PROJECT X CAVITY AND CRYOMODULE DEVELOPMENT*

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Abstract

Project X is a proposed multi-MW proton accelerator facility based on an H- linear accelerator using superconducting RF technology at Fermilab. The Project X 3 GeV continuous wave linac requires the development of two families of superconducting RF cavities at 325 and 650 MHz, to accelerate 1 mA of average H- beam current in the energy range 2.5-160 MeV, and 160-3000 MeV, respectively. These cavities must support possible acceleration of up to 4 mA beam current. The baseline design calls for three types of superconducting single-spoke resonators at 325 MHz having geometric phase velocities, β_G, of 0.11, 0.22, and 0.42, and two types of superconducting five-cell elliptical cavities having $\beta_G = 0.61$ and $\beta_G = 0.9$. The electromagnetic and mechanical designs of the cavities are well underway and prototype tests for some cavity designs have started. Because of the CW operation, the heat load on the cryogenic system is substantial; and for purposes of cryogenic system design, the dynamic heat load is limited to 250 W at 2K per cryomodule. The anticipated heat loads for the 650 MHz section lead to stringent requirements on cavity unloaded quality factor Q_0, and on cryogenic aspects of the cryomodule design. Status and plans for the Project X cavity and cryomodule development will be described.

INTRODUCTION

Project X is a proposed multi-MW proton accelerator facility at Fermilab based on an H- linear accelerator using superconducting RF technology; the schematic layout of the complex is shown in Fig. 1. The 3 GeV Project X linear accelerator (linac) provides a continuous-wave (CW) 3 GeV 1 mA H- beam to an experimental area, and is injected into a pulsed linac for further acceleration to 8 GeV and injection into the Main Injector. These beams will support a variety of experiments in kaon, muon, nuclear, and neutrino physics [1-3]. The 3 GeV linac will use superconducting 325 MHz single-spoke cavities, and 650 MHz elliptical cavities. The 3-to-8 GeV linac will use 1300 MHz Tesla-type elliptical cavities. Six distinct cavity designs are planned spanning the geometric phase velocity range from β_G=0.11 to β_G=1. These cavities will be assembled into three different types of cryomodules. All cavities will operate at a temperature, still under consideration, between 1.8 and 2.1 K. The designs of the cavities and cryomodules for the 3 GeV linac are in progress. The 3-8 GeV pulsed linac will take advantage of the well-developed 1300 MHz Tesla-type cavities in ILC-like cryomodules. The remainder of this paper will focus on the development of the new cavities and cryomodules for the CW 3 GeV linac; the main parameters of the linac sections are listed in Table 1.

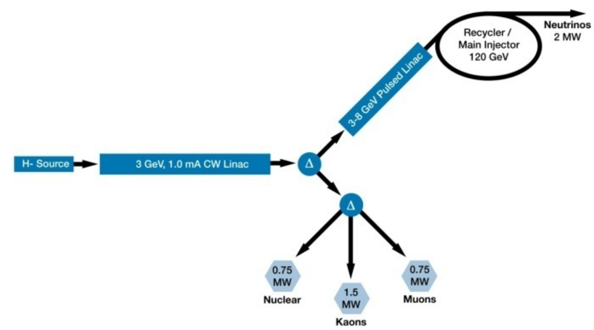

Figure 1: Schematic layout of the Project X accelerator complex.

Table 1: Parameters of the 3 GeV CW linac sections

Section	Freq (MHz)	Energy (MeV)	#cavities/ focusing elements/ cryomodules	Component Type
SSR0 β=0.11	325	2.5-11.4	18/18/1	single-spoke cavity, solenoid
SSR1 β=0.22	325	11.4-43	20/20/2	single-spoke cavity, solenoid
SSR2 β=0.4	325	43-179	44/24/4	single-spoke cavity, solenoid
LB 650 β=0.61	650	179-559	42/28/7	5-cell cavity, doublet
HB 650 β=0.9	650	559-3000	152/38/19	5-cell cavity, doublet

CAVITY DESIGN AND PERFORMANCE

The 3 GeV linac includes five distinct cavity types, spanning the geometric velocity factor range β_G = 0.11 to β_G = 0.9, with approximately 80 single-spoke cavities at 325 MHz and 200 elliptical cavities at 650 MHz.

