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Physics Procedia 67 (2015) 785 – 790

Physics Procedia

25th International Cryogenic Engineering Conference and the International Cryogenic Materials Conference in 2014, ICEC 25–ICMC 2014

The Cornell main linac cryomodule: a full scale, high Q accelerator module for cw application

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Abstract

Cornell University is in the process of building a 10 m long superconducting accelerator module as a prototype of the main linac of a proposed ERL facility. This module houses 6 superconducting cavities- operated at 1.8 K in continuous wave (CW) mode - with individual HOM absorbers and one magnet/ BPM section. In pushing the limits, a high quality factor of the cavities ($2•10^{10}$) and high beam currents (100 mA accelerated plus 100 mA decelerated) were targeted. We will review the design shortly and present the results of the components tested before the assembly. This includes data of the quality-factors of all 6 cavities that we produced and treated in-house, the HOM absorber performance measured with beam on a test set-up as well as testing of the couplers and the tuners.

Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014

Keywords: superconducting RF; accelerator cryo module; energy recovery linac

1. Introduction

The concept and the application range of Energy-Recovery Linacs (ERLs) have expanded dramatically over the past years, the LHeC and the ENC/EIC/ eRHIC are just two of the mayor projects. Cornell University has proposed an ERL as a driver for hard x-ray sources (Tigner (2013)) because of their ability to produce electron bunches with small, flexible cross sections and short lengths at high repetition rates, allowing us to pioneer the design and

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Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014
doi:10.1016/j.phpro.2015.06.133

hardware for such an ERL based light-sources. The National Science Foundation therefore has been funding Cornell University since 2005 to verify the required beam. On all these fronts, major milestones have been achieved: 75 mA beam currents, as reported by Dunham (2013) have surpassed the previous world record by a factor of two; the 90% x/y- emittance has become so small that an acceleration to 5 GeV would lead to 51/29 pm for 77 pC bunches and 23/14 pm for 19 pC (Gulliford (2013)). With 1.3 GHz bunch repetition, this 5 GeV beam could drive a hard-x-ray source with a brightness that is about 20 times larger than the brightest beam today (at PETRA-III).

Furthermore, it was important to show that the proposed operations cost of an ERL can be achieved, much of which is for cooling the SRF cryo-system. This paper will focus on this topic as it describes our effort to building a cryomodule based on high quality factors of the superconducting cavities.

2. Cryomodule layout, design choices and components

The general layout of the Main Linac Cryomodule (MLC) has been described in detail by Eichhorn (2013): It houses six superconducting 7-cell cavities and has an overall length of 10 m. The cavities were optimized in shape to have a high beam-break-up (BBU) limit for the beam current. As we expect an average of 200 W of higher order mode (HOM) power per cavity, HOM beam line absorbers are placed between the cavities, damping the RF by absorption. The cryo-module design has been guided by the ILC Cryomodule while necessary modifications have been made to allow CW operation. In addition, we decided to align all components inside the module by reference surfaces on the helium gas return pipe (HGRP). Fig. 1 gives an impression of the module layout.

