Nuclear Instruments and Methods in Physics Research A 834 (2016) 1–9

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Methodology for the structural design of single spoke accelerating cavities at Fermilab

Donato Passarelli [a,b,*], Robert H. Wands [a], Margherita Merio [a], Leonardo Ristori [a]

[a] Fermi National Accelerator Laboratory, 60510 Batavia, IL, USA
[b] Department of Civil and Mechanical Engineering, University of Pisa, 56122 Pisa, Italy

ARTICLE INFO

Article history:
Received 30 October 2015
Received in revised form
8 June 2016
Accepted 7 July 2016
Available online 9 July 2016

Keywords:
LINAC
SRF
Single Spoke Resonators
Pressure vessels
ASME Code

ABSTRACT

Fermilab is planning to upgrade its accelerator complex to deliver a more powerful and intense proton-beam for neutrino experiments. In the framework of the so-called Proton Improvement Plan-II (PIP-II), we are designing and developing a cryomodule containing superconducting accelerating cavities, the Single Spoke Resonators of type 1 (SSR1). In this paper, we present the sequence of analysis and calculations performed for the structural design of these cavities, using the rules of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC). The lack of an accepted procedure for addressing the design, fabrication, and inspection of such unique pressure vessels makes the task demanding and challenging every time. Several factors such as exotic materials, unqualified brazing procedures, limited nondestructive examination, and the general R&D nature of these early generations of cavity design, conspire to make it impractical to obtain full compliance with all ASME BPVC requirements. However, the presented approach allowed us to validate the design of this new generation of single spoke cavities with values of maximum allowable working pressure that exceeds the safety requirements. This set of rules could be used as a starting point for the structural design and development of similar objects.

1. Introduction

Superconducting radio-frequency (SRF) cavities are crucial components of modern high-performance particle accelerators to impart energy to the charged particles. Their dramatically lower electrical losses allow operation at substantially higher duty cycles than conventional copper cavities. Accelerators are used for high-energy physics, low-energy to medium-energy nuclear physics research and free-electron lasers. They are also essential tools in industry for industrial processes, in medicine for cancer therapy, for national security, and many additional future accelerator applications are envisioned and under study.

From a mechanical engineering standpoint, a jacketed SRF cavity is typically comprised of an inner niobium vessel (or SRF cavity) surrounded by a liquid helium containment vessel made of stainless steel or titanium. The helium bath may reach pressures exceeding 15 psi (0.103 MPa) and generally has a volume greater than five cubic feet (0.142 m^3). All this leads to consider a jacketed SRF cavity as a system of pressure vessels.

Based on the Department of Energy (DOE) directive 10 CFR 851, it is mandatory for safety reasons that all pressure systems designed, fabricated and tested by U.S. National Laboratories conform to ASME Codes. As a consequence, jacketed SRF cavities fall within the scope of the following sections of the ASME Boiler and Pressure Vessel Code:

- Section VIII – Pressure Vessels, Divisions 1 and 2
- Section II – Materials, Parts A–D
- Section V – Nondestructive Examination
- Section IX – Welding and Brazing Qualifications

It is acknowledged that a true Code design is not currently possible, primarily due to the use of non-Code materials, the unfeasibility of Code-required nondestructive examinations of welded joints and the use of unqualified procedures for welding and brazing. A set of rules have been developed by engineers at Fermi National Accelerator Laboratory [1] based on their current understanding of best practice in the design, fabrication, examination, testing, and operation of the jacketed SRF cavities. These guidelines comply with Code requirements wherever possible, and for non-Code features, procedures were established to produce a level of safety consistent with that of the Code design.

* Corresponding author at: Fermi National Accelerator Laboratory, 60510 Batavia, IL, USA.
E-mail address: donato@fnal.gov (D. Passarelli).

http://dx.doi.org/10.1016/j.nima.2016.07.013
0168-9002/

2. Design methods for jacketed SRF cavities

The mechanical design of jacketed SRF cavities can be approached starting with the ASME BPVC, Section VIII [2,3]. This section provides detailed requirements for the design, fabrication, testing, inspection, and certification of both fired and unfired pressure vessels. Section VIII contains three divisions, each of which covers different vessel specifications. Division 3 provides rules to pressure vessels that operate at pressures exceeding 10,000 psi. It is not applicable to the design of SRF cavities since they are designed for much smaller working pressures.

Division 1 (Div. 1) is directed at the design of basic pressure vessels, intending to provide functionality and safety with a minimum of analysis and inspection. Common component geometries can be designed for pressure entirely by these rules but they may be not enough for the design of all cavity components under all loading cases (cooldown, additional forces, etc.). Nondestructive examinations (NDE) of welds can typically be avoided by taking a penalty in overall thickness of a component.

