ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-THP106

AN SRF TEST STAND IN HIGH INTENSITY AND HIGH ENERGY PROTON BEAMS

G. Vandoni, K. Artoos, V. Baglin, K. Brodzinski, R. Calaga, O. Capatina, S. Claudet, L. P. Delprat, S. Mehanneche, E. Montesinos, C. Pasquino, J. S. Swieszek, CERN, 1211 Geneva 23, Switzerland

Abstract

In the framework of HL-LHC, a new infrastructure was installed in 2018, to test SRF structures in the proton beams of the SPS. Scope of the test stand is to study the operational performance of crab-cavities for HL-LHC - more generally, SRF cavities - through a wide range of proton beam parameters up to high energy and current, under safe conditions for equipment and personnel. The SPS beam instrumentation is used to monitor orbit centering, RF phase scans, bunch rotation. To minimize impact on beam time, infrastructure and services allow for full remote control. Critical aperture restrictions are overcome by placing the test structure and its ancillaries on a motorized table for lateral translation in- and out of beam. Two articulated Y- shaped vacuum chambers connect the test cryomodule on a beam by-pass. A new cryogenic refrigerator is installed in a split scheme, with an underground cold box fed from a surface compressor. The two Inductive Output Tubes (IOT) power amplifiers deliver up to 50kW cw via coaxial transmission lines to the two cavities and charges and circulators, the latter installed on the translation table. Interlocks and safety equipment complete the test stand.

INTRODUCTION

The High Luminosity LHC (HL-LHC) project [1] aims at increasing the integrated number of collisions the LHC provides to the experiments, to improve statistics on rare physics events. New inner triplet quadrupole magnets will focus beams into smaller transverse sizes at the interaction point – which results in larger beam sizes in the triplets themselves. To avoid parasitic collisions between the two beams in the two-beam vacuum chamber of the triplets, a crossing angle is introduced, which diminishes however luminosity by decreasing bunch overlap at the interaction point. To partially recover luminosity, crab-cavities are introduced on either side of the interaction point, providing a transverse momentum kick to the head and tail of each bunch [2]. The obtained bunch rotation brings bunches to collide head-on at the interaction point. A counter-kick is imparted after the interaction point, such that bunches recover their undisturbed orbit. Crab-cavities having never been applied previously on proton beams, the project required proton beam validation prior to launch series production. It was decided to validate and explore operational and technical performance in a dedicated test stand in the high energy and intensity SPS proton beams [3]. With up to 270 GeV and bunch intensity modulated from 10^9 to 10^{11}, the SPS provided the ideal range of parameters. Beam instrumentation of the machine was to be used to demonstrate the concept's validity.

In HL-LHC, two different types of cavities will be operated at the ATLAS and CMS interaction points. Two cavities of double-quarter wave type (DQW) for vertical crossing plane were assembled in a prototype cryomodule [4] operating at 2 K. Each cavity had been previously cold tested in a vertical facility, each exceeding the nominal operation voltage of 3.4 MV. The entire cryomodule had also been cooled down to 2 K and validated in the SM18 facility prior to installation in the test stand in the long straight section 6 (LSS6) and BA6 point of the SPS. See Fig. 1 for a 3D view of the test stand and Fig. 2 for the cryomodule at the end of installation.

THE TEST STAND

Integration

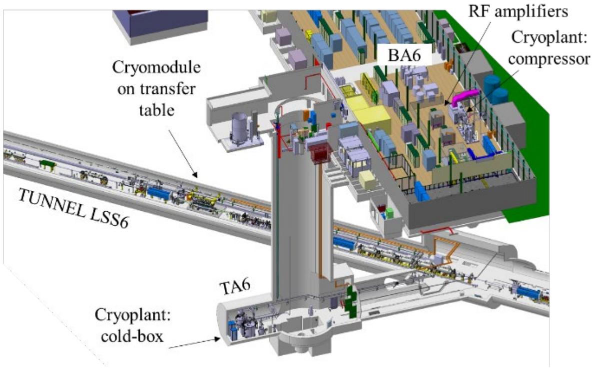

Figure 1: 3D integration view of the BA6 zone, with the main elements of the crab-cavity test stand.

The choice to install the crab-cavity test stand in SPS BA6 was determined by the need to integrate an important infrastructure, including cryogenics, RF passive equipment and a supporting lateral translation table. The SPS operates conventional magnets and accelerating cavities; the SRF proton beam test stand therefore required space to integrate an entirely new cryogenic refrigeration system. In LSS6, hosting extraction equipment to LHC (kickers and septa), an enlarged tunnel section with a 15 m long drift section was available. Nearby, at some 100 m, the large technical alcove TA6 at the lower extremity of the access pit was considered suitable for installation of the cryogenic cold box and distribution ancillaries. Low radiation, proximity to the access gallery, a large capacity freight-lift, the tunnel vault only encumbered by obsolete service infrastructures, completed the favourable scenario.