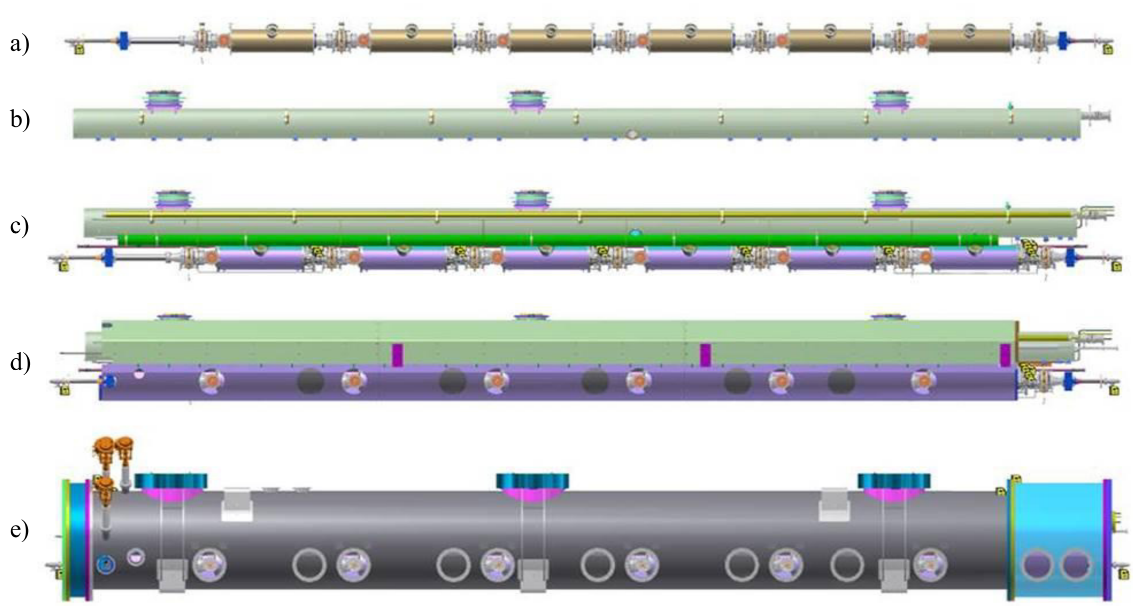

Fig. 1. Layout of the Cornell ERL linac Cryomodule, starting from the cavity string (a), helium gas return pipe (HGRP, b), the cold mass (c), thermal shield (d) and the vacuum vessel (e).

2.1. Cavity production

For the superconducting cavities, operated in CW mode, an operation temperature of 1.8 K has been chosen based on an optimization process. For these 7-cell cavities, oscillating at 1.3 GHz a quality factor of $2x10^{10}$ at an accelerating gradient of 16 MV/m has been envisaged, which, at the time of the decision, seemed to be very ambitious. So part of the R&D program was to ensure that these parameters can be achieved reliably. In addition, to guaranty a high BBU-limit, tight mechanical tolerances on the cavity shape had to be met.

All cavities for the MLC have been produced in-house. The process began with half cells formed by a deep drawing process in which sheet metal of 3 mm RRR niobium is radially drawn into a forming die by a first press at 3 tons, then a second forming press (100 tons). The dies for the center cells were carefully designed to deal with the spring back effect. The equators of each cup have an additional straight length on them (approx. 1.5 mm). The purpose of this extra length is to allow for trimming later on to meet the target frequency and length. Those dumbbells are built in an intermediate step by welding two cups together on their irises. Ultimately six dumbbells were be welded together by electron beam welding to form the center-cells of the seven cell cavity and end-cells with end-groups are added After welding, the assemblies were cleaned by both chemical etching and a high purity water rinse to rid them of any surface impurities that may have accumulated during the production process.

For the preparation of the cavity, a simple recipe – being modified with experience- based on BCP has been chosen. Starting after fabrication, the damage layer is removed by bulk buffered chemical polishing (BCP, 140 µm). While we started to measure the removal rate with a witness sample first we learned that an on-line ultrasonic head measurement is more appropriate. The hydrogen degassing is done at 650 °C for 4 days while we monitor the hydrogen residual gas inside the furnace. Studies showed that a higher temperature (800 °C) seems to remove more hydrogen but would slightly soften the cavity which would still be acceptable. One cavity has been treated such, showing a slightly higher Q.

During the cavity production, we improved the mechanical tolerances in the cavity forming and welding, leading to a mean length deviation of the last 3 cavities by only 0.2 mm. Bullock (2013) reported the measures takes.

The SRF properties of the 7-cell main Linac cavity were characterized at several stages before completing the assembly. Fig. 2 shows the Q data of all 6 cavities. As can be seen, all cavities surpass the design specifications. In addition, we saw a very reliable and reproducible performance which is quite remarkable.

