Abstract

Project X is a new SRF linac based multi-MW class proton source proposed for construction at Fermilab. It consists of a 3 MW, 1 mA, CW H\textsuperscript{+} SRF linac that feeds an Intensity Frontier Physics program and a 3-8 GeV pulsed linac that accelerates ~4\% of the output of the CW linac for injection into the Fermilab Main Injector synchrotron. The Main Injector then provides an additional 2 MW of beam power at 60-120 GeV in support of a world-class long baseline neutrino program. The project has chosen operating frequencies that are sub-harmonics of 1.3 GHz and is developing 6 separate Superconducting Radio Frequency (SRF) cavity designs for acceleration of H\textsuperscript{+} particles with various velocities. An R&D program is in progress to develop these cavities, the associated cryomodules, and the required fabrication and test infrastructure. A status and progress report on this R&D program is presented.

PROJECT X GOALS

Project X is being developed to meet the requirements described in strategic plans developed by Fermilab and HEPAP [1, 2]. Design goals are based on three principal physics goals defined within these strategic plans:

- A neutrino beam for long baseline neutrino oscillation experiments. The desired beam power is in excess of 2 MW, available at any energy over the range 60-120 GeV.
- High intensity, low energy proton beams for kaon, muon, and nuclei based precision experiments. The desired beam power is in excess of several 100 kW per experiment, in the energy range 1-8 GeV. It is essential that the delivered beams be available with a variety of duty factors and bunch configurations and that the program can operate simultaneously with the neutrino program.
- A path toward a muon source for a possible future Neutrino Factory and/or a Muon Collider. This requires an upgrade potential to ~4 MW of beam power in the energy range 5-15 GeV, and the ability to deliver this beam in intense pulses.

PROJECT X REFERENCE DESIGN

A schematic of the Project X Reference Design [3, 4] is shown in Fig 1. The design is based on a 3 GeV continuous wave (CW), superconducting H\textsuperscript{+} ion linac followed by a 3-8 GeV superconducting (SC) linac that is used to accelerate a portion of the beam to the injection energy of the existing Fermilab Main Injector synchrotron. The 3 MW, CW linac operates with an average current of 1 mA, but with peak currents as high as 5 mA for times less than the ~ 1 μsec required to extract <<1\% of the stored energy of the SC cavities. When combined with a broad band chopper and RF separation cavities, this permits beam intensities, pulse duration, and repetition rates to be tailored to a wide range of rare decay experiments. Provisions will be included in the design of the first 1 GeV of the CW linac to accelerate 2 mA which will permit generation of as much as 1 MW of beam power at 1 GeV to support a future low energy nuclear physics or materials irradiation program. Couplers for the CW SRF cavities are designed for average currents as high as 5 mA to support future machine upgrades. Approximately 4\% of the 3 GeV CW linac beam power is diverted to the pulsed linac for acceleration to 8 GeV. This pulsed linac operates with 4.3\% duty factor and sends beam into the existing 8 GeV fixed energy Recycler Ring via many turn injection. The 8-GeV linac also services a separate 8 GeV Physics program. When sufficient beam is accumulated in the Recycler, it is transferred by single turn injection into the existing Main Injector ring and accelerated to 60-120 GeV before extraction to serve the long baseline neutrino program.

![Figure 1: Project X schematic layout.](image)

The machine parameters for the Project X reference design are shown in Table 1. Key to the broad physics reach of the planned experimental program is that large beam powers can be delivered simultaneously to the 1 GeV, 3 GeV, 8 GeV, and 60-120 GeV programs. Moreover, the planned broadband chopper at 2.1 MeV and RF selection will enable a variety of bunch patterns to be delivered simultaneously to a broad program of rare decay experiments.
### Table 1: Project X Reference Design Goal

<table>
<thead>
<tr>
<th>CW Linac</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Type</td>
<td>H⁺</td>
<td></td>
</tr>
<tr>
<td>Beam Kinetic Energy</td>
<td>3 GeV</td>
<td></td>
</tr>
<tr>
<td>Average Beam Current</td>
<td>1 mA</td>
<td></td>
</tr>
<tr>
<td>Linac pulse rate</td>
<td>CW</td>
<td></td>
</tr>
<tr>
<td>Beam Power to 1 GeV program</td>
<td>1000 kW</td>
<td></td>
</tr>
<tr>
<td>Beam Power to 3 GeV program</td>
<td>2870 kW</td>
<td></td>
</tr>
</tbody>
</table>

