SRF DEVELOPMENT FOR A MW PROTON SOURCE AT FERMI NATIONAL ACCELERATOR LABORATORY*

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Abstract

Fermilab is planning a megawatt-level proton source, Project X, which will provide high-intensity H^- beams for research into the nature of matter at the "intensity frontier." Project X will utilize niobium superconducting RF (SRF) cavities: 162.5 MHz half-wave resonators, 325 MHz single-spoke resonators, and two types of elliptical multi-cell 650 MHz cavities in the 0-3 GeV portion of the linac. Performance requirements for these cavities and cryomodules in continuous-wave (CW) operation are extremely stringent to provide high accelerating gradients with acceptable total cryogenic load and overall accelerator capital and operating costs. This paper presents some highlights of the SRF R&D program and H^- linac development work at Fermilab.

PROJECT X

Project X [1] is a high intensity proton source that will support a world-leading U.S. program in Intensity Frontier physics over the next several decades, and will support simultaneously:

1. Neutrino experiments: Provide at least 2 MW of proton beam power at any energy between 60 – 120 GeV; several hundred kW of proton beam power on target at 8 GeV.
2. Rare process experiments: Provide MW-class, 1-3 GeV proton beams supporting multiple kaon, muon, nuclei, and neutron precision experiments.
3. Upgrade path toward a future Neutrino Factory and Muon Collider.
4. Materials science and nuclear energy applications: Provide MW-class beams at 1 GeV.

Project X is being developed by Fermilab with national and international partners. The SRF cavity and cryomodule layout is shown in Fig.1. Up to 3 GeV, the linac will be operated CW, and from 3-8 GeV, the linac will be operated in pulsed mode. The average beam current is 2 mA up to 1 GeV, 1 mA from 1-3 GeV, and 43 μA (4.3% duty cycle) from 3-8 GeV. The project requires six different types of SRF cavities operating at four different frequencies and seven different types of cryomodules, as shown in Table 1, all operating at 2ºK. Fermilab will test prototypes of each cavity and cryomodule type before starting the construction of the linac. Staging schemes are under development to allow the opportunity of physics output at each stage within funding constraints. The Project X Injector Experiment (PXIE) will demonstrate the Project X injector through the first SSR1 cryomodule. Continuous wave (CW) operation, narrow RF bandwidth, low average beam current, and 2 K dynamic heat loads in the HB650 cavities of up to 250 W per cryomodule result in some constraints and special features which differ from those of other SRF linacs, which are being addressed via our SRF R&D program.

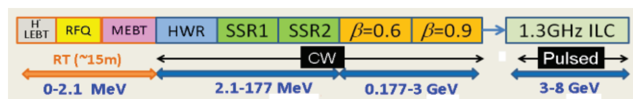

Figure 1: Layout of the Project X SRF cryomodules.

Table 1: Project X SRF Cavities and Cryomodules

Cavity Type	Freq, MHz	Energy, MeV	Cav/mag/CM	CM type, length
HWR (β_G=0.11)	162.5	2.1-11	8 /8/1	scscscscscscscsc, 5.3m
SSR1 (β_G=0.22)	325	11-38	16 /8/ 2	csccsccsccsc, 4.8m
SSR2 (β_G=0.51)	325	38-177	35 /21/ 7	sccsccsc, 6.5m
LB650 (β_G=0.61)	650	177-480	30 /20/5	cccfdccc, 7.1m
HB650 (β_G=0.9)	650	480-1000	42 /16/ 7	cccccc, 9.5m
HB650 (β_G=0.9)	650	1000-3000	120/30/ 15	cccccccc, 11.2m
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 / 28/ 28	ccccfcccc, 12.6m

PROJECT X SRF ISSUES

Cryostat Design

For several reasons there is a preference for separate liquid management in each cryomodule. These include large dynamic heat loads and their resulting high liquid flow rates, individual, small heat exchangers from 2 to 4.5 K, a preference for warm magnets and instrumentation between cryomodules, improved pressure stability, and the ability to remove and reinstall individual cryomodules more quickly and without the need to warm the entire string.

Cavity High Q_0 R&D

Significant project cost savings may be realized by maximizing the unloaded quality factor (Q_0) at the operational temperature. The cryogenic system capital cost is proportional to (RF load)$^{0.6}$ ~ $Q_0^{-0.6}$ for fixed gradient; the cryogenic system cost is ~20% of the project cost. The operational cost is proportional to the RF load ~ Q_0^{-1} for fixed gradient. Moreover, for a fixed RF load, higher Q_0 allows higher operational gradient, which may reduce the capital cost (length) of the linac. An increase of Q_0 by a factor two may save many tens of millions of dollars for this billion-dollar-scale project. An intensive