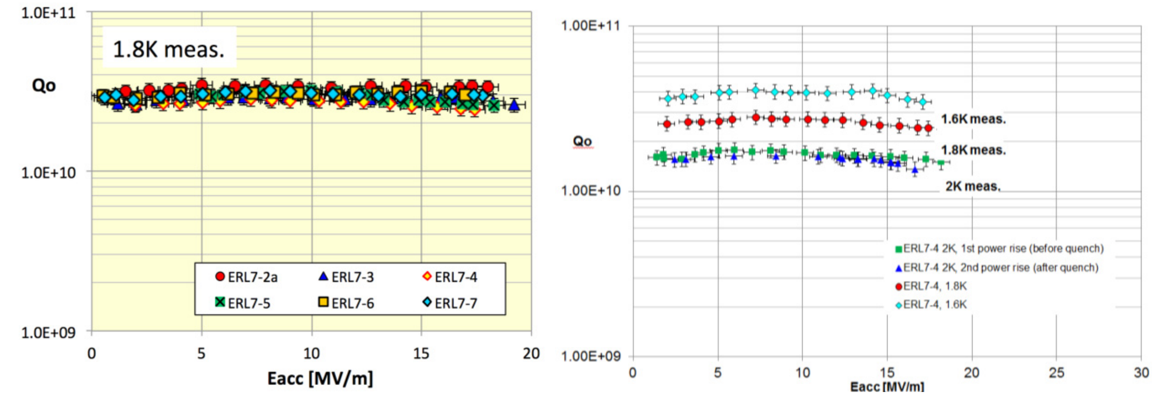

Fig. 2. Left: Vertical test results for all 6 ERL cavities. All cavities exceeded the design specifications for the ERL ($Q=2*10^{10}$ at 1.8 K). The right diagram shows the Q vs E curves for different temperatures of a single cavity. The reproducibility of the results, gained without any reprocessing of a cavity, is remarkable.

2.2. HOM absorber

The center assembly of the higher order mode (HOM) absorber consists of the absorbing cylinder which is shrink fit into a titanium cooling jacket and flange (see Fig. 3). The cooling jacket and flange locate, support, and provide cooling at 80 K to the absorbing cylinder using a cooling channel inside the titanium. For these production pieces, the absorbing material is Silicon Carbide, SC-35® from Coorstek. The shrink fit is designed so that all materials have a safety factor of at least 2 to yielding at 5 K and the fit will stay tight during a bakeout at 200 C. Details on that fit been reported by He (2013).

The end pieces of the assemblies contain a 3 convolution bellows, a 5 K cooling plate, and taper seal flange to mate with the cavities. The bellows allows for small length variations in the string, small angular misalignments of cavity flanges, as well as adds a long thermal path from 80 K to 5 K. Any rotational misalignment is accounted for in slots in the bolt holes of the central 3 flanges which allow for a few degrees misalignment of the cavity flanges on either end. There are positive stops that prevent the bellows from compressing and closing the gap between the 5 K cooling jacket and the absorbing cylinder to less than 1 mm. This prevents any rubbing of metal to ceramic that could create particles. The beam tubes have a copper plating about 10 micron thick to prevent beam induced heating.

The overhead support is designed to have a similar spring rate to the transverse spring rate of the bellows so that the vertical load is evenly shared between the three springs. The plates are titanium to try to match the thermal

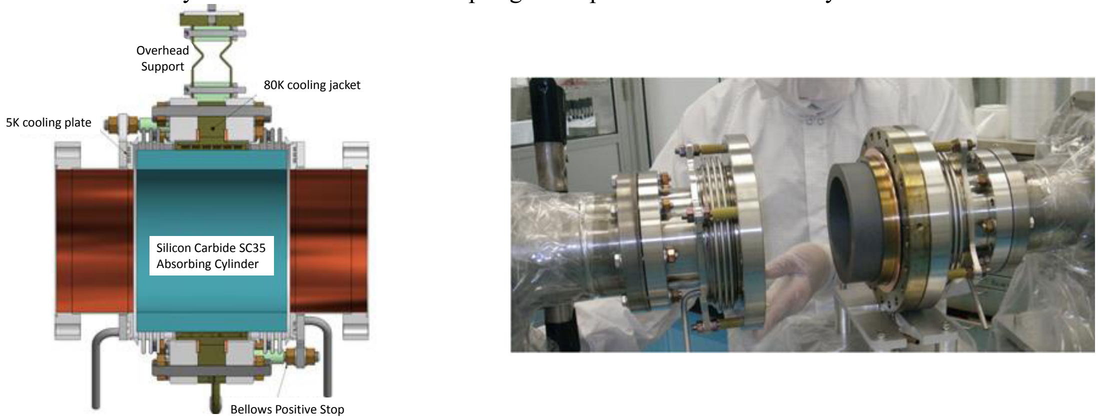

Fig. 3. Left: Cross section view of the HOM beam line absorber. It consists of an RF absorbing ceramics, shrink fitted into a titanium cylinder with a labyrinth cooling channel milled into it. The operation temperature is 80 K. The picture on the right shows the absorber being mounted to the cavity string inside the clean room.

expansion coefficient of the vertical supports on the other string components. The G10 pieces are included to reduce the thermal conduction from the 80 K cooling jacket to the helium gas return pipe it is bolted to.