325 MHz Single-Spoke Cavities

The three single-spoke cavities: SSR0, SSR1 and SSR2, have geometric velocity factors β_G = 0.11, 0.22, and 0.4, respectively. The cavity designs are described in detail in [4].

The SSR0 cavity design is challenging because it has very tight lattice requirements and a strong sensitivity to microphonics due to its small accelerating gap length. The design of the SSR0 cavity is complete, and initiation of procurements of two prototype SSR0's is planned for this year.

The SSR1 cavity was designed and prototyped in the context of the High Intensity Neutrino Source (HINS) program at Fermilab. Two prototypes have already been built and tested with encouraging results. Examples of cavity performance are shown in Fig. 2. The two

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prototype SSR1 cavities were tested in the Vertical Cavity Test Facility (VCTF) at Fermilab. Buffered chemical polishing (BCP) and high-pressure rinsing (HPR) of the cavities was performed at ANL as part of the Fermilab-ANL collaboration on superconducting cavity processing and testing. These cavities both exceeded their design specifications by about a factor of two in gradient. Peak surface magnetic fields of ~130 mT were achieved in a 2K test [5]. After vertical test, one of the cavities was welded into a stainless steel helium vessel, and outfitted with a cavity tuning system and RF power coupler. This cavity was tested at Fermilab in the Spoke Cavity Test Cryostat (SCTC), which is currently capable of 4.2 K operation and will be upgraded for 2 K operation within the next year. The cavity has been tested in the SCTC under both CW and pulsed conditions, greatly exceeding performance specifications in both cases [6].

Ten additional SSR1 cavities are under production at Niowave/Roark. The first one of these has been delivered; the remainder are expected this year. In addition, two cavities are being fabricated by our Project X collaborators at the Inter University Accelerator Center (IUAC) in New Delhi, India.

The SSR1 was designed for a pulsed machine; to optimize it for use in a CW machine, it was necessary to reconsider the frequency sensitivity to helium bath pressure variations. A new helium vessel, coupled to the end wall of the cavity, was designed to reduce the cavity df/dP to less than 5 Hz/torr.

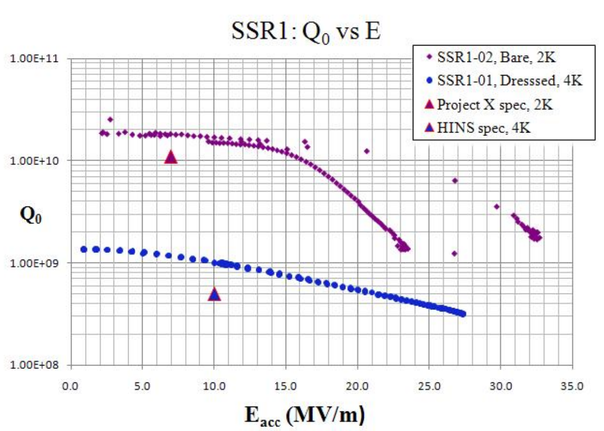

Figure 2: Performance of SSR1 cavities in bare (purple) and dressed (blue) cavity tests, at 2K and 4.2K, respectively, exceeded the specifications, shown by the purple and blue triangles, respectively, by a large margin.

The electromagnetic design of the SSR2 cavity for the β_G = 0.4 section is complete; the mechanical design is preliminary and underway.

650 MHz Elliptical Cavities

Two five-cell elliptical cavities are planned for Project X: β_G = 0.61 and β_G = 0.9 [7]. The anticipated heat loads for the 650 MHz section lead to stringent requirements on cavity unloaded quality factor Q_0. Each cryomodule for these cavities must dissipate no more than 250W average and peak power at 2K [8]; this leads to a requirement for cavities, using some assumptions about the power dissipation of other cryomodule components, of <35W per cavity for β_G = 0.61 cavities and <25W per cavity for β_G = 0.9 cavities.

