arrived in October 2015 to begin the initial conditioning of the modulator. Due to the unavailability of the originally planned beam stick load, equivalent to 12 CPI 700 kW klystrons, and the cost associated with installing that load, a decision was made to utilize a single 805 MHz, 5 MW Thales klystron as a load for the modulator. Initial commissioning and integration focused heavily on interfacing all the external interlocks for the modulator, interfacing the JEMA modulator controls to the SNS EPICS-based control system for remote operation to support the proposed 30-day test and testing various subsystems and components. Problems were discovered due to noise on diagnostic signals, failure of HV Module power supply transformers and others but commissioning proceeded. After optimizing the feed-forward control algorithm and resolving the issues, the modulator was delivering pulses to the klystron load by the end of November. At that time the JEMA team departed and proposed to modify the HV Module power supplies prior to beginning the 30-day test.

Repaired HV Module power supplies were delivered to ORNL in the first quarter of calendar year 2016. A subset of the JEMA engineering team returned to ORNL on April 25, 2016 to support interfacing the controls to the CO2 system and installing the new HV Module power supplies. This was successfully accomplished during their visit.

Training of operators and the ORNL Fire Protection staff was completed on May 4, 2016. All necessary Operations Procedure Manual materials were also completed at that time, including emergency response procedures and equipment return to service forms.

[4] SNS RAD Design Change Notice DCN-RAD-8320-012, JEMA Transformer and ESS-B Modulator Installation in SRF Building 8320.

[5] SNS RAD Design Change Notice DCN-RAD-8320-024, SRF Storage (Bldg 8320) JEMA Installation, July 2015.

Initial operation of the modulator began on May 5, 2016. In order to maximize the average power delivered by the unit the pulse width was initially stretched to 4.0 ms, corresponding to approximately 800 kW of average power at a pulse repetition rate of 60 Hz. The unit ran for several hours before tripping off on a HV Module 12 fault. After consulting with JEMA, the fault was determined to be a HV Module power supply problem. Rather than open the unit up for troubleshooting we decided to bypass the module and continue running.

The following week we began the 24 hours per day, 7 days per week test of 30 days. After several hours the unit tripped on a HV Module fault on Module 1, this time due to an over temperature. Our initial attempt to resolve the issue was to reduce the pulse width (and hence average power) to 3.5 ms. The module continued to trip on the temperature fault.

We also experienced a power supply problem on HV Module 2. Based on guidance from JEMA we were able to troubleshoot this further and verify that the problem was with the power supplies. Since we did not have adequate modified power supply spares on hand we decided to use the original units. We were eventually able to find enough power supplies to replace all the units that were faulty.

The faulty units were returned to JEMA for further troubleshooting. 3 were found to operate correctly in the JEMA test circuit. The fourth had a short circuit at the input stage IGBT. JEMA suspects that a fixed low modulation rate in the “Inverter On” stage (where these is minimal loading of the power supplies) may be insufficient for starting all the supply cards.

Additionally, we experienced problems during the heat of the day on the RTD sensors installed in the outside transformer windings. During initial commissioning in November 2015 we replaced one of these probes with a fixed 100 ohm resistor. This was done based on the belief that all windings were operating at essentially the same temperature, a conclusion supported by the ABB test reports which showed operation of all windings at <100 degrees C under full load conditions. Furthermore, difficulty in accessing the RTD probes in the transformer enclosure, the need to continue testing while the JEMA engineers were at the SNS and the low risk in proceeding with a fixed resistor installed supported the decision. After a 2nd RTD appeared to read erroneously, the decision was made to replace the faulty RTD probes. This took some time as we had to coordinate the LOTO of the feeder breaker with ORNL Utilities but was eventually completed with all RTDs reading properly.

After adding a 300 mm X 300 mm perforated opening to the enclosure at the base of HV Module 1 to improve cooling to that area and addressing the aforementioned issues we restarted our test on May 25, 2016. The unit ran without issue through approximately 2100 hours on May 31, 2016 for a total of 118 hours or approximately 5 days.

A rectifier fault caused the unit to trip off. Operators were able to clear the fault but were unable to turn the modulator back on. Based on the behavior we suspected a loss of communication with the unit via the EPICS interface. By cycling control power to the modulator we were able to resume operation of the unit at 0700 on June 1, 2016. At 0000 on June 3 the problem occurred again due to a klystron (load) fault. Rather than restore the unit to an operational condition we left it alone and discovered that once the fans ceased to operate (the fans run for several hours after the modulator is turned off to remove residual heat from the unit) control was restored. We did not resume testing pending resolution of the issue by JEMA engineers, especially after learning that ESS Bilbao’s similar modulator had experienced similar problems.

JEMA resolved the problem by permitting user control when the modulator is transitioning between STANDBY and OFF states (by not requiring the fans to be OFF to make the transition) and by reducing the time the fans run after going to STANDBY. JEMA sent the DSP software to make the upgrades to the modulator on June 8, 2016.