### Pulsed Linac

| Particle Type                 | H⁺       |          |
| Beam Kinetic Energy           | 8 GeV    |          |
| Pulse rate                    | 10 Hz    |          |
| Pulse Width                   | 4.3 msec |          |
| Cycles to Recycler/MI         | 2.7×10¹³ |          |
| Beams per cycle to Recycler/MI| 6        |          |
| Beams per 8 GeV program       | 170 kW   |          |

### Main Injector/Recycler

| Beam Kinetic Energy (maximum) | 120 GeV  |
| Cycle time                   | 1.2 sec  |
| Particles per cycle          | 1.5×10¹⁴ |
| Beam Power at 120 GeV        | 2400 kW  |

### SRF Cavities Development

- The Project must develop six different cavities optimized for the changing velocity (β) of the H⁺.
- The cavities operate at 4 different frequencies (162.5, 325, 650, and 1300 MHz).
- Five of these cavities are completely new designs for Project X. (the exception being the 1300 MHz cavity developed for XFEL and ILC).
- Operation at the high gradients, and high Q₀ to control cost.
- CW operation at 2 K ➔ large heat loads on cavities and cryomodules.
- Narrow bandwidths that require control of cavity microphonic detuning.

Significant cost savings are achieved in the pulsed linac by choosing technology developed for the European X-ray Free Electron Laser (XFEL) and the International Linear Collider (ILC). The XFEL/ILC cavity has enjoyed extensive development and industrialization efforts. Cavities used in the CW linac are based on sub-harmonic frequencies of 1300 MHz. Additional cost savings are achieved by eliminating HOM couplers in the CW linac which are not needed for average currents up to 5 mA.

The choice of the lowest frequency, 162.5 MHz, is driven by matching to the RFQ frequency which in turn was determined by the cooling requirements of a conservatively designed CW RFQ. An overview of the cavities and cryomodules (CM) required for Project X is shown in Fig. 2.
industry. Parts for these cavities can be seen at the vendor (Roark) in Fig. 3. Fermilab has currently taken delivery of six of these cavities. Two of these cavities have been BCP processed at ANL and tested bare at Fermilab at 2 K in a vertical Dewar. Fig. 4 shows the measured quality factor ($Q_0$) vs. accelerating gradient for these cavities. Both cavities comfortably meet Project X requirements. Additional cavity tests as well as tests of fully dressed cavities are planned as part of the overall effort to construct a complete prototype of the Project X SSR1 cryomodule.

**Figure 3: SSR1 cavities in fabrication at Roark.**

650 MHz Cavity and CM Development

From 160 MeV to 3000 MeV H$^+$ are accelerated by two families of 650 MHz 5-cell elliptical cavities with geometric $\beta$ values of 0.61 (LE) and 0.90 (HE). Single cell prototypes of both the LE and HE cavities have been fabricated. Two LE single cell cavities were fabricated and tested at Jefferson Lab (JLAB) and one of these cavities was also tested at Fermilab. Both cavities exhibit excellent $Q_0$ and exceed Project X gradient requirements. Fig. 5 shows the performance of the LE single cell cavities measure at JLAB. [7] The goal for Project X operating gradients for 650 MHz cavities is 16 MV/m for the LE Cavities and 19 MV/m for HE cavities with a $Q_0 > 1.7 \times 10^{10}$. The $Q_0$ at operating gradient has a significant cost impact on the overall project cost since 650 MHz cavities dominate the overall cryogenic load for Project X. As a result, an extensive R&D effort has been launched with the goal of increasing the quality factor of these cavities. Five single cell $\beta = 0.90$ cavities were recently manufactured in U.S. Industry (Advanced Energy Systems), Fig. 6, and work is in progress to process and test them with results expected over the next year.

A CAD rendering of a 5-cell HE cavity is shown in Fig. 7. Fermilab has also ordered an additional five single cell and nine 5-cell HE cavities from U.S. Industry with first deliveries of 5-cell cavities expected in fall of 2012.