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-THP106

Figure 2: The completed SRF SPS test stand, seen from the direction of the beam. The transfer table is in experimental position; the articulated Y-shaped chamber and cryogenic Service Box with jumper to the DQW cryomodule prototype are clearly visible, while the RF passive equipment is hidden behind the cryomodule.

In the surface building BA6, on which the access pit to LSS6 opens, a large area was used for storage only, with space under the false floor encumbered by obsolete cables. In the short 2015-2016 end-of-the-year technical stop of the SPS, it was easy to free all those areas and remove old cables and pipework from tunnel and surface building, then laser scan the entire area for a complete 3D numerical reconstruction.

Transfer Table and Vacuum

The aperture of the LHC crab-cavities being smaller than required for beam extraction in SPS LSS6, it was decided to install the crab cryomodule and closest ancillaries on a transverse displacement table; the cryomodule can thus be set in the beam orbit or parked out-of-beam. The remotely operated, motorized transfer table designed and produced by Added Value Solutions (Spain) supports a load of 8 tonne for a total displaced mass of 15 tonne and allows for lateral displacement of 510 mm, in slow motion, controlled by stepper motor resolvers and LVDTs up to a 4 µm reproducibility. The table position switches provide doubly redundant interlocks to the SPS beam. Figure 2 shows the table in in-beam position.

A new vacuum sector was implemented in LSS6, delimited by two gate valves. The sector is constituted by two Y-shaped vacuum chambers, articulated by highly flexible bellows and supported from the transfer table. One leg of the Y-chambers features a large aperture beam pipe, for circulating and extracted beams. The second leg is connected to the crab-cavity cryomodule, itself constituting a cryogenic vacuum sector, delimited by two gate-valves. The gate valves status interlocks table movement, to mitigate the risk of cold beam vacuum rupture during the movement of the table. Vacuum is first rough-pumped by mobile turbo pumping groups, while high vacuum is obtained by ionic pumps. All vacuum chambers connected to the cryomodule sector are coated with amorphous carbon to limit secondary electron yield and thus mitigate vacuum pressure from electron cloud.

Cryogenics and Radio-Frequency

The specification for the cryogenic system was to provide 48 W at 2 K refrigeration capacity, to fully cover the estimated static and dynamic losses of the crab-cavities with 50% contingency. New cryogenic infrastructure connects a mobile refrigeration unit to a fixed buffering, liquid and gas storage and cryogenic distribution system. The split-scheme, mobile refrigeration unit is constituted by a warm helium compressor with sonic insulation cover and oil removal unit, installed in the surface building BA6, connected via two high- and low-pressure helium lines to a cold-box installed in the technical alcove at the lower extremity of the access pit. Cold-box refrigerator capacity is boosted to up to 7 g/s liquefaction by a liquid nitrogen heat exchanger, supplied from a liquid nitrogen surface tank via a 60 m long flexible cryogenic transfer line and a phase-separator. Liquid and gaseous helium is fed to the cryogenic circuits of the cryomodule via a large jumper from a local Service Box (SB), installed on the transfer table to limit cryogenic losses.

The cold-box supplies liquid and gaseous helium via a valve-box to an 80 m long cryogenic distribution line covering the distance from the technical alcove to the test stand. A second valve-box provides regulation and connection to the Service box, via two large flexible transfer lines with a lateral stroke of 0.5 m. Two large pumping units, located in the tunnel and acting on the Service-box circuits via a warm water heat exchanger, provide 3.5 g/s refrigeration at 2 K / 30 mbar.

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-THP106

The layout and integration allow for removal of the main equipment of the refrigeration system, i.e. cold-box and compressor with oil removal skid, while the connecting pipework, distribution and storage infrastructure remain in place.

RF Power to the two crab-cavities is provided by two Inductive Output Tube (IOT) 50 kW amplifiers, located in the surface building BA6. High power transmission lines with low RF losses transfer power to the underground. Two passive RF loads and circulators are installed on the transfer table, connected to the cavity power couplers on the cryomodule via rectangular waveguides outfitted with bellows. The connection between the transmission lines and the table RF equipment is done via two V-shaped transmission lines with rotating joints, opening and closing the V to follow the table's movement.