As part of the Fermilab-JLab Project X collaboration, two prototype single-cell 650 MHz β_G = 0.61 cavities were designed, fabricated, processed and tested by JLab, with excellent results [9,10]. The cavities were processed with standard techniques, including bulk BCP, 600C for 10 hours hydrogen degassing, and another light BCP (no electropolishing). For this cavity, the 35W power requirement corresponds to Q_0>8.8E9 at 2K for E_{acc}=16 MV/m and Q_0>1.3E10 at 2K for E_{acc}=19 MV/m. The test results, shown in Fig. 3, demonstrate the achievement of the Q_0 requirement at 16 MV/m for cavity #2. Further surface processing is likely to bring both cavities into conformance with the performance requirement, and electropolishing may not be required. Further mechanical studies will be required to extend this design to a 5-cell cavity which is stiff enough reduce sensitivity to helium bath pressure variations, Lorentz force detuning, and microphonics, but still tunable.

In addition, a Fermilab electromagnetic design for single-cell and 5-cell β_G = 0.61 cavities was completed [11].

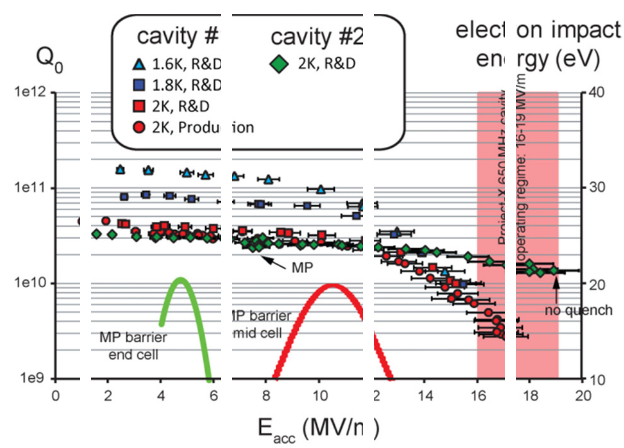

Figure 3: Test results from the JLab prototype cavities. Cavity #2 exceeded the specification at 16 MV/m. A multipacting simulation is shown on the secondary vertical axis.

The design for the 650 MHz β_G = 0.9 cavities is complete [12]. Six prototype single-cell cavities have been ordered from industry, and two five-cell 650 MHz β_G=0.9 cavities will be ordered soon. These cavities will be processed and tested at Fermilab/ANL facilities. Primary features of the cavities include a large beampipe aperture of 100 mm and conservative peak magnetic field of 70 mT. The more stringent power dissipation requirement is likely to require careful optimization of surface processing. The prototype cavities do not have HOM couplers [13].

CRYOMODULE DESIGNS

The cryomodules are in the conceptual design stage. Segmentation of the linac, which determines the number of cavities per cryomodule and the cavity spacing, is based on lattice requirements, heat load, and reliability issues. The cryomodule design work is being conducted with collaborative participation from colleagues at JLab and Raja Ramanna Centre for Advanced Technology (RRCAT) in Indore, India.

325 MHz Cryomodules

Conceptual design work is underway for 325 MHz cryomodules [14] for SSR0, SSR1 and SSR2 cavities. The three types of 325 MHz cryomodules, although containing different numbers and types of cavities and focusing elements, shall have as common a design as possible.

The SSR0 cryomodule is challenging because it contains the largest number of components and is therefore the longest cryomodule in the linac. The lattice calls for 18 cavities and 18 superconducting solenoids, with a maximum cavity-to-cavity spacing of 610 mm. This results in a cryomodule longer than 10 m. In comparison, the European XFEL cryomodule is about 12 m long and contains significantly fewer elements: eight 1.3 GHz superconducting cavities and one superconducting quadrupole. The lattice requires minimal spacing between the SSR0 and SSR1 cryomodules, further complicating their designs.

To minimize project risk, a prototype SSR1 cryomodule will be designed, constructed and tested; the conceptual design is shown in Fig. 4.

