SRF CAVITY RESEARCH FOR PROJECT X

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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^- 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^- 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^- 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.

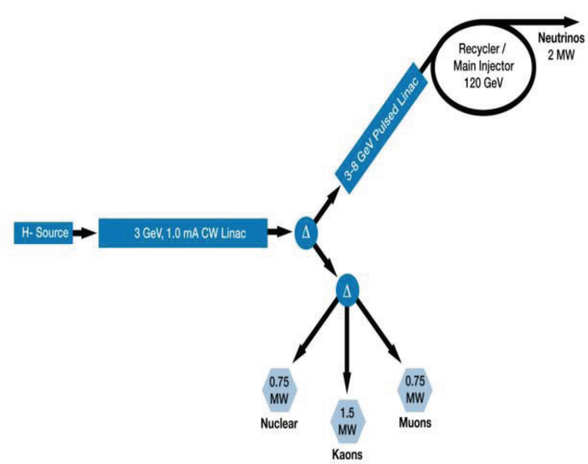

Figure 1: Project X schematic layout.

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.

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Table 1: Project X Reference Design Goal

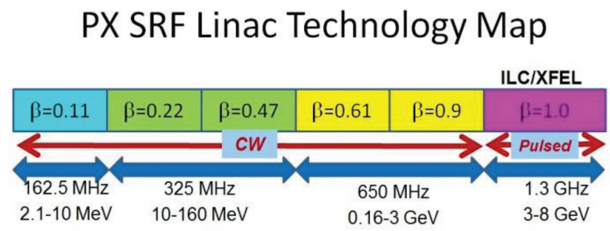
CW Linac		
Particle Type	H^-	
Beam Kinetic Energy	3	GeV
Average Beam Current	1	mA
Linac pulse rate	CW	
Beam Power to 1 GeV program	1000	kW
Beam Power to 3 GeV program	2870	kW
Pulsed Linac		
Particle Type	H^-	
Beam Kinetic Energy	8	GeV
Pulse rate	10	Hz
Pulse Width	4.3	msec
Cycles to Recycler/MI	6	
Particles per cycle to Recycler/MI	2.7×10^{13}	
Beam Power	340	kW
Beam Power to 8 GeV program	170	kW
Main Injector/Recycler		
Beam Kinetic Energy (maximum)	120	GeV
Cycle time	1.2	sec
Particles per cycle	1.5×10^{14}	
Beam Power at 120 GeV	2400	kW

SRF CAVITY DEVELOPMENT

The Project X 3 GeV CW SRF linac followed by a 3-8 GeV SRF pulsed linac results in a powerful new accelerator in support of the Intensity Frontier, but presents new challenges:

- 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 Q_0 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.



Section	Freq	Energy (MeV)	Cav/mag/CM	Type
HWR (β_G=0.11)	162.5	2.1-10	9 /6/1	Half Wave, solenoid
SSR1 (β_G=0.22)	325	10-42	16/8/ 2	Single Spoke, solenoid
SSR2 (β_G=0.47)	325	42-160	36/20/4	Single Spoke, solenoid
LB 650 (β_G=0.61)	650	160-460	42 /14/7	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	460-3000	152/19/19	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 /28 /28	9-cell elliptical, quad

Figure 2: Project X Linac Technology Map including cavities and cryomodule (CM) requirements.

162.5 HWR Development

The first SRF cavities in Project X are employed immediately down-stream of the 2.1 MeV RFQ and broadband chopper. The use of CW SRF acceleration at this very low energy is unique to the Project X design and presents additional challenges. The cavities must be compact longitudinally and the beam optics design requires strong magnetic focusing elements very close to the SRF cavities. Moreover, the first SRF cavities will be physically very close to a high power (> 10 KW) beam absorber that will be heated and ablated by the chopped 2.1 MeV beam.