**Figure 5: Single cell $\beta = 0.90$ 650 MHz cavity measured at JLAB in vertical Dewar.**

SSR2 cavity development will proceed with the fabrication of prototypes in industry in future years as overall R&D funding for the Project permits.

In parallel with the development of the SSR cavities, Fermilab is engaged in developing a design for the SSR cryomodules. The current design employs cavities and magnetic focusing elements supported from below; all housed in stand-alone cryostats; each fed by u-tubes and with its own 2K heat exchanger. The design is advanced and we anticipate ordering SSR1 CM parts in the next year.

**Figure 6: Single cell $\beta = 0.90$ 650 MHz cavities.**

Extensive design work is in progress to develop the required 650 MHz CW cryomodules. Fermilab is carrying out this work in collaboration with Raja Ramanna Centre...
for Advanced Technology (RRCAT), India. The design is a variant of the ILC/XFEL cryomodule modified for the higher expected heat loads, larger cavities, and stand-alone operation (i.e., each cryomodule is fed by u-tubes). The cavity Helium vessel, tuner, and coupler are also the subject of extensive design efforts.

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**1300 MHz Cavity and CM Development**

The 3-8 GeV linac in Project X is built around 1300 MHz technology developed for XFEL and ILC. This choice allows Project X to leverage the extensive worldwide R&D and industrialization program carried out with these cavities and cryomodules. The Project X pulsed linac would employ ILC-like cryomodules connected end-to-end in long cryogenic strings. Project X envisions several changes to the ILC CM and linac design. The Project X pulsed linac would operate at 1 mA and 10 Hz with 4.3 ms long pulses and at a reduced accelerating gradient of 25 MV/m. These changes are expected to increase cavity yield and reduce costs compared to ILC. A summary of 1300 MHz bare cavity vertical tests produced by the U.S. ILC R&D program is presented in Figure 8.

Fermilab assembled and tested a 1300 MHz cryomodule (CM1) from a kit of parts provided by the Deutsches Elektronen-Synchrotron (DESY) lab. CM1 achieved an average operating gradient of 23.7 MV/m, close to the Project X requirements, but less than might have been expected from tests of individual cavities at DESY before incorporation into the CM. Results from the test of CM1 [9] are summarized in Fig. 9. Fermilab has recently assembled CM2, a CM populated completely by 1300 MHz cavities processed in the U.S. and chosen to achieve an average CM gradient in excess of 31.5 MV/m. Figure 10 shows CM2 during installation. A summary of the cavity performance for CM2 is presented in Fig. 11. Experience gained in the assembly and test of CM1 and CM2 has been invaluable for the overall Project X cavity and CM development effort at Fermilab.

![Figure 7: CAD rendering of 5-cell $\beta = 0.90$ 650 MHz cavity.](image)

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![Figure 8: Summary of gradient performance for 1300 MHz $\beta = 1$ cavity processed and tested in the U.S. as part of the ILC R&D program.](image)

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![Figure 9: CM1 cavity performance. Blue corresponds to single dressed cavity tests, red is performance in CM1.](image)

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![Figure 10: CM2 Installation for testing.](image)

![Figure 10: CM2 Installation for testing.](image)
SUMMARY

Project X is a powerful and flexible new proton source proposed for construction at Fermilab. Fermilab has mounted a large R&D effort to develop the cavities, cryomodules, SRF infrastructure and trained technical staff required to build this machine. The FNAL SRF R&D program supports Project X, ILC, and other Office of Science goals. The program built an extensive new set of SRF infrastructure that is now in operation that supports the development of the required SRF cavities for Project X. A large effort has been made to transfer SRF technology to U.S. Industry and a focused effort to understand the science of SRF surfaces with the goal of improving SRF cavity performance (gradient, Q₀, reduced costs) is under way. The program is making steady progress towards the goal of a new high intensity proton source at Fermilab.

ACKNOWLEDGEMENT

The progress summarized in this paper is the result of the talent and tireless effort of both the Project X design team and the SRF teams at Fermilab, JLAB, and many other U.S. and international partners. The author wishes to thank these individuals, as well as the Department of Energy Office of High Energy Physics which funds these efforts.

REFERENCES