Low-level RF electronics are installed at the surface building, in a dedicated Faraday-cage, to shield it from the nearby IOTs. The cage shielding provides an attenuation of 80 dB minimum at 400 MHz and 1 GHz. Cavity control with long loop delay time exceeding 2 µs between the LLRF and the cavities was successfully achieved thanks to this configuration. In addition to electro-magnetic insulation, the Faraday cage provides sonic insulation larger than 18 dB in the frequency range 50 Hz to 4 kHz, to protect operators from the noisy neighbourhood of the cryogenic compressor. Controlled ventilation provides temperature stability to the LLRF electronics.

Other Infrastructure

New electrical distribution was required to cover the needs of the crab-cavity test stand. A new 2 MVA 18 kV /0.4 kV electrical transformer supplies 1100 kVA to two 400 V switchboards connected to all new client equipment. In addition to this, a new UPS ensures 17 kW emergency power, mainly dedicated to PLCs and controls.

The new test stand makes extensive use of the SPS general infrastructure and services. Raw and demineralized water are used for the cryogenic and RF power equipment cooling. The extended compressed air circuit is used to pilot pneumatic valves for vacuum and cryo. All safety equipment is connected to the existing secured electrical network.

Safety

The new cryogenic and RF test stand has introduced additional safety hazards in the LSS6 region of SPS. Electrons accelerated in the cavities generate X-rays by *bremsstrahlung*. Since the SPS tunnel is not partitioned by sectorization doors, it was decided to interlock the RF power generators with the access system to the entire machine, thus creating a new "Element Important for Safety" (EIS) in the SPS. EIS are equipment bound to specific layouts, procedures and documentation in the safety scheme. This safety feature bounds powering of the cavities to no access to the ensemble of the SPS tunnel. The important cryogenic liquid inventory in the tunnel (300 l helium) and technical alcove (150 l helium and 30 l nitrogen), combined with the risk of spilling the entire contents of the liquid nitrogen surface tank in the underground alcove, have demanded the installation of an extended network of oxygen deficiency hazard detectors, linked to the emergency beacons network and tunnel evacuation control. At the upper extremity of the vertical liquid nitrogen line, a safety orifice limits flow, in case of accidental rupture of the low extremity of the line and circuit. Further mitigation of cryogenic incidents was introduced by the already cited table movement interlock with vacuum valve closure. Strict testing procedures, specific training, access restrictions in particular during cryogenic transients, complete the safety scenario.

INSTALLATION & COMMISSIONING

Site preparation and installation were fractioned by the beam operation calendar of the SPS. During the 14 weeks extended year-end technical stop in winter 2016-2017, the beam vacuum layout was modified to introduce the new vacuum sector, with modification of all nearby vacuum chambers and installation of new carbon coated pipes. The two large helium pumping units were installed while the beam line was partially dismantled and a large portion of the tunnel floor was consolidated with a suitable resin to accommodate the transfer table basis. With a long scaffold covering all section of the SPS machine from the location of the test-stand to the tunnel extremity of the TA6 gallery, the cryogenic transfer line was installed in 6 m long segments, welded in situ then hoisted up to the tunnel vault. Figure 3 shows the cryogenic distribution line at the crossing between the tunnel (right) and the TA6 access gallery (left), during installation.

Figure 3: The cryogenic distribution line during installation in winter 2016-2017.

Two over-head rails, with a load capacity of 4 tonne each, were fixed at the tunnel vault above the location of the test stand, while a third rail of similar capacity was mounted in the TA6 alcove to prepare installation of the cold-box. The two low impedance coaxial transmission lines for RF power were pulled from the surface building through the access shaft PA6 to the test stand location. Pipework for high- and low- pressure helium was fixed and welded in situ all along the shaft. Most of the signal and control cables were also pulled during the same technical stop.

Time was allocated during the 2017 beam run of the SPS, to terminate the preparation and installation in the surface building: supporting structures and slabs were prepared for the new transformer, IOT RF amplifiers, cryogenic tanks and Faraday cage, before the IOTs were installed and Faraday cage assembled in situ. The new electrical distribution elements were positioned; waiting for connection after the SPS beam was stopped in December 2017.

All main equipment pieces were installed during the 8 weeks of the year-end technical stop 2017-2018. The transfer table, designed for partial assembly in-situ, was mounted first at the test stand location. Two distribution valve boxes, at each extremity of the cryogenic transfer line, were then positioned, connected and tested.

All passive proximity equipment for RF power, one charge and one circulator per cavity, was put on the table and rolled in position towards the tunnel wall. The Service-box, also used for the validation tests of the cryomodule in SM18, followed and was set on the table.