The SRF scheme adopted for low energy front end of Project X is based on a single cryomodule containing eight 162.5 MHz SRF Half Wave Resonators (HWR) alternating with SC solenoid/corrector elements. These cavities and the associated cryomodule are being developed in collaboration with Argonne National Laboratory (ANL), which has extensive experience with similar cavities and cryomodules developed for the ANL ATLAS accelerator. Prototype cavities are currently being fabricated in U.S. industry and the cryomodule design is in progress. [5] The HWR cryomodule will accelerate the beam to 10 MeV.

325 MHz Spoke Resonator Development

From 10 MeV to 160 MeV H^- are accelerated by 325 MHz Single Spoke Resonators (SSR). Project X employs two families of SSR cavities with β values of 0.22 (SSR1) and 0.47 (SSR2). The electromagnetic and mechanical designs for both families of cavities are complete. Prototypes for SSR1 are more advanced since two successful prototypes were fabricated and tested as part of High Intensity Neutrino Source (HINS) R&D program at Fermilab. One of these cavities was fully dressed with Helium vessel, tuner, and coupler. [6] Both cavities performed well in bare tests at 2 K. The dressed cavity performed well at 4.8 K with pulsed RF and plans are in place to test it at 2 K with CW RF. SSR activity has now moved to construction of ten SSR1 cavities in U.S.

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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.

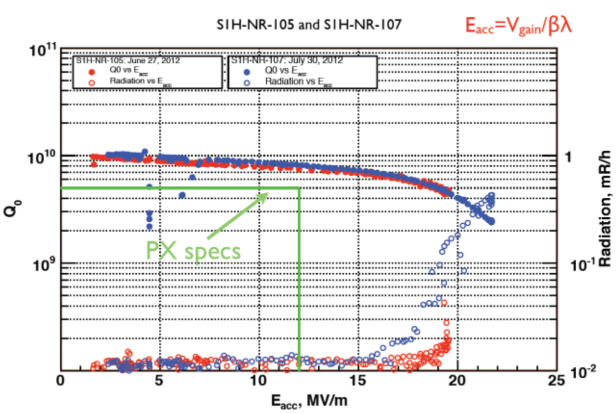

Figure 4: SSR1 cavity VTS results.

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.

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 β 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 β = 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.

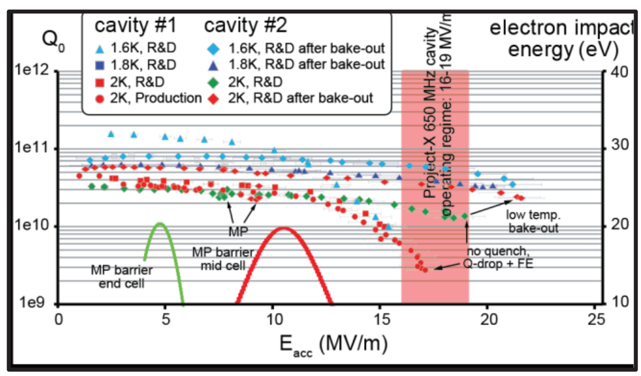

Figure 5: Single cell β = 0.90 650 MHz cavity measured at JLAB in vertical Dewar.

Figure 6: Single cell β = 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

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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.

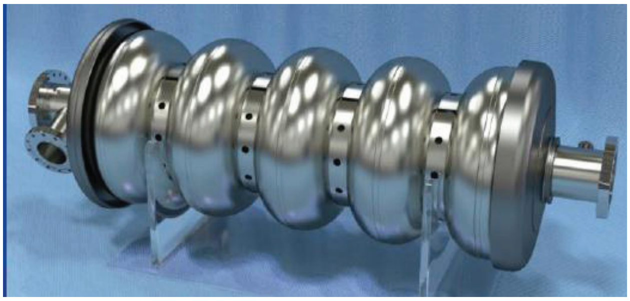

Figure 7: CAD rendering of 5-cell β = 0.90 650 MHz cavity.