A prototype of the absorber has been tested on a cavity running an electron beam of up to 40 mA. As Eichhorn (2014) reported, no significant heating was observed will all higher order modes where sufficiently damped.

2.3. Vacuum vessel

The cylinder of the vacuum vessel is 965.2 mm in diameter, rolled longitudinally welded carbon steel (A516 GR70) pipe and stainless steel flanges that use O-ring seals. Due to vendor's limited capability of final machining of the entire length of the vessel in a single setup, the vacuum vessel is made from three spool pieces. The spools are bolted with pins for alignment, and then welded together from the inside of the joining flanges to make up the full length. All precision required surfaces are machined in a single spool piece setup. Dowel pins and reference surfaces on the end flanges are used for the alignment to meet the GD&T requirements of the final vessel. Both the interior and exterior steel surfaces are painted, the interior being painted with PSX 700 Engineered Siloxane while a marine paint was chosen as the exterior paint. Figure 4 on the left shows a photograph.

Fig. 4. Left: Vacuum Vessel as received by Cornell University. Right: Marriage step: the cavity string coming from the clean room assembly is rolled under the HGRP providing precision alignment.

2.4. Helium gas return pipe and alignment

The Helium Gas Return Pipe (HGRP) is fabricated from a rolled and welded Grade 2 Titanium cylinder. During test fit of the baffle sub-assembly (which is needed in the prototype to guide the cold helium gas stream through the full length of the HGRP which lags the downstream flow from an adjacent module) in the Ti pipe, it was noticed that

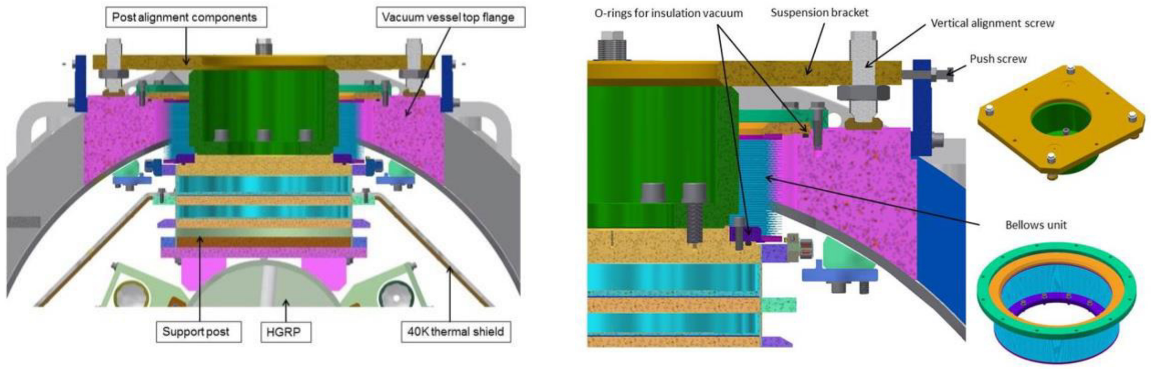

Fig. 5. HGRP support post cross section on the left. The right drawing shows the post alignment components.

the baffle tube was flexible and the spoke support rods did not all make contact to the Ti pipe. This was solved by extending the support rods to ensure a tight fit with an extra pressure.

Being the reference for the alignment of the beam-line string, the surfaces of the HGRP top and bottom supports are precision machined with a single machine tool setup at the final stage after all welding is done. The beam-line string is suspended under the Helium Gas Return Pipe (HGRP) which acts as the beam-line backbone and is supported by three support posts to the vacuum vessel (see Fig. 5). To accommodate the HGRP thermal contraction at cold relative to the vacuum vessel, the two side posts are slide-able over the top flanges while the central post is locked in position. The central position of the side posts are pre-shifted at room temperature and will be concentric to the vacuum vessel flange at cold.

The posts has a same design as those used in the TTF cryomodule, which is an assembly of a low thermal conduction composite material pipe (G10 fiberglass pipe) and four stages of shrink-fit metal discs and rings. The two stainless steel disc/ring sets are connected respectively to the room temperature and to the 2 K cold mass environments. The two aluminum disc/ring sets provide thermal intercepts at 40 K and 5 K, with the 40 K set also providing structural support to the 40 K thermal shield. The heat load through conduction of each post (see Fig. 5) is estimated to be 8.58 W to 40 K, 0.54 W to 5 K and 0.05 W to 1.8 K, respectively.