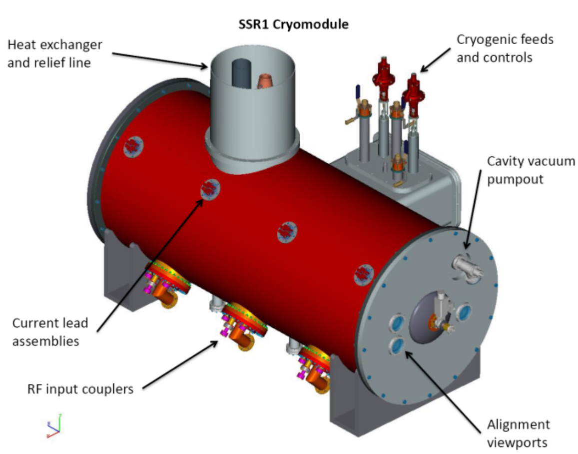

Figure 4: 325 MHz cryomodule concept.

650 MHz Cryomodules

The conceptual design of the 650 MHz cryomodules is also underway [8]; the two types of cryomodules, while containing different numbers and types of cavities and focusing elements, will be made as similar as possible. Most of the design work so far is for the β_G = 0.9 cryomodule, which contains eight cavities per cryomodule for an overall length of 12 m. The number of cavities per cryomodule is based on a practical heat load limit of 250 W to the 2 K circuit per cryomodule, which in turn is based primarily on sizing considerations for the helium piping and heat exchanger. The baseline design concept includes cryomodules closed at each end, individual insulating vacuums, with warm beam pipe and magnets in between cryomodules, so that individual cryomodules can be warmed up and removed while adjacent cryomodules remain cold. A cross section of the cryomodule conceptual design is shown in Fig. 5.

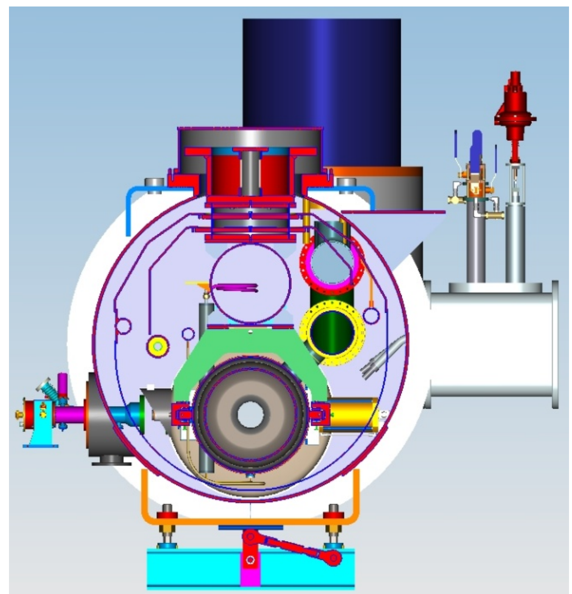

Figure 5: Cross section of 650 MHz cryomodule concept.

AUXILIARY COMPONENTS

The RF power couplers [15] and cavity tuning systems are being developed along with the cavities and cryomodules. Each cavity will have a slow frequency tuner driven by a stepping motor and a fast piezoelectric tuner that will be used to mitigate microphonics caused by ambient vibrations and helium bath pressure fluctuations. A sophisticated microphonics compensation has been demonstrated on a prototype SSR1 [16,17].

CONCLUSIONS

The cavity and cryomodule designs for the Project X 3 GeV linac are underway. The cavity prototypes built so far are performing to requirements: SSR1 cavities have shown excellent performance in vertical dewar and horizontal cryostat testing, and initial vertical test results from β_G = 0.61 single-cell 650 MHz cavities have demonstrated the feasibility of the design for 5-cell cavities. Cavity design, fabrication, and test are underway to confirm designs for the complement of cavities required for Project X within the next 1-2 years. Cryomodule conceptual design work has identified baseline configurations that will also be further developed over the next couple of years, and a prototype cryomodule will be built to confirm the design.

ACKNOWLEDGEMENTS

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