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ISBN 978-3-95450-122-9

cavity surface processing R&D effort is ongoing at Fermilab to find a recipe which maximizes Q_0 at 2 K for operating peak magnetic fields in the range 60-80 mT. In the first phase of the program, innovative surface processing and simple inexpensive twists to the typical processing stream are being evaluated. Some examples include furnace treatments with the injection of a small partial pressure of gases like nitrogen or argon at high temperature, an HF rinse following the 120ºC bake, and elimination of chemistry after hydrogen degassing. Very promising results have been achieved so far, including: via nitrogen furnace treatments, systematic BCS resistance improvements by 100% or more; via furnace treatments without subsequent chemistry, residual resistances <1 nΩ; via single HF rinse (5 min) followed by water rinse only, Q_0 gains of up to 35% [2]. This R&D is done on ILC f=1.3 GHz and β=0.9 f=650 MHz single-cell cavities at gradients of interest to Project X. The most promising surface treatments will be performed on 9-cell ILC cavities, which will then be dressed with a helium vessel and tested with high power, to confirm preservation of high Q_0. Emphasis will be placed on the minimization of trapped flux caused by inadequate shielding of the Earth's magnetic field, multipacting quenches, or thermal currents being generated during cooldown.

Cavity High-Order Modes

Coherent excitation of high-order modes (HOMs) in the SRF cavities in Project X might be a concern. Beam power lost to HOMs adds to the cryogenic losses and increases the operational cost of the linac. Interaction of the H^- beam with excited HOMs may also deteriorate the quality of the beam. Both non-propagating and propagating modes in the Project X linac have been simulated for each of the cavity types [3]. The effects of HOMs in a possible high-current scenario, up to 10 mA, have also been studied [4]. These studies show that power losses to HOMs are small, and the probability for losses to exceed 10 mW is less than 1%. In addition, the probability of longitudinal emittance growth is extremely small for a 1-2 mA average beam current. Based on these studies, HOM couplers are not needed for the Project X cavities.

Cavity Microphonics

For Project X, the low beam loading (1-2 mA) requirement implies a narrow cavity bandwidth which leads to a strong sensitivity to microphonics. The microphonics control strategies which are being implemented [5] are: to provide sufficient reserve RF power to compensate for the expected peak detuning levels, to improve the regulation of the bath pressure to minimize the magnitude of cyclic variations and transients, to reduce the sensitivity of the cavity resonant frequency to variations in the helium bath pressure *(df/dP)*, to minimize the acoustic energy transmitted to the cavity by external vibration sources, to actively damp cavity vibrations using a fast mechanical or electromagnetic tuner driven by feedback from measurements of the cavity resonant frequency. The microphonics design parameters of the Project X cavities are listed in Table 2.

RF Coupler Requirements

Project X couplers must provide reliable operation at power levels of ~ 30 kW CW, and be flexible enough to permit possible operation at higher current in the future. Table 3 lists the design parameters of the couplers being designed at Fermilab. To reduce complexity, the same coupler is used for SSR1 and SSR2 cavities, except for the antenna tip. Figure 2 shows the coupler design for 325 MHz SSR. Both designs feature single ceramic windows, fixed coupling, an air-cooled center conductor, and the possibility to bias.

Table 2: Project X Microphonics Parameters

Cavity Type	Freq, MHz	Microphonic amplitude (peak Hz)	Min half bandwidth (Hz)	Max req'd power (kW)
HWR (β_G=0.11)	162.5	20	24	4.9
SSR1 (β_G=0.22)	325	20	27	5.5
SSR2 (β_G=0.51)	325	20	23	17
LB650 (β_G=0.61)	650	20	23	34
HB650 (β_G=0.9)	650	20	23	50
HB650 (β_G=0.9)	650	20	23	31
ILC 1.3 (β_G=1.0)	1300	30	65	50

Table 3: RF Coupler Parameters

Cavity Type	Max energy gain (MV)	Max power (I_{ave}=1 mA)	Max power (I_{ave}=2 mA)
SSR1 (β_G=0.22)	2	4	6
SSR2 (β_G=0.51)	5.3	12	17
LB650 (β_G=0.61)	11.7	30	40
HB650 (β_G=0.9)	11.7	30	50

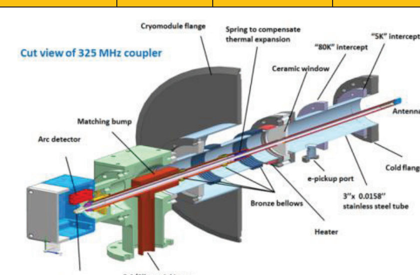

Figure 2: 325 MHz coupler.

CAVITIES & CRYOMODULES

325MHz β=0.22 Single-Spoke Resonator (SSR1)

The R&D for these cavities started as part of the High Intensity Neutrino Source (HINS), a technology demonstration program for a high-intensity pulsed linac. Two prototypes were fabricated in industry, processed in collaboration with ANL, and tested at Fermilab. One of the prototype cavities was dressed with a helium vessel, coupler, tuner, and was successfully tested at Fermilab in the spoke test cryostat (STC). Two cavities are currently

ISBN 978-3-95450-122-9

in fabrication at IUAC-Delhi as a part of a collaboration between Fermilab and a group of Indian institutions (IIFC). Ten production cavities were fabricated by US industry and delivered to Fermilab. Six cavities have been processed and tested, and all have reached the required performance: $E_{acc}=V_{acc}/\beta\lambda\geq12$ MeV/m and $Q_0\geq5E9$ at 2 K [6]. Figure 3 shows the test performance to date.