The HGRP defines the reference for the precision alignment of the beam-line string. Relative vertical alignment is ensured by precision machining on the interfacing surfaces of the supports, with a single machine tool setup at the final stage after all welding is done and a vibration stress relief is performed. The transverse and longitudinal alignment is obtained by the alignment pins on the support plates. The alignment key or a flexible cavity support allows the beam-line components to slide longitudinally relative to the HGRP during thermal cycling. The assembly sequence is that the beam-line string will be assembled in the clean room, and then attached to the HGRP. Once the cold mass is assembled, it will be rolled into the vacuum vessel on its rail system which seems to be more elegant than the ILC cryomodule assembly.

For the cold mass assembly, the HGRP was mounted to the 80-20 support structure (Fig. 4, right) via the 3 composite post support columns. An initial reference check of the 24 mounting feet along the bottom was conducted by pulling a string secured from the first and last mounting feet tight over the ~10 m length of the HGRP. The mounting surfaces near the center section of the HGRP appeared to be high by ~5 mm. This indicated a slight banana shape was present in the HGRP which was confirmed by laser tracking surveys.

During these surveys, it was observed that the Gr-2 Ti HGRP was more flexible than was initially understood through calculation and simulation. These surveys also indicated that a significant twisting along the HGRP axis was not present. Upon mounting the HGRP back on the support structure, an upward bow of now ~3 mm was observed. After much discussion and experiment, it was observed that the mounting surfaces on the bottom of HGRP could be brought to within ~1 mm of flatness across the entire span by applying an ~400 kg load near the center of the HGRP.

It was understood that this load would be present naturally when the ~3 ton cold mass was mounted and fully dressed. After mounting the raw cavity string, a final laser tracker survey was completed that indicated these surfaces to be within an acceptable tolerance and work resumed to complete assembly (see Fig. 4, right).

2.5. Thermal and magnetic shields

The fabrication of the 40 K thermal shield and magnetic shield, being attached to each other, are handled by the same vendor, to ensure they fit well at pre-mounting. Due to a limited furnace size for the hydrogen annealing after forming of the Mu-metal sheet, the magnetic shield sections are consists of many small patches in 1 m x 1.2 m, with overlaps at joints. Enough clearance is ensured between sections and the joints, to account for differential thermal contractions between the magnetic shield (Mu-metal) and the thermal shield (Al1100-14). Details are shown in Fig. 1. It should be noted that every cavity is enclosed by a second magnetic shield, made from cryoperm®.

3. Status and outlook

Cornell University has achieved important milestones for the construction of ERL light sources: world-record currents from a photo injector; ultra-small emittances; long-lived photocathodes and SRF cavities with extremely high Quality factors which had been the focus of this article. The design goal of $2*10^{10}$ at 16 MV/m and 1.8 K, set a decade ago seems unrealistic at that time but is being achieved and outperformed regularly, today.

We have measured a Q as high as $6*10^{10}$ for a cavity being fully dressed with a power coupler and two adjacent HOM absorbers in our Horizontal Test Cryostat (HTC), as reported by Liepe (2013). It should be noted that this cavity in a vertical test achieved only $2.7*10^{10}$ displaying more the limitations of the vertical testing area (for example due to limited magnetic shielding or the lack of cryo-control to perform a slow cool-down transition through the critical temperature. Based on this we expect the 6 cavities produced for the MLC, having an average Q in the vertical test of $2.8*10^{10}$ to have Qs around $5*10^{10}$ in the full module.

For the cryomodule assembly, all components have been received and all critical performance parameters have been verified. The cavity string has been mounted inside the cleanroom in spring 2014. This string has been attached to the HGRP providing the alignment with only minor issues. Currently, the cryogenic piping is attached to the cold mass and we expect the shields to be mounted in early fall 2014. The full cryomodule is expected to be assembled by the end of 2014. The work currently is slightly ahead of schedule.

So far, some components behaved differently as designed (as we reported above). Nevertheless, all issues could be resolved. To conclude, we think it was well justified to build this prototype and to adjust the design based on that experience. The fabrication is also seen as a preparation step for future industry collaboration, defining key procedures and quality standards. We believe that these technologies have sufficiently progressed years to allow the construction of an ERL-based light source.

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