Division 2 (Div. 2) is directed at engineered pressure vessels, which can be thought of as vessels whose performance specifications justify the more extensive analysis and stricter material and fabrication controls and NDE required by this Division. The design is governed by two loosely-coupled provisions: Part 4 (Design by Rule), and Part 5 (Design by Analysis). A device may be designed by either Part; regardless of the Part used, the provisions of Parts 3, 6, and 7 (materials, fabrication, and inspection) must be met. The rules of Part 4 are very thorough, duplicating many of the rules of Div. 1, while expanding them to cover a wider range of geometries. The rules of Part 5 provide for a strictly analytical approach to the vessel design. A numerical analysis technique is assumed, and either an elastic or an elastic–plastic analysis is permitted. The mandatory NDE for welded joints in this Division is extensive.

The ASME BPVC Section II is a “Service Section” for reference by the BPVC construction Sections providing tables of material properties including allowable, design, tensile and yield strength values, physical properties and external pressure charts and tables. Part D contains appendices which include criteria for establishing allowable stresses. Some of the materials for the construction of SRF cavities are not accepted by the Code. As a result, the mechanical properties of these materials are not available in Section II, Part D of the Code. Therefore, experimental tests have to be used in the determination of the material properties for non-Code recognized materials. Subsequently, the material properties determined have to be utilized to calculate the maximum allowable stress values using the Code methodology.

The ASME BPVC Section V contains requirements and methods for nondestructive examination which are referenced and required by other BPVC Sections (i.e. Section VIII). Examination methods are intended to detect surface and internal discontinuities in materials, welds, and fabricated parts and components. Examination as per the ASME BPVC is not practical because SRF cavities are constructed of non-Code materials. The ASME Process Piping Code, B31.3, does allow for construction with non-Code materials and is deemed more applicable to the SRF cavity.

The ASME BPVC Section IX contains rules related to the qualification of welding, brazing, and fusing procedures as required by BPVC Section VIII for component manufacture. It also covers rules relating to the qualification of welders, brazers, and welding, brazing and fusing machine operators. The manufacturing of jacketed SRF cavities implies the use of electron-beam welding, gas tungsten arc welding (also known as tungsten inert gas welding), and brazing. Procedures that will guarantee a reasonable level of certainty that the SRF accelerating structure to be fabricated will be in compliance with ASME BPVC must be developed. In each case, if the welded joint or brazed joint is not a standard ASME Code joint, the development must also include sufficient analysis and testing to support the conclusion of equivalent safety. A base set of acceptable weld and braze parameters has to be established for each non-standard joint to assure their integrity examining with a microscope, metallograph or SEM weld and braze samples made by using the contractor's welding/brazing machine. Weld and braze samples for each joint must be as representative as possible: mass, geometry and material thickness, of the actual joint on the structure. Moreover, a sufficient number of samples per weld and braze should be produced to allow tensile tests and bend tests (face and root) at 300 K, 77 K and 4 K. Samples must also be radiographed or ultrasonically examined.

3. SSR1 case

SRF cavities called Single Spoke Resonators of type 1 (SSR1) are fundamental to the design of a superconducting linear particle accelerator for PIP-II project at Fermi National Accelerator Laboratory [4,5]. They were optimized for interactions with proton beam at $\beta = 0.22$ and will operate at 325 MHz in continuous wave (CW) regime.

The jacketed SSR1 cavity consists of two nested cryogenic pressure vessels: the inner vessel is the superconducting SSR1 cavity, see Fig. 1,

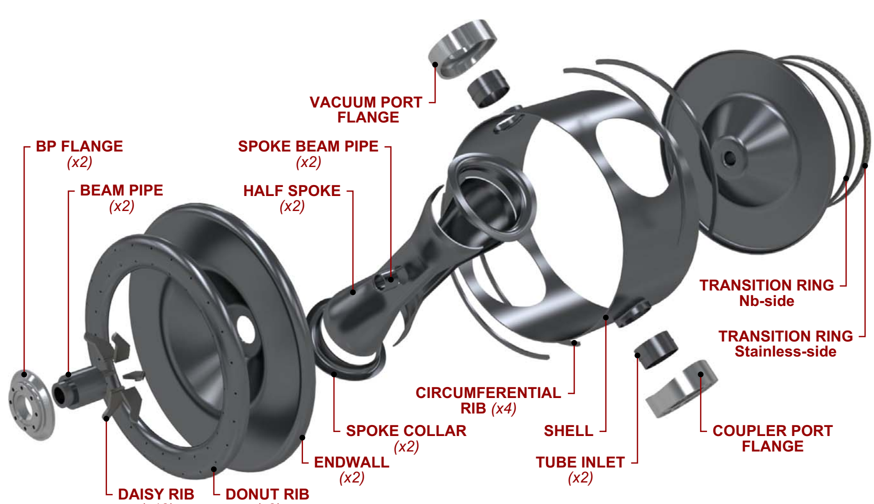

Fig. 1. Exploded view of the niobium SSR1 cavity.