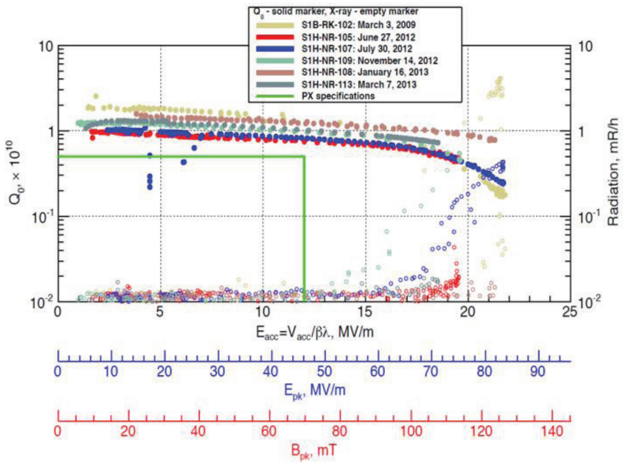

Figure 3: SSR1 bare cavity test performance.

SSR1 Cryomodule

The conceptual design of the SSR1 cryomodule has been completed and is being peer reviewed. See Figure 4. The detailed design is in progress. Prototypes of the critical components including solenoid, solenoid current leads, and fundamental power coupler, have been ordered and will be tested before the detailed design is finalized.

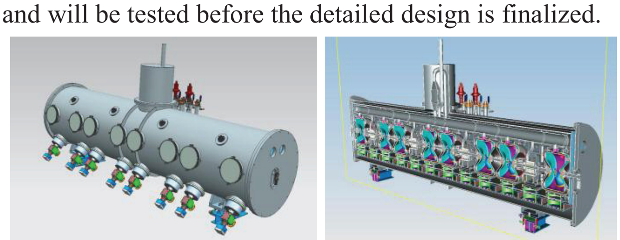

Figure 4: A view of the SSR1 cryomodule.

325MHz, β=0.51 Single Spoke Resonator (SSR2)

The electromagnetic design of the SSR2 cavity is completed, and the mechanical design is quite advanced [7]. The final design and fabrication of the cavities and cryomodules will be managed between Fermilab and RISP (Korea), once the collaboration is established.

650MHz Cavities (β = 0.61 and 0.9)

The 650 MHz sections contain ~75% of the total number of the Project X CW cavities, consume ~ 90% of the RF power and provide ~90 % of cryogenic system losses. Thus, the 650 MHz cavities drive both the capital and operational cost of Project X. Design optimizations are underway to better establish electromagnetic parameters including field enhancement, R/Q, G-factor, multipacting, HOMs, and coupling; mechanical parameters: deformation, stress, and thermal analysis; and self-consistent electromechanical (cavity + helium vessel) parameters: stiffness, tuning efficiency, df/dP, and mechanical resonances. Two single-cell prototypes of the β=0.61 cavity were built, processed, tested at JLab, and exceeded requirements [8]. Six single-cell prototypes of the β=0.9 cavity were built in industry, and two have been processed and tested at Fermilab. Both tested cavities significantly exceeded performance requirements (17 MeV/m @ 2e10 Q0). The maximum gradient achieved was 31 MeV/m, and Q_0 at 17 MeV/m is 3.2~4.5E10. Additional single-cell and 5-cell cavity prototypes for both *β* are currently being fabricated in industry.

650MHz Cryomodule

The baseline design concept includes closed-end cryomodules with individual insulating vacuum, warm beam pipe and magnets in between cryomodules. Some design features minimize cavity vibration and coupling of external sources to cavities, provide good cavity alignment (<0.5 mm), allow removal of up to 250 W at 2 K per cryomodule, and provide excellent magnetic shielding for high Q_0. Cryomodule design work is progressing through IIFC. Figure 5 shows a conceptual design of the 650 MHz cryomodule.

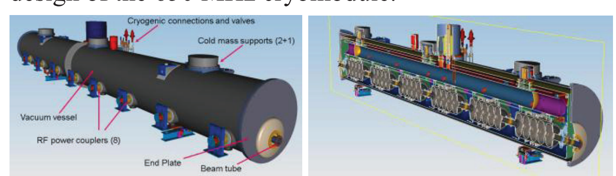

Figure 5: 650 MHz cryomodule conceptual design.

SUMMARY

Project X is central to the strategy for future development of the Fermilab accelerator complex. The critical SRF R&D needed to provide proof-of-principle for Project X has been described.

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ISBN 978-3-95450-122-9