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 world-wide 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.

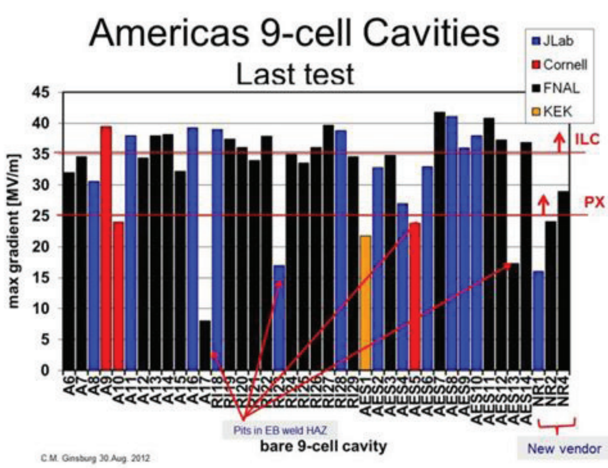

Figure 8: Summary of gradient performance for 1300 MHz β = 1 cavity processed and tested in the U.S. as part of the ILC R&D program.

Many cavities comfortably exceed Project X gradient requirements. Although not apparent from the figure, recent improvements in EP processing; understanding of the effects of Nb material residual stress in producing pits during EP; and newly developed cavity repair methods based on Centrifugal Barrel Polish (CBP) [8] all will serve to increase yields and reduce Project X costs.

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.

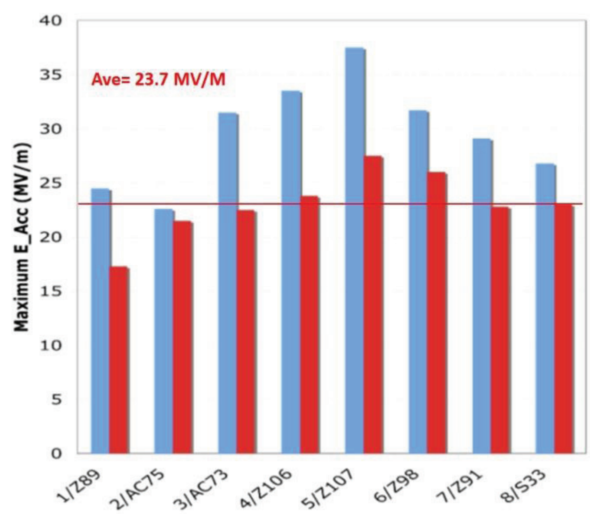

Figure 9: CM1 cavity performance. Blue corresponds to single dressed cavity tests, red is performance in CM1.

Figure 10: CM2 Installation for testing.

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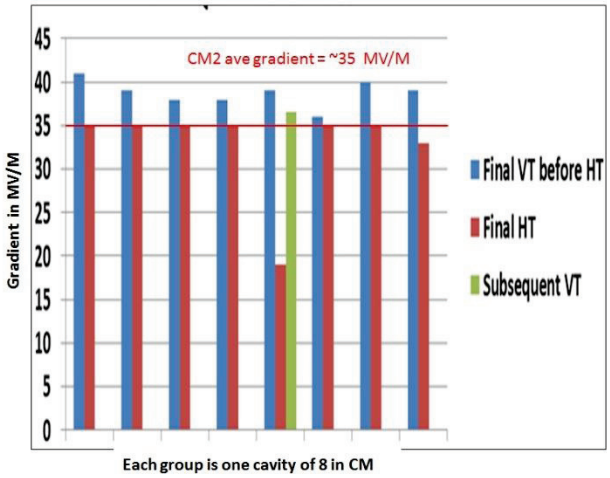

Figure 11: CM2 Individual Cavity Performance.

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, Q_0, reduced costs) is under way. The program is making steady progress towards the goal of a new high intensity proton source at Fermilab.

ACKNOWLEDGEMENT

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