Transport of the cryomodule from the test hall SM18 to its final location on the transfer table was monitored with tri-axial accelerometers and inclinometers to ensure that the transportation specification was respected. The cryomodule was finally lifted from the transport trailer and lowered on the table; supporting jacks were slid under the module and attached to the table, before lowering the cryomodule. Figure 4 fixes the moment when the cryomodule was lowered on the transfer table.

Figure 4: Installation of the prototype cryomodule on the transfer table. The two skids supporting one RF charge and circulator for each cavity are visible on the table, to the right.

All systems were then connected and validated progressively, including RF transmission lines, cryogenic flexibles, then the vacuum Y-chambers. Cables were connected at the end, allowing for precise cryomodule alignment via the frequency-scanning interferometric system [5].

The movable cryogenic plant had been designed for easy relocation with both compressor and oil-removal skid on a supporting frame. The skids were positioned on two supporting metallic structures fixed at the concrete slab in the surface building. The cold-box was transported to the tunnel in horizontal orientation via the freight lift, lifted and turned vertically with a hoist attached to the over-head rail, then transport fixtures were removed before lowering the 4 tonne cylinder to its final position. The whole cryogenic system was subsequently connected by welding and bayonet joints to the already installed infrastructure.

Once the RF power lines connected both to the cryomodule and to the IOT amplifiers, all systems were in place.

Commissioning of the cryogenic system proceeded along its layout, starting from the surface and progressively being extended to the underground equipment. Once the whole refrigeration and distribution system validated without the cryomodule charge, cooldown of the pumped cryomodule could start.

Before the SPS tunnel closure, all safety systems were tested and validated, ending with the access system. Once this last interlock removed, RF conditioning was performed on the cavities at 4 K.

CONCLUSIONS

The first beam, of intensity 0.2 - 0.8·10^{11} protons per bunch crossed the two crab-cavities on the 23rd May, with the cavities operated at 4 K due to some initial difficulties in the helium pumping units control. Nominal cryogenic operation conditions at 2 K could be achieved in August. It was the start of a fruitful harvest of results [6-9], the report of which is out of the scope of this paper.

An integrated, global approach to design, modelling and installation planning was essential to the success of the challenging task – both in space and time – asked by the HL-LHC project to the crab-cavities project.

ACKNOWLEDGMENTS

The design, integration and assembly of the SPS crab-cavity test stand was the achievement of a collective effort by several teams at CERN and numerous industrial partners. The contribution of each and every person was precious and essential to constructing what is now the first proton beam test stand for SRF structures.

REFERENCES

[1] G.Apollinari et al., “High-Luminosity Large Hadron Collider (HL-LHC): Technical design report v.0.1”, in *CERN Yellow reports: Monographs*, CERN, Switzerland, 2017.

[2] R. Calaga, “Crab Cavities for the High-luminosity LHC”, in *Proc. 18th Int. Conf. RF Superconductivity (SRF'17)*, Lanzhou, China, Jul. 2017, pp. 695-699. `doi:10.18429/JACoW-SRF2017-THXA03`

[3] R. Calaga, O. Capatina, and G. Vandoni, “The SPS Tests of the HL-LHC Crab Cavities”, in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 846-849. `doi:10.18429/JACoW-IPAC2018-TUPAF05`

[4] M. Garlasché *et al.*, “Assembly of the DQW Crab Cavity Cryomodule for SPS Test”, in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 2561-2564. `doi:10.18429/JACoW-IPAC2018-WEPMF078`

[5] H. Mainaud Durand *et al.*, “Frequency Scanning Interferometry as New Solution for on-Line Monitoring Inside a Cryostat for the HL-LHC project”, in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 1986-1989. `doi:10.18429/JACoW-IPAC2018-WEPAF068`

[6] B. Lindstrom *et al.*, “Machine Protection Experience from Beam Tests with Crab Cavity Prototypes in the CERN SPS”, in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, paper MOPMP036, pp. 520-523, `doi:10.18429/JACoW-MOPMP036`

[7] L. R. Carver *et al.*, “First Machine Developments Result with HL-LHC Crab Cavities in the SPS”, in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, paper MOPGW094, pp. 338-341, `doi:10.18429/JACoW-MOPGW094`

[8] S. Verdu-Andres, R. Calaga, E. Cano-Pleite, R. Leuxe, and J. A. Mitchell, “Design of LHC Crab Cavities Based on DQW Cryomodule Test Experience”, presented at the 19th Int. Conf. RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, paper THP035, this conference.

[9] K. Artoos *et al.*, “Status of the HL-LHC Crab Cavity Tuner”, presented at the 19th Int. Conf. RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, paper TUP081, this conference.