The remainder of the summer of 2016 was spent with short periods of operation (1-2 days) followed by faults, troubleshooting and repair. HV Modules experienced many of the problems. Initially, a problem was indicated when it became apparent that no power was present on the HV Module power supply card. After multiple attempts to replace the card and extensive troubleshooting of the signals on the HV Module, the problem was eventually isolated to a faulty IGBT Chopper module that had short-circuited. We were able to replace the Chopper module with a spare provided by JEMA.

The next problem occurred on the Inverter section feeding the HV Module 11. We attempted to install test points on the Inverter Module to check for the presence of gates to the individual IGBTs. While attempting to install these test points, a technician shorted out the gate to emitter on one of the IGBTs which damaged the commercial IGBT driver. Since we could not consult with JEMA due to Spanish holidays, a replacement Concept driver was ordered which took a few weeks to receive. After JEMA returned from holiday, they advised us that it was acceptable to use a spare Infineon driver they had provided. We installed the spare driver, which restored the controls signals (that initially prevented us from operating the unit).

After monitoring the Inverter Module for IGBT gate signals, it was found that some of the signals were missing. Rather than taking time to troubleshoot further, we decided to operate the modulator with this bypassed. The unit was turned on one morning and the following afternoon building occupants reported a strong smell of burning electronics. The unit was shut down when it became obvious that the odor originated from the modulator.

After performing LOTO on the modulator and undergoing an extensive inspection, several burned resistors were seen. We removed the HV module and discovered that the printed circuit board suffered extensive damage. We had one spare unit available but did not want to install it until discovering the root cause of the problem. After obtaining schematics from JEMA of the damaged PCB and further investigation, it was determined that a metal screw used to support brackets was positioned too close to a capacitor on the board resulting in arcing between the two locations and extensive collateral damage. The spare board was installed, insulation was installed between the screw and capacitor in all locations, and operation resumed on October 13.

The modulator was run at 2.5 ms, 60 Hz, through the weekend until October 17th. We then increased the pulse width to 3.5 ms. After almost exactly 1 week of operation, the modulator failed again. Attempts to resume operation resulted in an arcing sound from inside the modulator enclosure accompanied by a HV Module 2 fault. Operating with the panel removed in front on HV Module 2 indicated arcing on the HV Module Power Supply PCB transformer (an area where we had experienced problems previously) and arcing (one time) on HV Module 1 near the inductor. The troublesome PCB was replaced with a spare and operations resumed again on October 27, 2016.

Early on Monday, October 31, 2016, the modulator failed again due to a lack of communication between the host computer and the modulator. This appears to have been a Windows operating system issue. A full reboot of the host computer and re-initializing the IOC script solved the problem. Operation was restored at 1000 on the 31st.

Another loss of communication fault, this time between the host computer and EPICS, occurred on November 8, 2016. Exact time is unknown since the Control Room had no indication the modulator had gone to “Off”. We were able to regain operation by restarting CSS on the host computer but decided to terminate operation due to the communications vulnerability.

The modulator accumulated 17.5 days of operation during October / November 2016. 5 days of operation were accumulated during the long run of May 2016. Multiple 1-2 day periods of operation of the modulator during the summer of 2016 resulted in another 8 days of operation of the modulator.

Therefore, the combined duration of operation of the modulator was 30.5 days at 750-800 kW of average power, therefore achieving the goal of the testing program, although not into the correct impedance load for reasons discussed earlier. Unfortunately, technical issues with the modulator did not allow us sufficient time to complete a continuous 30 day test before the deadline to return the modulator to Spain.

VII. Subject Inventions

None. The design of the JEMA modulator is intellectual property possessed by JEMA.

VIII. Commercialization Possibilities

The JEMA modulator appears to be a viable solution to modulator applications globally. Some additional reliability testing, coupled with minor redesigns of components, printed circuit boards and subassemblies will be required to achieve reliability commensurate with operational neutron facilities but experience at SNS indicates this can be achieved. Modulators will always be a niche market, customized to the requirements of the facility, and hence the market is determined by specific projects as opposed to normal market drivers.

IX. Plans for Future Collaborations

None at this time. The equipment had to be returned to Spain to avoid payment of duties and tariffs. The future plans for the equipment are at the discretion of ESS-Bilbao and no additional discussions are occurring with ORNL. ORNL will reclaim the space occupied by the JEMA modulator, utilize the infrastructure provided to support testing, and install another modulator solution to support the Beam Test Facility in its location.

X. Conclusion

The equipment testing and associated CRADA was successful. All the objectives, with the exception of the choice of klystron load for the modulator, were demonstrated. The load substitution was agreed to by both parties. Additional work remains to make the JEMA modulator a viable, reliable modulator solution for powering klystrons, but there are no fundamental issues with the design. Had time permitted, an additional 30 day continuous test would have been desirable. Had funds been available to support keeping the modulator at ORNL long-term, some additional engineering effort could have been provided to resolve the remaining issues.